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Mash Separation in the Lauter Tun – a Particle Size Dependent Separation Process

Lautering is a solid liquid separation in the brewhouse for which the dominant filtration mechanisms are still unknown. The wide particle size distribution of the involved solids leads to the hypothesis that during lautering different particle size fractions are experiencing different filtration mechanisms. To investigate this matter sedimentation behavior, particle size distribution in the lautering filter cake, and the concentration of free fatty acids were analyzed. It can be shown that coarse particles (> 500 µm) are forming a cake by sedimentation whereas fine particles (< 500 µm) are experiencing a cake filtration on top of this sediment and colloidal particles such as fatty acids are separated by depth filtration.

Descriptors: lautering, mash separation, fatty acids, particle size distributions, sedimentation

1 Introduction

Mash separation is a solid liquid separation in the beer brewing process. There are two main approaches for this process. On the one hand the mash filter, a classic membrane filter press [1]. On the other hand the lauter tun an unusual kind of filtration device [2] and the focus of this research project. The mash, a suspension of sugary liquid and particles of a very wide particle size and shape distribution, is transferred into the lauter tun. Afterwards a sedimentation takes place to form a filter cake of significant height [3] and to enable the separation [4]. Due to the wide particle size and settling velocity distribution of the solids, the sediment consists of horizontal layers of different properties. Literature reports mainly two layers: coarse particles form the so called Unterteig above the filter medium whereas fine particles form a jellylike layer on top, the so called Oberteig [5, 6]. Figure 1 shows the layered structure of the spent grains filter cake.

After the start of filtration, the filtrate is passing through the sediment and particles kept in suspension are forming a growing layer (Oberteig) of fine particles on top of the sedimentation layer (Unterteig). The developing cake is not only inhomogeneous but highly compressible [7]. The different layers feature different particle sizes, particle shapes, and filter cake resistances. The resulting filter cake is compressing over time and problems like cake blocking are often reported [5, 8–10]. These factors and the hydrostatic pressure as the only driving force are making the lautering process a challenging task [4].

After the end of the filtration step the cake is washed by flushing the cake with hot water. Remaining sugars are flushed out and the filter cake is further compressed to its end height. To prevent the cake from blocking during filtration, special devices, the so called raking knives, are used. These vertical knives rotate on a horizontal arm circular through the packed bed. The raking knives are loosening the cake but their use leads to a higher turbidity, which is an important quality characteristic [11, 12]. Therefore breweries aim to reduce raking in general.

One knowledge gap and often cited need for further research is the determination of predominant kinds of filtration. Literature often reports of a superposition of surface filtration, cake filtration and depth filtration whereas it´s unclear which kind of filtration is dominant at which step of the process [2, 4, 13]. The classification and identification of dominant filtration mechanisms is the aim of this work. This knowledge is important for the improvement of the lautering process and can serve as a basis for new approaches in this field.

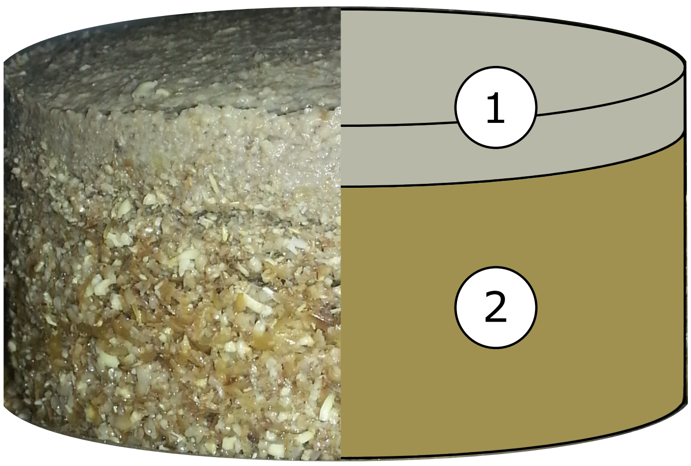

Fig. 1 Obvious separation of fine jellylike particles in the above Oberteig (1) and coarse particles in the Unterteig (2)

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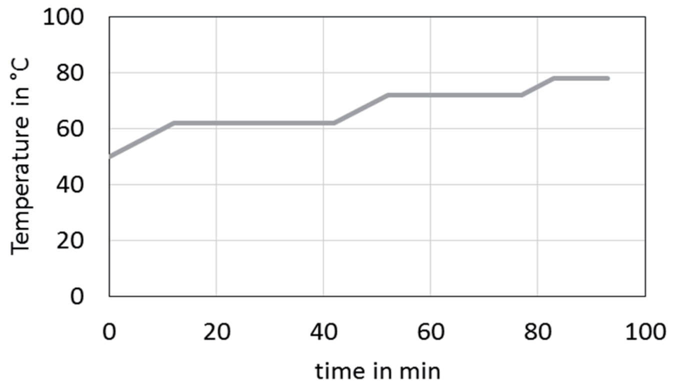

Fig. 2 Mashing regime for all trials with mash in at 50 °C and rests at 62 °C (for 30 min) and 72 °C (for 25 min) with a heat-up rate of 1 °C/min

2 Material and methods

For mashing 390 g Pilsner malt was ground with a two roller mill (Model 16/16, Künzel Maschinenbau GmbH, Germany) with a grinding gap of 0.8 mm. The ground malt was added to 1.9 L of deionized water and mashed according to mashing regime shown in figure 2. Mashing took place in a stirred laboratory reactor with external heating.

Sedimentation behavior was determined by image analysis. Therefore mash was transferred into a glass cylinder of 100 mm diameter and 350 mm height. A digital camera mounted on the side of the cylinder was used to take pictures at certain time steps. With the software MATLAB the height of different cake layers was measured in pixels and with a metal strip of known height these values were calculated in millimeters.

Lautering took place in a laboratory lauter ton with 100 mm diameter and and a respective filtration area of 78 cm². The lauter tun enables the analysis of 2 Liters of mash with cake heights of around 200 mm. In wall proximity effects like higher porosity and permeability are reported [14–16]. Since the filtration area is four times higher than the required area of 20 cm² [17] wall effects can be neglected [18].

To enable the analysis of different cake layers the lautering filter cake was cut in horizontal layers. Therefore after the filtration, the lautering filter cake was transferred into a tube and cut into discrete layers with a blade. The cake height was adjusted by a metal plunger that was inserted into the tube and pushing the cake out of the tube. The protruding cake layer was then cut with a metal blade and kept for further analysis.

To determine particle size distributions in different filter cake layers wet sieve analysis was conducted. Therefore spent grains cakes (or layers) were transferred in wet state to a tower of sieves and water was flushed through to enable sieve analysis. Subsequently all particles of each sieve were dried and weighed.

Free fatty acids were measured by a method based by Schütz and Back 2005 [19]. The fatty acids measurements were conducted at the Bavarian Biomolecular Mass Spectrometry Center at the TUM School of Life Sciences Weihenstephan, Technical University of Munich.

3 Theory

Basis for every filtration is the flow through porous media, usually described with Darcy´s law (eq. 1):

$$v = \frac{\Delta p}{\eta \cdot R \cdot h} \qquad \text{Eq. 1}$$

Whereas υ equals the superficial velocity calculated as volume filtrate per filter area per time, Δp describes the differential pressure, h is the cake height, R is the filter cake resistance and η is the viscosity of the fluid.

Applied to filtration processes this equation is altered where it gets differentiated between the flow through the filter media with a constant height and the growing filter cake to get to the common filtration equation (eq. 2).

$$\frac{dV}{dt} = \frac{\Delta p \cdot A}{\eta} \cdot \frac{1}{\left(\frac{\alpha \cdot \chi}{A} \cdot V(t) + \beta\right)} \qquad \text{Eq. 2}$$

In Equation 2 the term R·h has been expanded to $\frac{\alpha \cdot \chi}{A} \cdot V(t) + \beta$, where β represents the flow resistance of the filter medium. The flow resistance of the growing cake is not only depending on the specific resistance itself, now called α but also on the growing cake height. Since the cake height is depending on the flow velocity and the already passed filtrate, the height can be expressed as $h = \frac{\chi}{A} \cdot V(t)$. Here χ is the ratio of cake volume to filtrate volume.

As mentioned above the main filtration types that are associated with lautering are surface filtration, cake filtration, and depth filtration. These different mechanisms are explained below.

Surface filtration or dead end filtration is used to filter slurries with low solids concentrations and is characterized by a filter medium with smaller pores than the actual particle size. Separated particles block openings in the filter medium therefore the filtrate flux is getting slower over time. After all openings are blocked the filtration has to be interrupted to clean the filter medium [20]. The fact that lautering filter cakes are tending to block completely but can be loosened with the raking knives indicates that dead end filtration is involved in the lautering process.

Cake filtration however is distinguished by particles significantly smaller than the filter medium pores. Particles form bridges over the pores and the separation happens on top of these bridges. So the forming cake is growing over time and due to the increasing filter cake resistance the flux is decreasing. With this filtration, slurries with high solids concentrations can be effectively filtered. After the initial deposition of particles on the filter medium, the filtration itself is taking place on the top of the cake. Deeper in the cake, the process is described as a flow through porous media [20]. The obvious cake and it´s growth during lautering is a fact that leads to the assumption that cake filtration is the dominant filtration type.

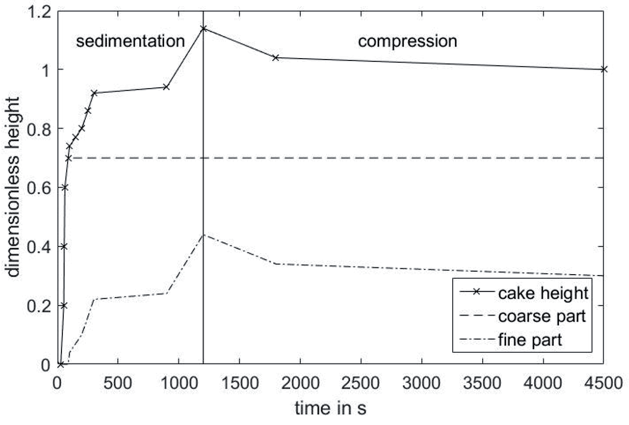

Fig. 3 **Height of sediment, fine upper part, and coarse bottom part over time**

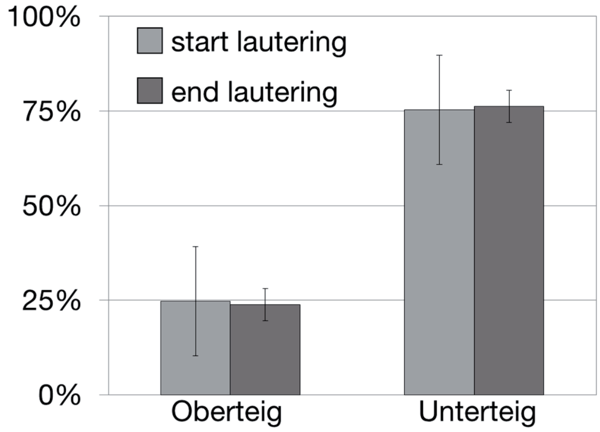

Fig. 4 **Mass fraction of Oberteig and Unterteig at start and end of lautering**

A special kind of cake filtration is the filtration with compressible cakes. When filtrate flows through the pores of the filter cake, the hydraulic pressure drops as the liquid is frictionally passing the particles. The drag force transmitted to the particles causes the porosity of compressible filter cakes to decrease [21]. Therefore most of the porosity reduction is happening in the filter layer nearest to the filter medium (skin effect). The lautering filter cake however shows higher compressibility levels in the Oberteig consisting of fine particles rather than in the coarse grained Unterteig [22].

The depth filtration differs from the above mechanisms in the point of particle deposition. Whereas in both mechanisms, dead end and cake filtration, particles bigger than certain pores are deposited at the top of a porous structure, the particles in the depth filtration are deposited within a porous media. The filter layer is a porous structure often consisting of filamentous particles. Particles in the fluid are attracted to the surface of the filter layer and the suspension gets filtered as it passes through this layer. Separation mechanisms are diffusion, sedimentation and interception [20]. The fact that colloids (very small in relation to the pore size), like free fatty acids, are reduced during lautering in a significant amount [23] is suggesting that depth filtration is an important separation mechanism for lautering.

These indications and the fact that the solids are separated by size over the cake height lead to the hypothesis of this work: different size-fractions of particles are experiencing a different type of filtration mechanism during lautering.

4 Results and Discussion

Since the filter cake is partly formed by sedimentation, the settling behavior of the spent grains particles is determined. Wort was transferred in a lauter tun and sedimentation of particles was observed via image analysis. Figure 3 shows the sediment height over time relative to its finals height after 24 hours of sedimentation. As illustrated, the coarse part (dot-dashed line) of the sediment is fully formed after few seconds and stays at a constant height whereas the sediment consisting of fine particles (dashed line) takes 1200 s to reach its maximum. After the sedimentation is completed, the cake gets compressed by rearrangement and consolidation of particles. This hindered settling behavior is well known [24].

Due to the fact that at the start of the process there is a sedimentation step allowing big particles to settle quickly, particles of the coarse part of the cake are not filtrated at all but rather are forming a porous layer at the bottom of the vessel where the fluid is passing through. Therefore big particles are separated by sedimentation. In the contrary, fine particles of the Oberteig are separated by filtration since their settling velocity is too low. This confirms the hypothesis that coarse and fine particles are experiencing a different separation mechanism.

For a mathematical description the resistance of the coarse part has to be added to the constant part β in equation 2. But since the coarse Unterteig is compressible [5], this so called filter medium resistance is no longer constant but a function of the filtrate flux υ (t).

Possible separation mechanisms for fine particles of the Oberteig are depth filtration and cake filtration with or without the migration of fines through the cake. To determine the applicable filtration mechanism for fine particles in the upper part of the filter cake, the mass of the fine particle layer is measured after sedimentation (before filtration) and at the end of the filtration process. Figure 4 shows that the mass of the fine top layer remains constant. This shows, that for small particles < 500 µm the separation takes place on top of the Unterteig consisting of coarse particles: fine particles are separated by cake filtration on top of the Unterteig.

To determine if there is a migration of fines through the cake, the ratio of fine particles in horizontal layers of the Unterteig is measured. The analyzed cakes were 7.5 – 8.5 cm high and layers 1 – 3 were 2 cm high and layer 4 was the respective rest. As figure 5 shows, the fine particles ratio is constant for both cake height and process time. This leads to the conclusion that fine particles are neither passing through the coarse Unterteig (depth filtration) nor that there is an accumulation of fines in any other (deeper) layer. The only applicable filtration mechanism for this behavior is the mechanism of cake filtration, where the particle deposition is happening continuously on top of the coarse layer of the cake.

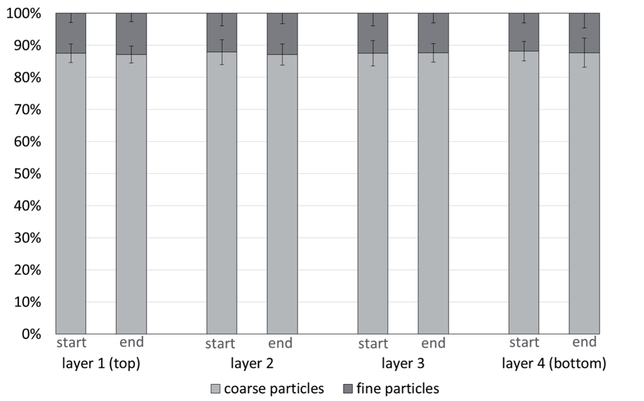

Fig. 5 **Mass fraction of fine and coarse particles in horizontal layers of the Unterteig at start (left columns) and end (right columns) of lautering**

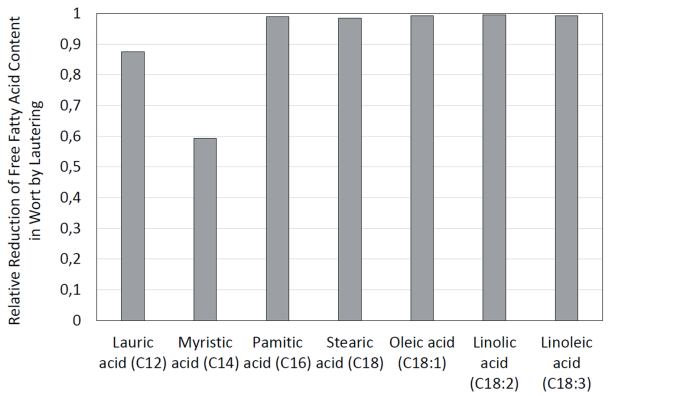

Fig. 6 **Relative Reduction of the free fatty acids content in wort by lautering, modified from [4]**

To apply the filtration equation (Eq. 2) on the lautering process, the filter medium resistance has to comprise both the resistance of the false bottom and the resistance of the sedimentation cake (Unterteig). Here, the filter cake resistance describes the growing top layer of fine particles. Equation 2 applies to processes where no sedimentation occurs: where the relative velocity between fluid and particles above the cake is zero. This is not applying to the lautering process. Fine particles like coarse ones are experiencing a sedimentation during first wort run off. Therefore χ is not constant but time depended.

Haze forming colloids are reduced significantly during lautering [23, 25]. As one example for dissolved colloids free fatty acids are analyzed to determine the filtration mechanism for colloidal particles. For the removal of (foam negative) free fatty acids lautering is the most important process step. Values can be reduced by over 90 % [26]. The hypothesis for the filtration mechanism for colloids is that due to their size, they are removed by depth filtration. Therefore horizontal layers of the lautering filter cake are analyzed regarding their free fatty acid content.

Figure 6 shows the relative reduction of the free fatty acids content in wort by lautering according to *Narziß* [4]. The tremendous reduction of fatty acids shows the effectiveness of the lautering filtration process.

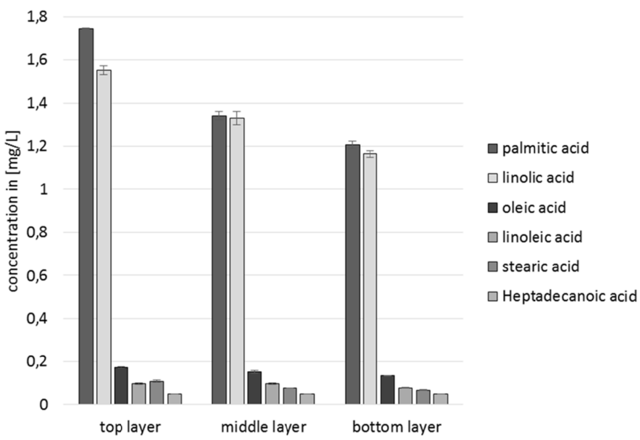

Fig. 7 **Amount of free fatty acids in horizontal layers of the lautering filter cake**

To determine the separation mechanism of colloidal substances, the amount of free fatty acids in horizontal layers of the lautering filter cake was determined. Figure 7 shows the amount of free fatty acids in three horizontal filter layers. The cakes were separated in three layers of similar height then the different layers were mixed and the respective samples were taken.

The fatty acid concentration in the filter cake is decreasing in deeper cake layers. This corresponds to the expectation for depth filter processes where the concentration is also decreasing in flow direction [27, 28]. So unlike coarse and fine particles colloidal particles are separated by depth filtration.

According to the understanding of depth filtration, the pores of the filter media are getting occupied by particles over time and therefore the permeability of a porous media and the separation efficiency (e.g. increasing filtrate turbidity) is decreasing over filtration time. To fit all of the observed phenomena with a common filtration equation is not possible. Therefore the main reason for the lack of a sufficient mathematical models for lautering is the fact that there are three different overlapping separation mechanism involved.

The hypothesis that different size fractions are separated by different filtration mechanism could be verified: coarse particles are separated by sedimentation, fine ones by cake filtration and colloidal particles are retained in the cake by depth filtration.

5 Conclusion

The predominant filtration mechanisms during lautering are depending on the particle size. The transfer time of the mash into the lauter tun is rather slow (minutes), so the fast settling (seconds) coarse particles are not separated by filtration but by sedimentation. Coarse particles form a sediment where the liquid is passing through but no filtration occurs. Fines however are separated by cake filtration with superimposed sedimentation. These fine particles are forming a growing filter cake on top of the sediment consisting of coarse particles. Migration of fines through the cake does not take place. Colloidal particles like free fatty acids are separated by depth filtration, they are deposited in the filter cake according to well-known depth filtration processes.

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