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Improving Resistance to Aging and Increasing Haze Stability in Southern German Wheat Beer Through Process Optimization

Flash pasteurizing beer not only stabilizes it microbiologically, but the process also has a favorable influence on the aroma and flavor of the beer. Changes in the sensory profile of the beer occur to a greater degree at the start of the aging process. These changes are perceived as particularly negative by consumers who only purchased the beer a short time before. The primary reason for customer dissatisfaction with beer they have purchased is not that the beer becomes unpalatable before the expiration date, but rather the last bottle in the case does not taste like the first. This situation can be remedied through utilization of a flash pasteurizer, if the concentration of yeast cells in the beer entering the pasteurizer does not exceed a certain level. Although the conversion reactions occurring at temperatures from 60 to 80 °C for 30 seconds during pasteurization do, in fact, result in a certain amount of forced aging, this does not necessarily mean that it will have a negative effect on the sensorial attributes. The use of a flash pasteurizer is especially advantageous in the production of cloudy Southern German-style wheat beer – otherwise known as ‚weißbier'. The stability of a permanent (protein) haze is a key characteristic of cloudy German-style wheat beers. A stabilizing effect can be achieved by shifting the particle size to between 200 and 1000 nm through thermal agglomeration. The sensory attributes and the energy usage are both positively impacted by reducing the thermal stress, due to shorter boiling times, thus resulting in further advantages.

Descriptors: Southern German-style wheat beer, turbidity, colloidal stability, haze stability, flavor stability, flash pasteurizer

1 Introduction

The goal of increasing the colloidal stability is to bring about a uniform level of turbidity or haze in beer by employing a method of thermal treatment. By doing so, this enables a brewery to achieve a distribution of particle sizes amongst the proteins in suspension, which – unlike the turbidity caused by the presence of yeast cells – remains stable during storage. The further coagulation of extremely fine protein particles (microparticles) changes the distribution of particle sizes [11]. Particles with dimensions ranging from 200 to 1000 nm are considered especially relevant [1, 2, 3, 4, 8].

This agglomeration, which can extend up to the size of macromolecules, increases the haze stability of the product in the container after filling [5, 8].

Also of significance was the realization that thermal treatment is not the only factor influencing the increase in particle size but that turbulent conditions and the resulting collisions of the coagulable particles in motion also play a role in agglomeration. Because turbulent conditions are absent in tunnel pasteurization, the haze stability of beer subjected to heat treatment of this kind remains unaltered. Flow conditions are turbulent in flash pasteurizers due to the heat exchanger, flow control valves and pumps, which exert shearing forces on the beer. These factors all play a role in improving the haze stability [9]. *Narziß* reports similar findings with regard to quantities of hot trub and coagulation, which are higher when the wort is boiled intensely [6].

Differences in protein haze and “traditional” haze, i.e. the turbidity brought about by yeast in suspension, are particularly noticeable when the yeast sediment out. This is typically observed in kegged beer between dispensing the first and last beers from the keg; therefore turbidity of this nature is considered to be less significant. The optimal concentration of yeast cells at the flash pasteurizer inlet is crucial to the sensory profile once the beer has been pasteurized and packaged. Since the thermal stress results in autolysis by the yeast, which in turn causes undesirable compounds, such as decanoic acid [8], to be released into the beer the yeast cell count must be reduced via centrifugation prior to pasteurization.

The full potential of sustainably enhancing the quality of wheat beer can only be realized, if the entire process is assessed and then optimized technologically. Research findings have already shown that a certain particle size distribution of proteinaceous material is required to attain lasting turbidity in beer [5, 9, 11]. In order to ensure that the proper composition of the protein fractions in the beer at the inlet of the flash pasteurizer is reached, brewhouse operations such as the mashing schedule and wort boiling must be modified. Post-fermentation values for coagulable nitrogen of > 3 mg/100 ml are recommended in the literature [11, 17]. *Schwarz* was able to show that the turbidity remained more stable when the boiling

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time was reduced [9]. Through examination of reaction kinetics, *Huang* provided further evidence of this relationship, showing that the majority of coagulable nitrogen coagulates as the lauter wort is heated prior to boiling and during the first 30 minutes of the boil [10].

Consequently, excessive protein denaturation in the brewhouse eliminates a large quantity of these micromolecules. Through the force of gravity, a physical separation (Stokes' law and adsorption) of these micromolecules from the wort takes place via sedimentation and flotation during the removal of hot trub and fermentation [9, 14]. For this reason, the only viable method is to employ a process which will ensure that a sufficient number of particles < 1 µm are in the packaged product. Only particles of this size are small enough to sediment out extremely slowly under normal gravitational conditions. Particles of this size are also sufficiently large to scatter enough light [17]. Analogous to the research contributed by Huang, the temperature is critical for the denaturation of proteins in the flash pasteurizer. Although the temperature in the flash pasteurizer has the desired effect on the particle size distribution, increasing the number of pasteurization units through longer holding times in the pasteurizer does not appear to generate this effect [10, 17].

Naturally, the additional thermal stress originating from pasteurization also affects the aroma profile of the beer. The influence of both 150 and 300 pasteurization units (PU) on the compounds 4-vinylguaiacol, isoamyl acetate and ethyl acetate, the compounds responsible for the typical aromas in wheat beer, was investigated on a laboratory scale. No evidence was found that the added thermal stress from further heat treatment had significant influence on the aroma compounds found in Southern German-style wheat beer [18]. *Hermann* determined that wheat beer stabilized using a flash pasteurizer exhibited a higher instance of retaining positive aroma compounds over time and less yeast autolysis [19]. *Schneiderbanger et al.* reported that the concentration of the indicator compounds typically present after forced aging, such as 2-furfural and γ-nonalactone, increases linearly with the number of pasteurization units [18]. *Wackerbauer et al.* determined that the number of pasteurization units alone does not yield a reliable prediction for aging. Exposure to a high temperature for a short time has a much more beneficial effect on resistance to aging than reaching the same number of pasteurization units with a long holding time at a low temperature [20].

As efforts are made to optimize the brewing process, the focus is shifting increasingly towards traditional wort boiling practices and their corresponding reaction kinetics, which occur simultaneously and independent of evaporation (isomerization, DMS-P cleavage, coagulation, sterilization, color and formation of aroma compounds) [15, 16].

There are numerous examples, which include equipment for pre-isomerization and downstream post-kettle evaporation. This equipment is absolutely essential to maintain the target values for wort boiling, such as free DMS with respect to coagulable nitrogen and the overall reduction in thermal stress when attempting to shorten boiling times.

Ultimately, the goal of these measures is to create advantages both from a technological and an economic perspective [7]. With respect to coagulation and haze stability, a combination of reduced boil times, downstream evaporation equipment, adjustment of yeast cell concentration and flash pasteurization, represents a promising option to further optimize wheat beer quality through lower thermal stress with enhanced resistance to aging and greater haze stability.

2 Materials and Methods

The equipment and processes used in the trials

In order to test whether haze stability could be enhanced in Southern German-style wheat beers by reducing the duration of wort boiling and utilizing a flash pasteurizer, a suitable process management concept was developed for the experimental trials and implemented under realistic operating conditions, i.e. in an operational brewery (Fig. 1).

The wort was produced for the experimental trials in a traditional four-vessel brewhouse with decoction mashing. The wort was boiled using an internal calandria followed by a single evaporation step in a "Merlin". The sequence on the hot side of the brewing process allowed the boiling time in the internal calandria to be reduced to 30 minutes, followed by gentle evaporation. This resulted in minimal thermal stress. All of the required reaction kinetics mentioned above can successfully proceed during this wort production

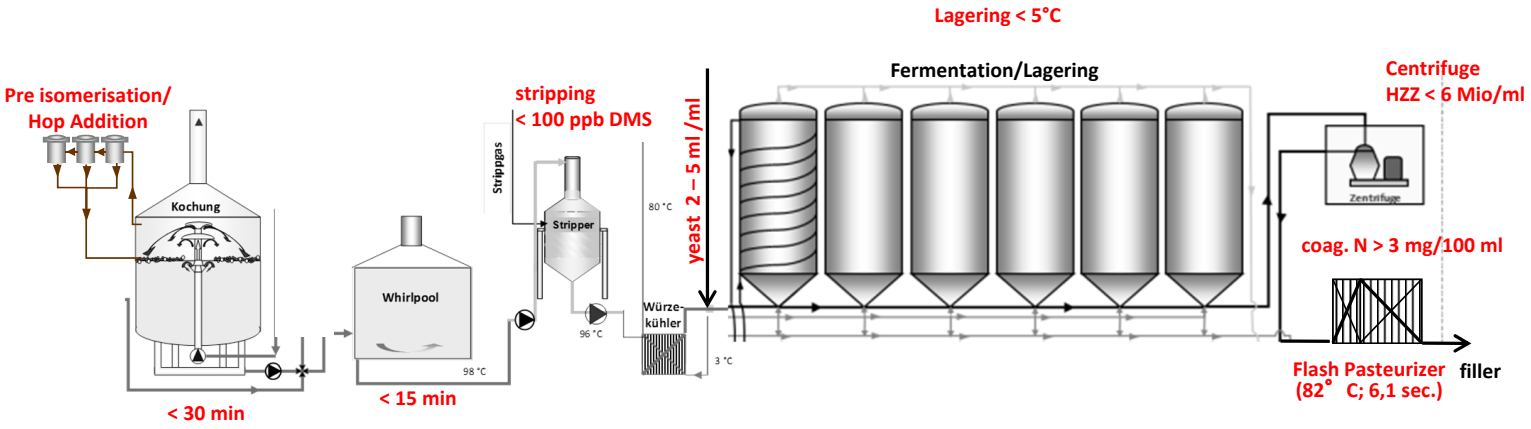

Fig. 1 Equipment/process concept for the experimental trials

process, whereby the choice was consciously made to remove the undesirable aroma compounds from the wort using the "Merlin" thin film evaporator in addition to further protein coagulation in later process steps in the flash pasteurizer.

After chilling, the wort was fermented according to a traditional two-tank method. If deemed necessary, prior to thermal treatment with the flash pasteurizer, the yeast cell concentration in the beer was adjusted to six million cells/ml using a disc-type centrifuge to ensure consistent product quality. In order to avoid inconsistencies in turbidity measurements, a time span was designated for sample collection during which a constant change in turbidity was observed as beer was being removed from the tank to be pasteurized.

A "VarioFlash" flash pasteurizer manufactured by Krones AG was utilized to achieve the different levels of pasteurization (number of pasteurization units) and the effect of pasteurization on beer quality was subsequently investigated. Pasteurization was performed at a constant throughput and holding time; the various levels of pasteurization were adjusted by changing the temperature. Pasteurization units (table 1) are calculated according to equation 1 below.

$$PU_{Beer} = t \times 1.393^{PT - 60\,°C}$$ Eq. 1: Pasteurization units

Analysis of Wort and Beer

Samples subjected to various levels of thermal stress were collected to determine the effect of flash pasteurization more precisely (Tab. 1).

Table 1 Pasteurization parameters in the experimental trial

Time	Temperature	Beer PU
[s]	[°C]	[PU]
30	77.2	150
30	79.3	300
30	81.4	600

The wheat beers exposed to different levels of thermal treatment were filled immediately following flash pasteurization in kegs purged and pressurized with CO_2. On average, oxygen uptake rates of < 0.1 mg/l were recorded for the subsequent bottling process. This is representative of the values typically reported in commercial brewing operations. The analyses listed below in table 2 were developed to identify the optimal combination of product quality, resistance to aging, and haze stability and the impact of the thermal stress from flash pasteurization.

Fresh beer samples and those subjected to forced aging (shaken 24 h, held at 40 °C for four days) were analyzed for the typical indicator compounds associated with aging, oxidation and thermal stress. A sensory evaluation was also performed to determine the stability of the beers with respect to aging. The aroma profile of the fresh wheat beer was also analyzed to assess whether flash pasteurization had any effect on the composition of the aroma compounds. The values for color and TBI were also measured in order to provide additional data for the trials. Also, ESR measurement techniques were employed to monitor changes in the endogenous antioxidative potential and in the generation of free radicals with regard to various levels of pasteurization. The effect of flash pasteurization on the colloidal behavior of fresh beer samples and their corresponding stability was evaluated with a turbidity prediction test. Data, such as particle size distribution and charge titration measurements, are used as the basis for this test [1, 2]. A determination of total nitrogen, coagulable nitrogen and free amino nitrogen in the fresh beer samples was also performed, so that conclusions could be reached regarding the changes in the nitrogen fractions as a result of thermal treatment.

3 Results and Discussion

The impact of the yeast cell count on the sensory profile of beer

To determine the effect of the centrifuge on the broader process, samples of unpasteurized wheat beer and wheat beer treated at 600 PU, both with and without centrifugation, were evaluated sensorially. The average yeast cell count after centrifugation was 6 million cells per milliliter, while uncentrifuged samples contained 20 million cells per milliliter. A comparison of the results from the sensory analysis (Fig.2) shows centrifugation does not affect the sensory profile of fresh, unpasteurized wheat beer.

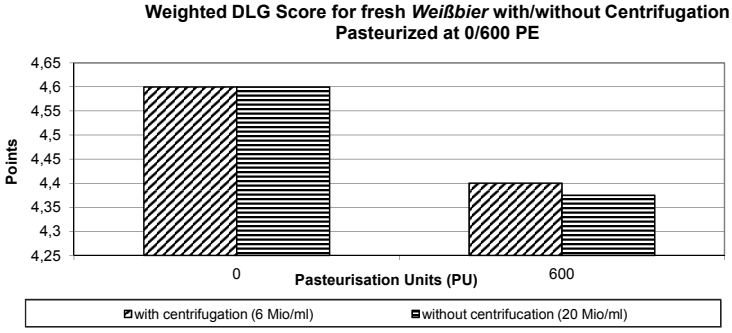

Fig. 2 Weighted DLG score for fresh wheat beer with/without centrifugation, pasteurized at 0/600 PU

Both samples received a score of 4.6. The fresh wheat beer sample with the lower yeast cell count and pasteurized at 600 PU was deemed to have a slightly better sensory profile. By measuring the quantity of decanoic acid (Fig. 3) in fresh beer, it becomes clear that the concentration is higher as a result of flash pasteurization. The increase in the concentration is higher in the uncentrifuged wheat beer (0.6 mg/l) compared to that in the beer which underwent centrifugation (0.3 mg/l). The total amount of decanoic acid was

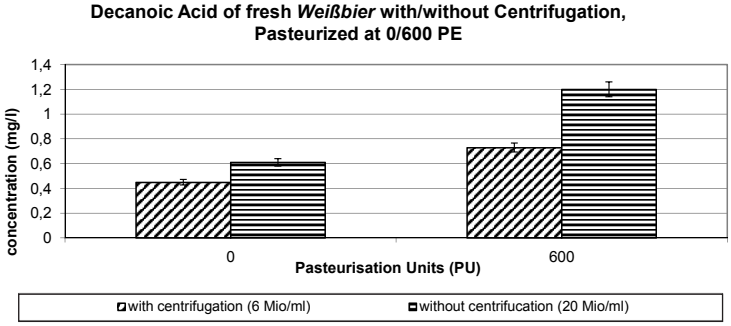

Fig. 3 Decanoic acid in fresh wheat beer with/without centrifugation, unpasteurized (0 PU)/pasteurized at 600 PU

Table 2 Analysis methods

Analysis	Analysis Method
DLG quality assessment for beer	MEBAK Sensory Analysis, method 4.5.2.1
Aging, oxygen and heat indicators	MEBAK Wort, Beer and Beer-based Beverages, method 2.23
Aroma profile	Contract analysis offered by Weihenstephan Research Center for Brewing and Food Quality (BLQ) Freising-Weihenstephan, performed according to MEBAK Wort, Beer and Beer-based Beverages, method 2.21
ESR measurement	MEBAK Wort, Beer and Beer-based Beverages, method 2.15.3
Color (photometric)	MEBAK Wort, Beer and Beer-based Beverages, method 2.12.2
Free amino nitrogen (FAN)	MEBAK Wort, Beer and Beer-based Beverages, method 2.6.4.1
Total nitrogen	MEBAK Wort, Beer and Beer-based Beverages, method 2.6.1
Coagulable nitrogen	MEBAK Wort, Beer and Beer-based Beverages, method 2.6.2
Magnesium sulfate precipitation of nitrogenous compounds	MEBAK Wort, Beer and Beer-based Beverages, method 2.6.3.1
Original gravity	MEBAK Wort, Beer and Beer-based Beverages, method 2.9.2.3
Thiobarbituric acid index (TBI)	MEBAK Wort, Beer and Beer-based Beverages, method 2.4
Decanoic acid	WBBM2.23.6

significantly higher in the beer pasteurized at 600 PU and was not centrifuged (1.2 mg/l) than it was in the beer which received the same amount of pasteurization and was centrifuged (0.73 mg/l). Similar results for unpasteurized beer samples were obtained for the total amount of decanoic acid in relation to the yeast cell count.

Sensory evaluation of wheat beer subjected to forced aging (Fig. 4) yielded an even greater difference between beer with and without centrifugation. The centrifuged beer without flash pasteurization received a higher score at 4.13 points than the non-centrifuged beer with 4.07 points. The widest margin in the data for the samples pasteurized at 600 PU was 0.13 points.

Based on this information and given the high yeast cell count, it was concluded that a greater amount of yeast excretion occurred, which in turn was reflected in the higher values for decanoic acid, an indicator for yeast excretion [8]. In addition, excretion is promoted by higher thermal stress and negatively affects the sensory profile of the beer, especially in aged beer. For these reasons, all trials described below were conducted with a yeast cell count of 6 million cells per milliliter.

The impact of the number of pasteurization units on the sensory profile of beer

Of the fresh beer samples, the unpasteurized wheat beer (0 PU) received the highest score at 4.6 points (Fig. 5). After flash pasteurization, the sensory panel gave the fresh beer scores of 4.43 (150 and 300 PU) and 4.35 (600 PU). By contrast, the samples subjected to forced aging with no pasteurization (0 PU) and pasteurization at 150 PU, each received 4.13 points while a score of 4.03 was given to beer pasteurized at 300 and 600 PU. Accordingly, pasteurization at 150 and 300 PU had a slightly negative impact on the sensory impression of the freshness, but this effect was most perceptible at 600 PU. Interestingly, the unpasteurized samples and those pasteurized at 150 PU received the same favorable scores after forced aging, while the samples with 300 and 600 PU were also given the same scores.

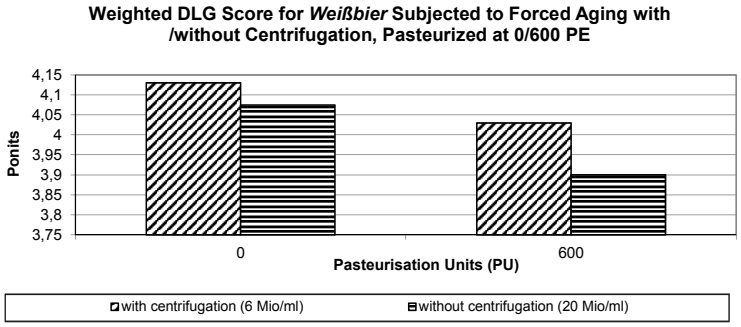

Fig. 4 Weighted DLG score for wheat beer subjected to forced aging, with/without centrifugation, unpasteurized (0 PU)/ pasteurized at 600 PU

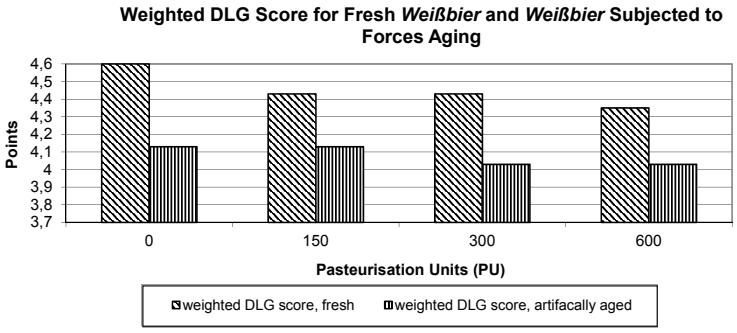

Fig. 5 Weighted DLG scores for fresh/artificially aged wheat beers with different levels of pasteurization

These results were directly reflected in the flavor stability of the wheat beers (Fig. 6). Sensory analysis showed that the unpasteurized sample (0 PU) possessed the lowest resistance to aging, with a difference of 0.47 points. Pasteurization at 150 PU did not appear to have a negative impact on the sensory profile of the aged beers compared to the reference sample and exhibited the highest flavor stability with a difference of 0.3 points. Compared to the samples pasteurized at 150, lower scores for flavor stability were given to the fresh wheat beer pasteurized at 300 PU and also to samples subjected to forced aging and pasteurized at 600 PU. Therefore, from a sensory perspective, pasteurization at 150 PU imparts a high degree of flavor stability with only a slight decrease in the freshness compared to unpasteurized beer (0 PU).

The analysis results for the aging compounds (Fig. 7) were also corroborated by the sensory evaluation. The unpasteurized wheat beer contained the lowest amount of aging compounds with a concentration of 88 µg/l. All of the pasteurized beers exhibited slightly elevated concentrations in the range of 104-110 µg/l.

By contrast, the rise in aging compounds after forced aging was complete was higher at 91 µg/l for the unpasteurized (0 PU) wheat beer than the values of 64 µg/l and 52 µg/l measured in the wheat beers pasteurized at 150 PU and 300 PU, respectively. A similar in-

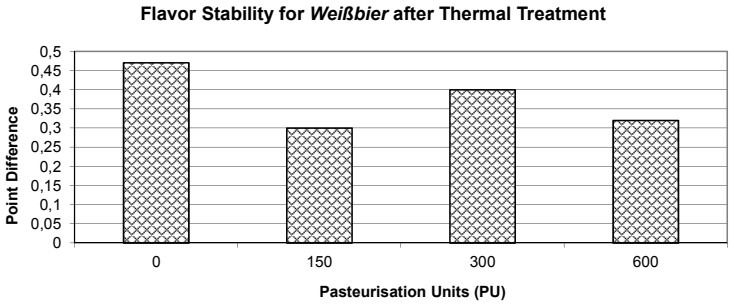

Fig. 6 Flavor stability in wheat beer after pasteurization at 0/150/300/600 PU

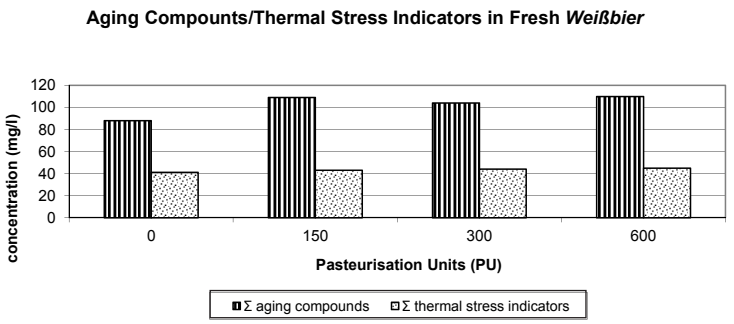

Fig. 7 Aging compounds and thermal stress indicators in fresh wheat beer after pasteurization at 0/150/300/600 PU

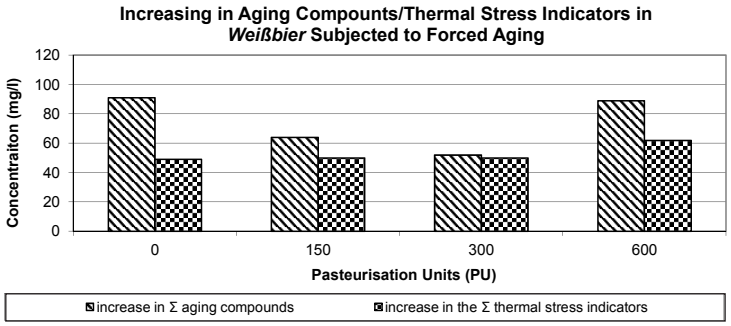

Fig. 8 Increase in aging compound and thermal stress indicators in wheat beer after artificial aging

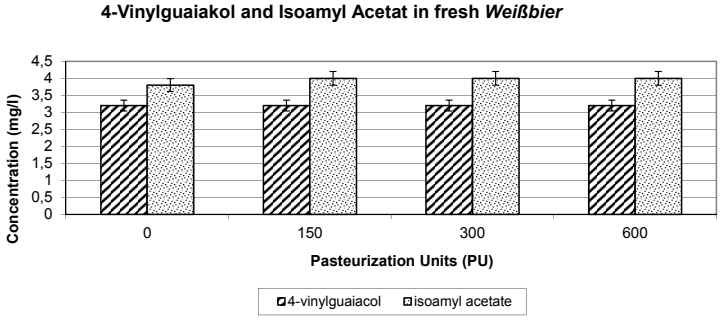

Fig. 9 Concentration of 4-vinylguaiacol and isoamyl acetate in fresh wheat beer

crease was only observed in the beer pasteurized at 600 PU (89 µg /l). No difference was measured in the amount of thermal stress indicator compounds in all of the fresh samples, while among the samples subjected to forced aging, only a slight increase (62 µg/l) was seen in the beer pasteurized at 600 PU, compared to the rest of the samples.

The concentrations of compounds responsible for the typical aromas in wheat beer, namely 4-vinylguaiacol, isoamyl acetate (Fig. 9) and ethyl acetate (Fig. 10) appear to be completely unaffected by the flash pasteurization process. No change in the absolute quantities of these compounds was observed, which also confirmed the findings of Schneiderbanger [18], who pasteurized wheat beer at levels of up to 300 PU in a flash pasteurizer. The sum of amyl alcohols remained at 66 mg/l in all of his trials.

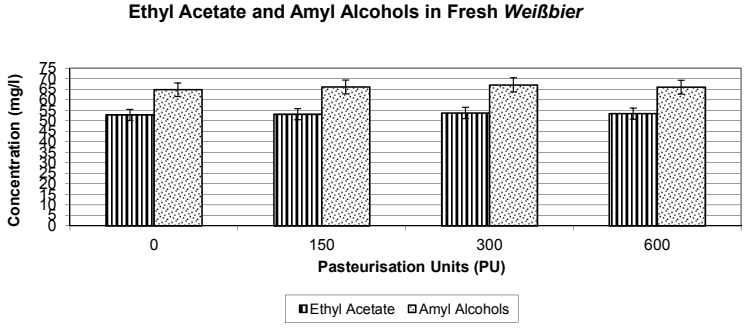

Fig. 10 Ethyl acetate and amyl alcohols in fresh wheat beer

The impact of flash pasteurization on the particle size distribution and nitrogen fractions

As previously described, a reduction in the duration of the wort boiling process, followed by an evaporation step downstream in the "Merlin" thin film evaporator, allowed the reaction kinetics to be selected to some degree (protein coagulation and evaporation of undesirable aroma compounds). An evaporation system downstream from the wort kettle, which does not utilize primary energy, would be advantageous for further enhancement of the process and would also reduce thermal stress to the wort.

Nevertheless, the recommended concentration found in the literature of > 3 mg/100 ml [11, 17] was easily achieved in the unpasteurized sample (0 PU, 4.4 mg/100 ml). At 74 µg/l, the concentration of the indicator substance free DMS was within the normal range, as specified by MEBAK. Particle size analysis of the control sample (0 PU) yielded a distribution (Tab. 3) indicating that a quarter (25.6 %) of all particles possessed an average diameter of less than 200 nm. The percentage of particles smaller than 100 nm amounted to 13.6 %, while 45.1 % of the particles were grouped in the fraction relevant for haze stability. This means that less than half of all the particles in the sample were of a size able to generate permanent haze or turbidity in wheat beer.

A distinct shift in the particle size distribution towards larger particle diameters after thermal treatment in a flash pasteurizer can be seen in figure 11.

The effect was more pronounced for particle sizes in the range of 200 to 1000 nm. The fraction increased to 80.2 % in beer pasteurized at 150 PU. The percentage of particles in this fraction rose to 73.9 % and 82.9 % in beer pasteurized at 300 PU and 600 PU, respectively. At the same time, the fraction with a particle diameter of < 200 nm decreased to less than 2 %, which can be attributed to the formation of larger particles through the agglomeration of small coagulable particles. Interestingly, this process appears to occur independently of the degree of pasteurization chosen. The slight reduction in this fraction resulting from pasteurization at 300 PU cannot be explained. Therefore, thermal treatment at 77.2 °C for 30 seconds (150 PU) is sufficient to induce an agglomeration

Table 3 Particle size fractions (%) after thermal treatment with a flash pasteurizer

Particle size distribution		0 PU	150 PU	300 PU	600 PU
Fraction < 100 nm	%	13.6	0.4	1.1	0.3
Fraction < 200 nm	%	25.6	1.8	2	1.4
Fraction 200-1000 nm	%	45.1	80.2	73.9	82.9
25 % quantile	Nm	198	459	417	441

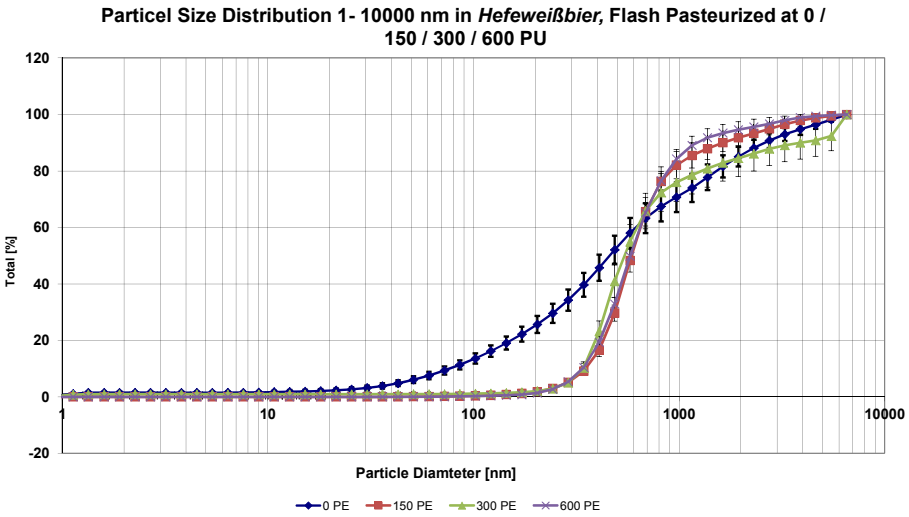

Fig. 11 Particle size distribution in wheat beer after various levels of pasteurization in a flash pasteurizer

of proteins to create particles of a size capable of generating a permanent, stable turbidity. The fraction of particles with a diameter of > 1000 nm is largest in beer pasteurized at 600 PU; however, this is not suitable for a consistent level of turbidity.

At the value $r = 0.8$ mg/100 ml specified for the analysis, no statistically significant difference could be determined for the quantity of residual coagulable nitrogen in the samples as a whole (Tab. 4).

As expected, the total nitrogen content did not change significantly at $r = 1.5$ mg/100 ml. In addition, the values for FAN also did not exhibit any significant changes due to the thermal stress from flash pasteurization. For this reason, the mechanisms behind particle agglomeration occurring in a flash pasteurizer cannot be evaluated on the basis of this analysis. Confirmation of these results can be found in the relevant literature [9] and indicate that the increase in particle size is primarily due to the agglomeration of individual particles. Although a certain temperature is necessary for agglomeration to take place, it plays a lesser role in protein coagulation. This conclusion appears to be logical, since the research conducted by Schwarz showed that no improvement in haze stability could be established after tunnel pasteurization of filled bottles [9]. This can be explained by the fact that no turbulence was present during pasteurization through the action of pumps, valves or heat exchangers. This is necessary to increase collisions among the particles and for their subsequent agglomeration.

The foam stability of all testes beers shows no significant differents.

Impact of the number of pasteurization units on haze stability

An analysis method developed by the Weihenstephan Research Center for Brewing and Food Quality was used to predict haze stability in wheat beer [1, 2]. In addition to the conventional measurement of scattered light at 90° and 25° (Tab. 5), a charge titration was performed to provide further data for the evaluation of haze stability.

Particularly relevant for turbidity as the human eye perceives it is the measurement of light scattered at 90° [22]. A higher initial value measured at this angle in combination with a high turbidity index of 90°/25° generally indicates a high level of haze stability [1, 2, 9]. The initial turbidity (measured with the scattered light method at 90°) almost doubled after flash pasteurization at 150 PU from 89.2 EBC to 174.5 EBC compared to the control. The turbidity index 90°/25° (ratio of 90°/25° measurements) increased significantly from 0.60 to 0.82. This result is supported by the shift observed from particles < 200 nm in size to the 200-1000 nm fraction. An increase in the turbidity measured at 90° was achieved through the corresponding coagulation of "smaller" nanoparticles to create "larger" sub-microparticles.

The values obtained from the measurements at 90° for the samples pasteurized at 300 and 600 PU were 141 EBC and 155 EBC, respectively, and showed a distinct increase compared to the unpasteurized control sample. Coming up with reasons why the values for samples pasteurized at 300 and 600 PU are somewhat lower than the ones measured for the sample pasteurized at 150 PU lies purely within the realm of speculation. There appears to be a correlation with the particle size distribution, because the percentage of particles in the 200-1000 nm fraction is smaller than those in the samples treated at 150 and 600 PU. The 90°/25° index at 0.73 (300 PU) and 0.78 (600 PU) is again significantly higher than the control sample but lower than that measured for 150 PU. In general, it can be said that pasteurization at 150 PU is sufficient to bring about a distinct increase in the 90°/25° index as well as

Table 4 Nitrogen fractions after thermal treatment with a flash pasteurizer

Nitrogen fractions		0 PU	150 PU	300 PU	600 PU
Coagulable nitrogen	mg/100ml	4.4	4.6	4.4	4.5
Total soluble nitrogen	mg/100ml	84.4	86.1	85.8	86.1
FAN	mg/100ml	4.8	4.9	4.9	5

Table 5 Initial turbidity measured at 90° and 25° in shaken samples

Turbidity		0 PU	150 PU	300 PU	600 PU
Initial turbidity at 90°, shaken	EBC	89.2	174.5	141	155
Initial turbidity at 25°, shaken	EBC	149.5	210.5	192	200
Turbidity index, 90°/25°, shaken		0.60	0.83	0.73	0.78

in the initial turbidity. Increasing the pasteurization levels beyond this point does not result in a further increase but instead tends to produce lower values.

A relationship has emerged from the results of the charge titration that indicates a correlation between high positive initial potential and favorable haze stability [1, 2, 22]. The effect of flash pasteurization on turbidity has already been documented by *Tietze* in his dissertation on wheat beer [22]. Upon examination of the titration curves of wheat beers with different degrees of pasteurization (Fig. 12), it is immediately apparent that the unpasteurized sample possessed a negative initial potential of –17.3 mV. By contrast, thermal treatment with a flash pasteurizer causes the potential to be shifted into the positive range. The highest value measured for the initial potential was 35.3 mV for the sample pasteurized at 300 PU, followed by 29.5 mV for samples pasteurized at 600 PU and 25.4 mV for samples at 150 PU. Two hypotheses are possible as an explanation. The first hypothesis states the internal Helmholtz layer of the particle still possesses a negative (net) surface charge, but experiences a switch in potential due to the adsorption of positive ions. The second hypothesis assumes that a change in the particle surface occurs, induced by the presence of a larger number of positively charged groups than negatively charged ones. This then creates a positive potential on the surface of the particle [22]. Flash pasteurization at 300 PU appears to promote these effects to the greatest extent. The values in table 6 were calculated using the statistical prediction of turbidity values falling below 10 EBC according to the analysis done by Haslbeck.

Table 6 Turbidity prediction according to Haslbeck [1]

Time until turbidity reaches < 10 EBC		0 PU	150 PU	300 PU	600 PU
Beer storage temperature: 20 °C	[weeks]	1.2	57.3	52.2	81.2
Beer storage temperature: 10 °C	[weeks]	5.9	181.5	167.3	247.3

A turbidity of 10 EBC is frequently encountered as a reference value; however, consumers generally do not perceive any turbidity in beers at this level [2]. In this instance, the significant increase in haze stability of flash pasteurized wheat beers compared to their unpasteurized counterparts is of immense importance. For beers predicted to fall below a turbidity of 10 EBC based on a theoretical calculation, flash pasteurization at 600 PU would appear to be the most advantageous. Given the information described above regarding the modification of the process, it is essential that flash pasteurization be utilized to improve the haze stability, though it has been shown that low pasteurization levels in the range of 150 PU have generated very satisfactory results.

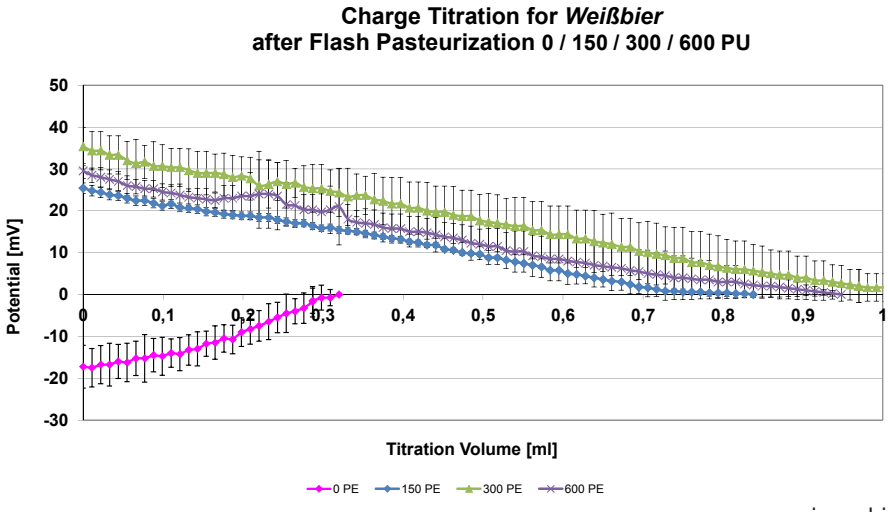

Fig. 12 Charge titration for wheat beer after 0/150/300/600 PU in a flash pasteurizer

Impact of flash pasteurization on additional thermal stress to the beer

Selected indicator parameters were measured in order to quantify the impact of additional thermal stress stemming from flash pasteurization. Measurement of conventional indicators of thermal stress, such as TBI and color, exhibited no differences among beer samples with increasing levels of pasteurization (Tab. 7).

Table 7 Analysis of thermal stress indicators

		Upstream from FP	150 PU	300 PU	600 PU
Color	EBC	11.1	11.1	11.1	11.1
TBI	µg/L	24	24	24	24
T300 ESR	x 10^6	2,08	–	2,27	2,25

In analyzing the pasteurized beers, a higher value for the generation of free radicals was recorded using electron spin resonance, compared to the unpasteurized beer; however, no difference could be recognized among the different levels of pasteurization.

With reference to zero-order reaction kinetics and the time/temperature dependency with respect to the formation of products as a result of thermal stress, it should be noted that the total added thermal stress originating from a flash pasteurizer, with average holding times of less than two minutes at a temperature below 80 °C, has no impact on the beer quality. This is especially true, if the duration of the wort boiling process is reduced and holding times are lowered in the flash pasteurizer, which is much more beneficial for the quality of the final product. The signal intensity measured during boiling is much higher, which is evident in the differences of $< 0{,}20 \times 10^6$ shown here (Table 7).

Despite somewhat higher D and z values for microbiological stability in wheat beer [21], compared to filtered beers, pasteurization is limited to 100 PU or a maximum of 150 PU. If this is taken into consideration with regard to the advantages afforded the flavor stability by higher temperatures and shorter holding times [20], the fixed holding time in the flash pasteurizer can be further reduced, something that was not possible in this experiment for technical reasons. In doing so, it could be possible to achieve greater resistance to aging while retaining the same level of haze stability in the beer. Using a temperature of 84 °C, as recommended by Wackerbauer

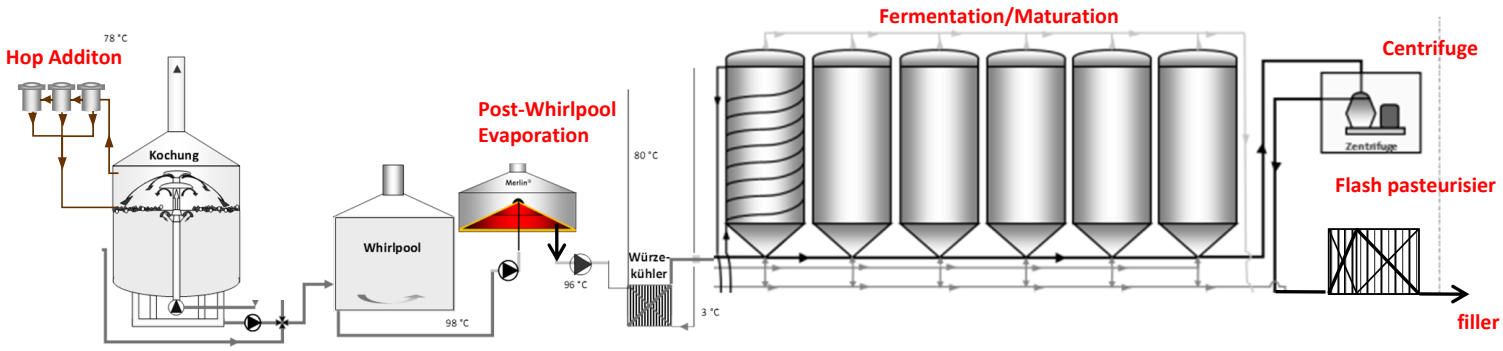

Fig. 13 Optimized production process for wheat beer including process parameters [2, 4, 10, 13, 15]

Table 9 Process Optimization

Process Enhancement	Description	Recommendations for Individual Parameters
reduction in thermal stress during wort boiling	reduction in primary energy consumption conversion reactions occur to a sufficient degree independent of evaporation, also while the wort is simmering [10] protein coagulation is reduced [2, 4]	holding time at target temperature < 30 min [4, 5] coag. N > 3 mg/100 ml
pre-isomerization of the hop addition	required due to the reduced duration of wort boiling	10-15 EBC units [6]
integration of downstream, non-thermal evaporation [10]	further elimination of undesirable aromas required due to the shorter boiling time no additional thermal stress to the wort in the stripping process	DMSfree < 100 ppb
lowest possible lager temperatures [12]	low temperatures enhance haze stability	below 5 °C
integration of a separation step to achieve an optimal yeast cell count	**prevention of undesirable aromas as a result of thermal stress to the yeast**	**< 6 million cells/ml**
integration of a flash pasteurization unit	**the temperature is key for protein coagulation, not the holding time in the flash pasteurizer** **a short holding time at a high temperature is preferred to restrict the formation of the carbonyl compounds responsible for aging [13, 15]**	**150 PU at 82° C for 6.1 s**

[20] for purposes of orientation, a holding time of merely 3.2 seconds would be required to achieve a pasteurization level of 150 PU, based on equation 1. Considering the average throughput of flash pasteurizers and the regulation of the pasteurization units (temperature adjustment dependent on the actual volumetric flow rate through a defined length of tubing functioning as a physical construct of holding time), this would be extremely difficult to realize from a technical standpoint. Furthermore, higher pressures would be necessary in the flash pasteurizer at temperatures above 82 °C, given the problems associated with having to maintain sufficient saturation pressure (Tab. 8).

4 Summary

The findings explicated above demonstrate that there is potential for optimization of the processes traditionally employed to produce wheat beer. One fundamental prerequisite is an analysis of the existing situation at the brewery in question, in order to correctly adjust factors, such yeast cell counts, prior to the introduction and implementation of optimization measures. This, in turn, will ensure that the advantages associated with flash pasteurization can be fully realized, namely an increase in the colloidal and flavor stability of beer while simultaneously reducing the duration of the wort boiling process, while preventing the negative effects of thermal stress to the wort. Based on the author's own research and that of recognized contributors to this area of knowledge, a selected list of parameters is provided in table 9 and figure 13, which offer the potential for a sustainable improvement in quality with respect to haze stability in beer and its sensory profile.

Table 8 Optimized process parameters for the pasteurization of wheat beer at 7g/l CO_2; 94 % heat recovery

Throughput	Time	Temperature	Beer PU
[%]	[sec]	[°C]	[PU]
50.0	14.2	79.5	150.0
100.0	6.1	82.0	150.0

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