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Utilisation of bubble formation for energy-efficient wort boiling while maintaining high wort quality

Reducing primary energy consumption is a significant challenge in modern beer production. This study examines a patented boiling system that reduces this energy demand by significantly lowering the evaporation rate without negatively affecting relevant wort quality parameters compared to a state-of-the-art boiling system. The wort is heated in an external boiler and recirculated through nozzles at the bottom of the wort kettle. There, the change in pressure conditions results in the formation of bubbles. These bubbles rise, support uniform homogenization of the wort, and allow the expulsion of volatile components such as DMS-free. Trials in a 10 hL pilot plant show that primary energy consumption during wort boiling can be reduced by 23 % while maintaining MEBAK quality parameters such as TBI, DMS-free, coag. N, etc.. The results highlight the potential of this system to make a significant contribution to sustainable beer production and open up perspectives for the development of further energy concepts that were previously limited by a required minimum evaporation rate of approx. 4 %.

Descriptors: evaporation efficiency, wort boiling, wort quality, DMS, energy saving

1 Introduction

Wort boiling is a central process step in beer brewing that significantly contributes to the quality and stability of the final product. Some important goals of boiling in the beer brewing process include the coagulation of protein compounds, sterilization of the wort, and the evaporation of undesirable compounds such as dimethyl sulfide (DMS), which at high concentrations causes a corn-like odour and taste and should not exceed a content of 100 µg/L at mid of cooling [1–3]. During germination the precursor DMS-P is formed. At higher temperatures, DMS-P is converted to volatile DMS-free [4, 5].

To effectively remove DMS from the wort, sufficient boiling time and intensity are required. Its removal is significantly influenced by the evaporation rate and thus the thermal energy. Conventional boiling systems use evaporation rates of 4 % or more to efficiently expel off-flavours, which is associated with high thermal energy consumption [6, 7].

Recent developments aim to develop energy-efficient methods for DMS reduction without compromising the quality of the beer. This is often achieved only with enormous mechanical effort [8], expensive inert gas [9, 10], or high investment costs [7].

A patented process has been developed that enables gentle and energy-efficient wort boiling without compromising quality. The process is also characterized by low mechanical effort, making it easy to retrofit existing systems [11]. The new boiling system was developed to reduce primary energy consumption during wort boiling, support homogenization in the wort kettle, and ensure high wort quality. The wort is heated in an external boiler (EB) and recirculated through a ring geometry with nozzles at the bottom of the kettle. In the EB, wort reaches a temperature where its vapour pressure allows phase transition. As the wort exits the nozzles, a pressure drop caused by the narrowing cross section lowers the local pressure initiating bubble formation [12, 13].

The bubble rises due to their lower density in the liquid and ensures homogenization of the wort. At the same time, the surface area of the volatile phase is increased, where unwanted volatiles such as DMS can accumulate and be expelled. It is essential that these remain stable until they reach the surface. To prevent the bubble from condensing, the temperature of the surrounding liquid phase must be near the boiling point, resulting in low heat conduction out of the bubble. The likelihood of condensation before the bubble reaches the liquid surface decreases with increasing temperature of the surrounding phase [13]. The bubble remains stable as long as the vapour pressure inside the bubble is higher than the pressure of the surrounding liquid. The internal pressure is determined by surface tension and diameter of bubble formation [14–16].

Smaller bubbles are more stable and particularly effective for DMS expulsion due to their higher surface tension and larger surface area but promote foam formation. Foam is a dispersed system of a continuous liquid phase and a dispersed gas phase, whose stability is influenced by surface-active substances such as proteins [17].

Uncontrolled foam formation during wort boiling must be avoided as it can lead to efficiency deterioration or contamination [18]. On

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the other hand, a foam layer can promote DMS expulsion through a stripping effect. Scheuren et al. attributes this to an increase in the contact area between the gas phase and the liquid induced by the foam. This allows DMS to transition more efficiently into the vapour phase. The vapour within the bubbles condenses and evaporates again, creating a kind of rectification column within the foam layer, effectively expelling DMS [19].

2 Aim

The goal is to develop a boiling system that ensures high product quality while minimizing energy use. The mass transfer of volatile, undesirable substances is favoured by a high surface area of the bubbles, while many small bubbles create an uncontrollable amount of foam. An optimal process setting was developed to support mass transfer, prevent uncontrolled foam formation, and allow the evaporation of undesirable substances with minimal thermal energy input.

3 Materials and Methods

Trials were conducted in a 10 hL pilot brewery. Preliminary trials were first conducted to investigate the influence of various factors on bubble formation. Based on these results, wort boiling trials were conducted to maximize DMS expulsion with minimal primary energy input.

3.1 Preliminary Trials

The goal is to generate bubbles that form a large surface area to which DMS can accumulate and rise to the liquid surface without condensing beforehand. To determine the optimal process conditions for forming as many small bubbles as possible across the entire kettle cross-section and height, trials were conducted with a 13 % sugar solution. The parameters flow rate, opening control valve, external boiler temperature (T_{EB}), and inlet geometry were varied according to a full factorial experimental design. The rising bubbles were visually assessed by an observer and qualitatively classified into categories based on apparent bubble size (1 = small; 10 = large) and bubble quantity (1 = few; 10 = many). An ANOVA was used to determine the significant influencing parameters on bubble formation. The levels of the varied factors are listed in table 1.

Table 1 **Factors and levels with which a 2^{IV} factorial experimental design was carried out in a 13 % sugar solution**

	– 1	**+ 1**
Flow rate	6.000 l/h	10.000 l/h
Opening control valve	30 %	80 %
T_{EB}	101 °C	105 °C
Inlet Geometry	A	B

Inlet Geometry A featured three nozzles, each with a diameter of 24 mm, whereas Geometry B consisted of 18 nozzles, each 10 mm in diameter. Both geometries provided comparable total cross-sectional areas, facilitating bubble formation through an induced pressure reduction. This design allowed for a systematic investigation into how nozzle number and diameter influence bubble formation. Additionally, both geometries were designed to support effective clean-in-place procedures.

3.2 Wort boiling trials

For the boiling trials, wort was produced using 175 kg of Pilsner malt (Mich. Weyermann GmbH & Co. KG, Germany), with a DMS-P content of 2.3 mg/kg in the congress mash. The malt was milled with a 6-roller mill and mashed with 525 L of brewing water.

The mash temperature was set to 64 °C, and the pH value was adjusted to a target value of 5.6 by adding phosphoric acid (70 % concentration). The mashing process followed a step mashing program: 64 °C (40 min), 72 °C (20 min), 78 °C (final mash). The wort was filtered in the lauter tun until kettle-full volume of 10 hL and concentration of 13 °Plato was achieved, and the wort boiling was carried out for 60 min at a constant pressure of 30 mbar to exclude atmospheric influences. An EB was used for energy supply. The EB temperature and flow rate were varied according to a statistical experimental design. At the beginning of boiling, 370 g of bitter hops were added to achieve 20 bitterness units (Hop variety: Titan, BarthHaas GmbH & Co. KG, Germany).

There were two trial series a) Reference boiling system (n = 6) and b) New boiling system (n = 10), which differ in terms of the wort circulation and T_{EB}. The goal is to make a comparison between the evaporation efficiencies of both systems and to analyse what set-

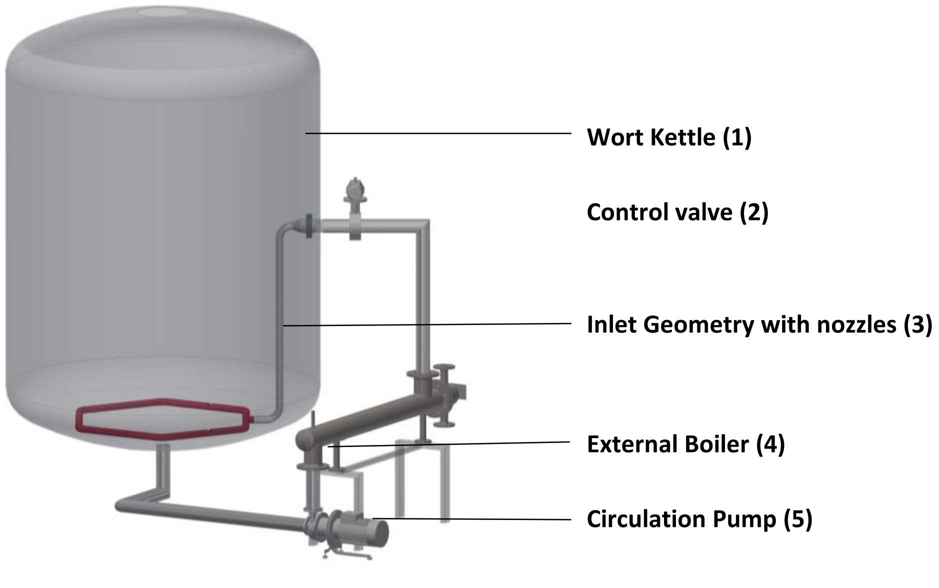

Fig. 1 **Schematic illustration of the new boiling system**

Table 2 **Factors and levels with which a 2^{II} factorial experimental design was carried out in 13 °P wort**

	+ 1	– 1
T_{EB}	101 °C	103 °C
Flow rate	5.000 l/h	8.000 l/h

tings make the new system evaporate most efficiently.

a) **Reference boiling system:** In the reference boiling system, the wort was circulated by a pump, heated in the external boiler and then passed via a spreader with a typical umbrella design.

b) **New boiling system:** In the patented boiling system, the wort circulation after the EB (> T_{Boil}) (4) was pumped (5) into an inlet geometry with nozzles (3) lying at the bottom and added to the lower part of the kettle (Fig. 1).

In initial feasibility trials, the relationship between the T_{EB}, ring geometry, and flow rate on the responses foam quantity and DMS expulsion was analyzed, and the levels for the full factorial experimental design were defined.

The results from the feasibility trials served as the basis for the subsequent trials with 13 °P wort. The factors T_{EB} and flow rate were randomized according to a full factorial experimental design as shown in table 2.

Control valve opening and inlet geometry were held constant at 80 % and Geometry A. Sampling was carried out in the recirculation line of the EB at the start of boiling, defined by a wort kettle temperature of 99 °C (t = 0 min) and at the end of boiling (t = 60 min). Immediately after sampling, the samples were cooled in ice water to reduce further conversion of DMS-P to DMS-free and stored at – 18 °C until further laboratory analysis. Each experiment was analysed at t = 0 min for the parameters DMS-P, DMS-free, and extract. At t = 60 min additional analyses were conducted for DMS-P, DMS-free, Thiobarbituric Acid Index (TBI), extract, coagulable nitrogen (coag. N), and colour. At t = 10 min the foam quantity on the wort surface was assessed and categorized on a scale from 1 (= high foam formation) to 10 (= no foam).

The evaporation rate was calculated according to equation 1.

$$Evaporation\ rate\ [\%] = \frac{\Delta Extract}{Extract_{t=60}} \quad \text{(Eq. 1)}$$

Unlike other volatile compounds in wort, DMS expulsion and formation is less influenced by factors like thermal stress, which makes it to a suitable boiling marker to compare the evaporation efficiency between different boiling systems [20, 21]. Equation 2 represents the DMS reduction during boiling in relation to the energy input expressed as the evaporation rate [21].

$$Evaporation\ efficiency\ [-] = \frac{(DMS_{t=0} - DMS_{t=60}) \cdot 100\%}{DMS_{t=0} \cdot Evaporation\ rate} \quad \text{(Eq. 2)}$$

The goal is to maximize evaporation efficiency.

3.3 Sensory analysis

After ensuring a stable and reproducible boiling process with the new system, the wort was fermented in comparison to a beer produced with the reference boiling system to analyse the sensory differences of the resulting beers. A fully randomized triangle test was performed with 56 untrained panellists. The samples were tempered to 11 °C [22].

3.4 Energy saving potential

To evaluate the system's energy efficiency, the primary energy consumption for an example brewery with an annual production of 2 Mio. hL and a brew size of 465 hL was calculated. A vapour condenser was assumed, which recovers the energy evaporated during the boiling process and uses it to heat the subsequent brew. The required energy amounts for heating and evaporating the wort per hL cast out wort were determined for a reference boiling system with an evaporation rate of 4.9 % and for the new boiling system with an evaporation rate of 1.6 %. These evaporation rates correspond to the measured values obtained from beers evaluated in triangle test. Consequently, energy savings could be compared among beers that exhibited no discernible sensory differences.

4 Results and Discussion

4.1 Significant process factors

In the described preliminary trials with a sugar solution, the process factors and their interactions that significantly influence bubble size and bubble quantity were identified. Table 3 shows the p-values between bubble quantity and bubble size on the investigated process parameters. The reported p-values indicate the statistical significance of each process variable's effect on bubble quantity and bubble size. Factors with p-values lower than 0.05 were considered statistically significant.

A significant correlation was found between the T_{EB} and bubble quantity and size. Higher temperature leads to higher vapour pressure, resulting in more stable bubbles [13]. The opening of the control valve affects the bubble size. The cross-sectional narrowing changes the flow profile and pressure drop in the system. The pressure change influences whether bubbles form [12, 13].

Table 3 **Significant correlations (p-values) of various process variables on the responses bubble quantity and bubble size in a 13 % sugar solution**

	Bubble quantity	Bubble size
T_{EB}	0.0300	0.0003
Opening control valve	0.6000	0.0200
Flow rate	0.0008	0.0700
Inlet Geometry	0.1200	0.0600

Table 4 **Comparison of various wort quality parameters at the end of boiling between the reference boiling system and the new boiling system**

	Reference boiling system	New Boiling system
Total evaporation [%]	4.9	1.6
DMS-P [µg/L]	65	71
DMS-free [µg/L]	15	24
Evaporation efficiency	16	36
Coag. N [mg/L]	25	26
Colour [EBC]	6.25	5.8
TBI [–]	33	33.8

There is also a significant correlation between flow rate and bubble quantity. An increased flow rate leads to more turbulence, which was expected to result in smaller and more bubbles. It is likely that the bubbles split due to high turbulence, making more bubbles visible at the surface [16], however the bubble size was not significantly different.

The ring geometry showed no significant influence on bubble quantity or size. It was expected that smaller nozzle diameters would produce smaller bubbles. The coalescence and dispersion behaviour of two-phase mixtures is complex, and the size distribution is influenced by factors such as pressure loss, heat, and mass transfer [23]. The difference between the two inlet geometries may have been too small to visually determine a difference in bubble formation.

As the evaluation of bubble size and quantity was carried out visually, there are uncertainties in the classification of bubble size and quantity. The preliminary tests were primarily aimed at determining relevant process parameters that contribute to bubble formation.

Further feasibility trials with wort showed that smaller nozzle diameter tend to uncontrollable foam formation. As already the Geometry A achieved DMS values below the desired limit of 100 µg/L [2, 3], the flow rate and T_{EB} were identified as the decisive factors. These two process variables were further investigated in the subsequent trials.

4.2 Comparative evaluation of reference and new boiling system

In addition to the DMS-free content, which must be below the MEBAK limit to avoid off-flavours in the beer, other wort quality parameters such as TBI, wort colour, and coag. N. should also be within the MEBAK limits [2, 24, 25]. The target for the boiling system is an evaporation rate of < 2 % that does not show significant differences in wort quality parameters compared to a state-of-the-art boiling system.

Table 4 shows the laboratory analyses of wort produced with the new boiling system at an evaporation rate of 1.6 %, compared to the reference boiling system with an evaporation rate of 4.9 %.

The DMS-free content measured in the new boiling system is 24 µg/L, which is slightly higher than the value of the reference system at 15 µg/L, but still below the MEBAK threshold [2]. The evaporation efficiency is significantly higher in the new system at 36 compared to the reference system at 16, indicating that the new system achieves equivalent DMS-free levels while consuming less thermal energy.

The proportion of coag. N shows no significant differences between the two boiling systems. Both values are within the MEBAK limits of 15 – 30 mg/L [25]. The content of coag. N is influenced e.g. by the raw material, the pH value, the formation of dead zones, the boiling duration, and intensity [1]. The same raw material was used, the pH value was adjusted to constant process conditions in the mash tun, and the boiling duration was kept constant. The intensity of boiling differed between the experiments in terms of different T_{EB}. An increase in the coag. N content was expected due to the temperature reduction. The absence of this effect suggests that a factor responsible for the decrease in coag. N content was eliminated with the new system. One possible explanation is that the additional ring geometry introduced increased turbulence, potentially offsetting the effect of reduced temperature in the EB. Another theory, based on Huang et al., suggests that coag. N levels stabilize after 40 minutes [26]. Since the wort was boiled for 60 minutes, sufficient time was available to compensate for a potentially lower boiling intensity.

A reduction in the evaporation rate was achieved by reducing the T_{EB}. It was assumed that the lower thermal load would result in less thermal markers like TBI and a lower colour intensity, as fewer Maillard products are formed [27]. This correlation could not be confirmed. At the same evaporation rate, the new boiling system shows a higher thermal load. The wort boiling system of the pilot plant is designed for evaporation rates of > 4 %. The residence time can be reduced with an EB designed to fit the system (smaller). In this case, the TBI value could be lower with an identical evapora-

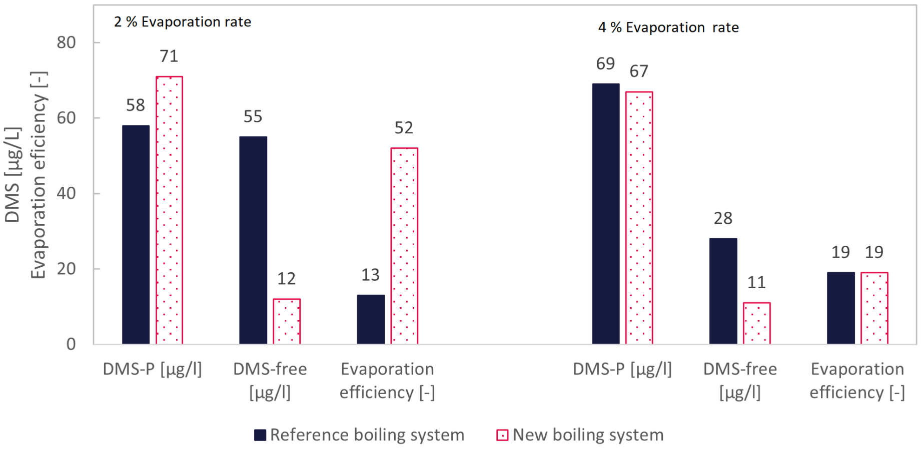

Fig. 2 **Comparison of evaporation efficiencies and DMS values between the two boiling systems at 2 % (left) and 4 % (right) evaporation rates**

tion rate. Nevertheless, it can be stated that the TBI value for the new system is still within the limit value of < 45 defined by MEBAK [25].

A triangle test between the two beers with 56 untrained panellists showed that no significant difference could be detected. This is consistent with the analyses. Both samples had a DMS-free content at end of boiling below the threshold, therefore, no impact on the taste of the beer is to be expected based on this [2]. Furthermore, the TBI and coag. N values were comparable, so the beers could not be visually distinguished based on foam stability or colour.

The results discussed so far have demonstrated that there are no detectable sensory differences between a beer brewed with the reference boiling system and the new boiling system. In order to provide a comprehensive assessment of evaporation efficiency, figure 2 compares the concentrations of DMS-P and DMS-free at the end of boiling, as well as the evaporation efficiency of both boiling systems at equivalent evaporation rates. The results illustrate that a reduction in the evaporation rate alone by adjusting the T_{EB} and or flow rate in the reference system is not sufficient to achieve comparable efficiency as in the new system.

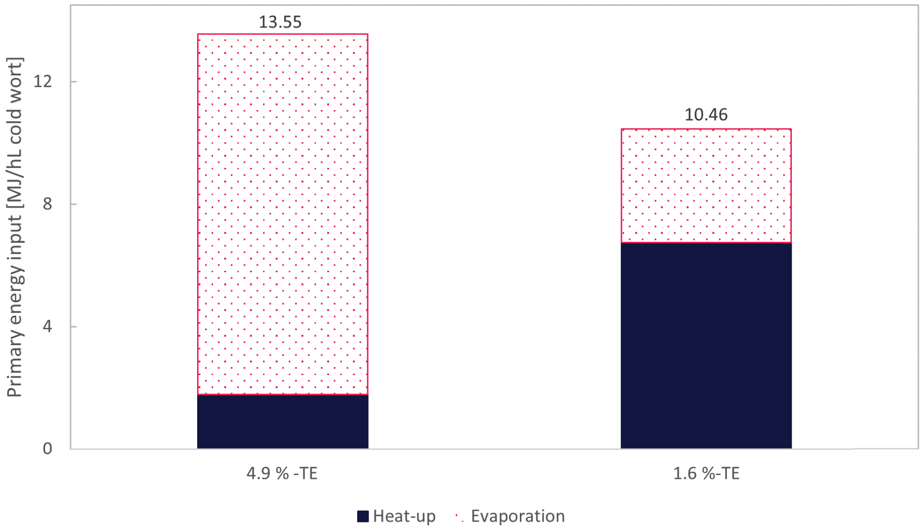

Fig. 3 **Primary energy input required for the heat-up and evaporation steps of the two boiling systems at their total evaporation rates (TE)**

At an evaporation rate of around 2 %, more DMS is expelled in relation to total evaporation in the new boiling system than in the reference system, as quantified by the parameter of evaporation efficiency (Eq. 2). Presumably, the formation of bubbles compared to the reference system leads to a larger gaseous surface that favours the DMS release. However, this advantage disappears at higher evaporation rates, as although the evaporation rate is increased, a certain residual DMS-free content will always remain due to the concentration equilibrium of DMS-free and DMS-P.

Scheuren and Dillenburger examined the evaporation behaviour of DMS when the wort coming from the EB is returned above or below the wort surface and found that the latter requires a 2.5 % lower evaporation rate for the same reduction of flavour compounds. Forming vapour bubbles rise in the liquid and act as a carrier for DMS molecules, effectively transporting them to the wort surface [28]. At the surface, a continuously collapsing and regenerating foam layer facilitates a rectification-like process. The vapour rising through the foam enhances the removal of DMS and increases the evaporation efficiency [19].

4.3 Energy saving potential

Figure 3 shows how much energy would be required to boil the wort of the two trials shown in table 3.

The bars represent a wort boiling system with evaporation rates of 4.9 % and 1.6 %, respectively. The lower section of the bars shows the amount of primary energy required to heat the wort coming from the lauter tun to boiling temperature. Since less energy can be recovered at a low evaporation rate to heat the next batch, more primary energy is required to heat up for a 1.6 % boiling system than for a 4.9 % boiling system.

The upper section of the bar represents the primary energy required for the phase transition of 4.9 % or 1.6 % of the kettle-full amount from the liquid to the gaseous phase. The significant energy savings in the new boiling system result from the reduction in the evaporation rate, as the phase transition from liquid to vapour requires more energy than heating the wort. Although the primary energy requirement for heating increases in the new boiling system, the total energy requirement for the entire boiling process is reduced. This is due to the high enthalpy of evaporation, which overall leads to a 23 % reduction in energy consumption during wort boiling.

5 Limitations

Like any system, the new boiling system is subject to natural limits and requires consideration of certain factors that may necessitate preventive measures.

Foam is formed by the dispersion of gas in protein-rich liquids like wort [5]. The bubbles are formed in the new boiling system by the nozzles located at the bottom of the kettle, rise, and lead to foam formation on the surface. Controllable foam is not problematic and, according to Scheuren et al., should even favour the thermodynamic separation process [18]. However, excessive foam formation that could lead to production disruptions have to be avoided. It is crucial to find a balance between sufficiently high flow rate and temperature to promote bubble formation without risking excessive foam formation. If a specific flow rate – T_{EB} combination is required that would lead to excessive foam formation, alternative foam avoidance solutions could help. These include, e.g. the use of ultrasonic sensors to prevent foam, the installation of a spreader (an evident solution, especially for retrofits), pressure boiling, the use of foam inhibitor solutions or tangential introduction of the wort at the bottom of the wort kettle to create a rotational flow [28, 29].

Bubble formation occurs due to the pressure difference that arises when the wort exits the nozzle into the kettle. The pressure depends, among other things, on the temperature and flow rate. To generate bubbles, both factors must exceed a certain minimum value. Since these parameters positively correlate with the evaporation rate, a minimum evaporation cannot be undershot without losing the effect of bubble formation and thus efficient DMS expulsion. The evaporation rate can generally be adjusted continuously upwards. However, measures to control foam may need to be taken once the critical foam amount is reached.

The physically determined and experimentally determined minimum evaporation rate for bubble formation in a 10 hL kettle is approximately 1 %. By adjusting the flow rate and T_{EB}, the evaporation rates can be continuously set to all values > 1 %. This allows for further optimization potential through the insertion of simmer phases or similar. Additionally, no inert gas is required, which on the one hand does not hinder the efficiency of the vapour condenser, does not pose a fouling risk due to non-condensable bubbles in the EB in the case of short-circuit flow, and does not require expensive inert gas to be safely stored [10, 30].

6 Conclusion and Outlook

The new boiling system offers a highly efficient and sustainable alternative to reference boiling systems by significantly reducing primary energy consumption by 23 % through a substantial reduction in the evaporation rate, without significantly affecting the sensory and analytical quality characteristics of the wort. The reason for this is the evaporation efficiency, which is significantly influenced by the system design and the adjustable process parameters. A key advantage of the new boiling system is its simple retrofit into existing plants and its high flexibility. It enables the adjustment of process parameters such as temperature and flow rate, allowing energy consumption to be tailored to specific production requirements.

In future work, the reproducibility of the experiments on a large scale will be tested. In addition to monitoring wort quality parameters, the focus will also be on the impact on further downstream process steps such as fermentation, filtration, storage stability, etc. In particular, further optimizations of the inlet geometry and process parameters could contribute to further efficiency improvements.

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