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Validation of a Low-Evaporation Retrofit for Industrial Wort Boiling: Impact on Wort Quality and Sensory Attributes

Wort boiling is one of the most energyintensive steps in brewing and is traditionally operated at an evaporation rate of approximately 4 % to ensure sufficient expulsion of DMS. This paper reports the first industrial-scale evaluation of the retrofitable boiling system *BubbleBoil*, which generates bubbles via a controlled pressure drop at a ringshaped nozzle below the liquid surface, aiming to maintain wort quality at lower evaporation rates.

The retrofitted boiling system delivered higher evaporation efficiency than the reference system at similar evaporation rates, consistent with intensified stripping due to the increased gas-liquid interfacial area. Industrial operation achieved target evaporation rates as low as approximately 1.5 - 2.0 % while preserving wort quality, with no significant sensory differences compared to a brew produced with a conventional boiling system operating at a 4 % evaporation rate.

Descriptors: Evaporation efficiency, Evaporation rate, Wort boiling, Wort quality, DMS, Energy saving

1 Introduction

Wort boiling remains one of the most energyintensive unit operations in beer production. Traditionally, evaporation rates exceeding 4% are employed to ensure sufficient removal of volatile compounds such as dimethylsulfide (DMS) [1].

DMS is an undesirable aroma compound that must be removed during wort boiling to prevent off-flavours in the final beer. It is formed through the thermal cleavage of its precursor, dimethylsulfide precursor (DMSP), which originates from malt. This reaction follows first-order kinetics and is highly temperature-dependent [2, 3].

The kinetics of DMSP degradation can be described by Equation 1:

$$c_{\text{DMSP}}(t) = c_{\text{DMSP},t=0} \cdot e^{-k \cdot t} \quad (1)$$

Here, k denotes the reaction rate constant [1/s], t the boiling time in seconds, and $c_{\text{DMSP}}(t)$ the concentration of DMSP at time t . While the DMSfree content reflects both formation and evaporation dynamics, analysing DMSP degradation in isolation enables a focused evaluation of the formation kinetics. Conversely, DMS evaporation is influenced by the evaporation rate, bubble dynamics, and the thermodynamic volatility of the compound. Therefore, a compre-

hensive assessment of boiling efficiency requires the combined analysis of DMSP conversion and DMS removal [4, 5].

To reduce the evaporation rate while still achieving low concentrations of volatile compounds at the end of boiling, the efficiency of DMS removal must be increased [2]. The boiling system *BubbleBoil* by *Ziemann* has demonstrated this capability in 10 hL pilotscale trials. By inducing bubble formation through a controlled pressure drop at the outlet of a ringshaped nozzle at the kettle bottom, the system increases the gas-liquid interfacial area and thereby enhances DMS stripping [6].

Building on these findings, the system has now been implemented in an industrial-scale brewery for the first time. Commissioning was accompanied by targeted experimental trials to validate the transferability of pilotscale data to fullscale operation.

2 Aim

The objective of this study is to evaluate the industrialscale performance of *BubbleBoil* in wort boiling. The investigation focuses on two key aspects: (i) the impact on wort and beer quality parameters, and (ii) the quantification of evaporation efficiency and energy consumption under production conditions.

3 Materials and Methods

3.1 Industrial Setup and System Integration

Trials were conducted in an industrial-scale brewhouse equipped with a wort kettle of 240 hL capacity. Figure 1 illustrates the process and instrumentation diagram (P&ID) of the brewhouse configuration

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used for the trials. The existing boiling system (hereafter referred to as the reference System) comprised an external boiler (EB) (3), a recirculation pump (2), and an umbrella-type spreader (5). For the *BubbleBoil* retrofit, the kettle's tangential inlet was utilised to install a ring-shaped nozzle assembly (4). Both systems share the same flow path from the kettle through the pump to the EB, with the operating mode defined by actuating valve 1 (*BubbleBoil*) or valve 6 (reference system).

3.2 Wort boiling trials

Wort was produced from 100 % malt (DMSP \approx 3 mg/kg, based on congress mash analysis). After mashing in a conventional mash kettle and lautering, a kettle-full of 240 hL at 12 °Plato was obtained. This wort was used to produce a Pilsener beer. All wort boiling lasted 50 min with thermal energy supplied by the EB. Bitter hops were added during heat-up to achieve 20 bitterness units.

A comparative analysis of the wort quality parameters was conducted using both boiling systems:

- **Reference system** (n = 4): Trials were carried out following the brewery's standard recipe, with all factor settings kept unchanged and aligned with highlevel conditions of the full factorial design.
- **BubbleBoil** (n = 8): Trials followed a 2² full factorial design.

The two experimental factors Outlet Temperature at EB (T_{EB}) and the number of circulations were varied according to Table 1, while all other recipe parameters were kept identical to those used in the reference system.

Sampling was conducted in the EB recirculation line at t = 0 min (kettle temperature 99 °C) and t = 50 min (end of boil). Samples were cooled in ice water and stored at -18 °C. Laboratory analysis included:

- t = 0 min: DMSP, DMS-free and extract were analysed to confirm identical initial wort conditions
- t = 10 min: Foam height, as foam formation peaks early in the boil and is not informative later
- t = 50 min: DMSP, DMS-free, extract, Thiobarbituric Acid Index (TBI), coagulable nitrogen (coag. N), colour were analysed to assess the impact of the boiling system on wort quality

The foam height was assessed visually using a fixed scale inside the kettle, measuring the vertical distance between the wort level and the foam peak.

3.3 Calculation of Evaporation Parameters

DMS was selected as a marker for evaporation efficiency because its formation and removal during wort boiling are less affected by thermal stress compared to other volatiles [2]. The objective was to maximize evaporation efficiency. The value was calculated according to Equation 2 relat-

ing DMS reduction to the energy input expressed as evaporation rate [4].

$$\text{Evaporation efficiency [-]} = \frac{(\text{DMS}_{\text{Start}} - \text{DMS}_{\text{End}}) \cdot 100\%}{\text{DMS}_{\text{Start}} \cdot \text{Evaporation rate}} \quad (2)$$

The evaporation rate was determined from extract change (Equation 3):

$$\text{Evaporation rate [\%]} = \frac{\Delta \text{Extract}_{\text{End-Start}}}{\text{Extract}_{\text{End}}} \cdot 100\% \quad (3)$$

DMS formation during boiling results from thermal cleavage of its precursor (DMSP), which follows first-order kinetics [2]. For the three boiling regimes i) reference boiling with 4 % evaporation rate, ii) *BubbleBoil* with 4 % evaporation rate, and iii) *BubbleBoil* at 1.8 % evaporation rate, the mean rate constant (k) was calculated from DMSP concentrations measured at the start and end of boiling (Equation 1). For the *BubbleBoil* at reduced evaporation rate, only the trials conducted with the final process parameters were considered, while the process parameters of the higher evaporation rates were exactly the same. Just the open/close position through valve 1) or 6) (Figure 1) was adjusted. Using these kinetic parameters, the theoretical DMSP concentration after 60 min of boiling was calculated for each system. This approach enables a direct comparison of the impact of boiling technology and evaporation rate on the resulting DMSP levels. A boil time of 60 min was selected, as this represents a typical duration applied in brewery practice.

3.4 Sensory Evaluation

Based on the factorial boiling trials, a recipe optimised for *BubbleBoil* was developed to achieve comparable wort quality at an evaporation

Table 1 Factors and levels used for a 2² factorial experimental design was carried out in 12 °P wort

	-1	+1
T_{EB}	101 °C	104 °C
Number circulations	6	10

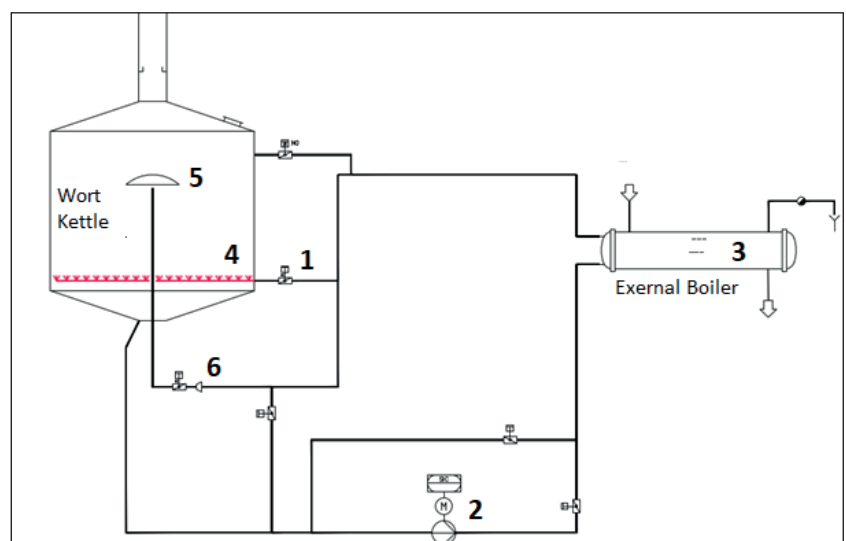


Fig. 1 The schematic illustrates the integration of *BubbleBoil* into the existing external boiling system. 1) and 6) Control valves; 2) Circulation pump; 3) External boiler; 4) *BubbleBoil* Ring; 5) Spreader

rate of 1.5 %. The optimisation focused on adjusting the flow rate, which affected the number of circulations of the kettle volume, the EB outlet temperatures, and the duration of location-specific wort boiling phases within the standard wort boiling program.

Using this adapted recipe, nine brews were produced and fermented together in a single fermentation tank. For direct comparison, nine brews using the same raw materials but boiled with the reference System at a 4 % evaporation rate were fermented in a second tank under identical conditions. In addition, a random selection of brews was analysed using the same laboratory parameters as in the full-factorial plan to verify whether these trials were consistent with previous findings.

Evaluation of the two final beers produced with the respective boiling systems included:

- Triangle test with 22 untrained panellists (serving temperature: 11 °C)
- Descriptive analysis by an expert panel
- Foam stability measurement (Steinfurth)

3.5 Energy Saving Potential:

The energy consumption of both systems was assessed under real production conditions. Calculations included:

- Primary energy for heating from a lautering temperature of 78 °C to boiling point
- Energy for phase transition (evaporation)
- Consideration of heat recovery via vapour condenser ($\eta = 95 \%$)

4 Results and Discussion

4.1 Dimethylsulfide

Evaporation efficiency, (Equation 2), is a key indicator for assessing the thermodynamic effectiveness of wort boiling systems [2]. Figure 2 compares the evaporation efficiency of the reference system with that of the *BubbleBoil* system.

The median evaporation efficiency of *BubbleBoil* is higher than that of the reference system. This is in line with theoretical considerations suggesting that bubble formation may facilitate the mass transfer of volatile compounds through an enlarged liquid-vapour interface [2]. This effect had already been indicated at pilot scale and could now be confirmed under industrialscale brewing conditions [6]. It must be noted that evaporation efficiency generally increases with decreasing evaporation rate [5]. Therefore, comparisons should be made at similar evaporation rates to ensure validity. Pilotscale trials had already indicated that, at comparable evaporation rates, *BubbleBoil* achieves higher evaporation efficiency [6]. However, under industrial conditions, only a small number of trials with the

reference system at reduced evaporation rates were conducted. Further trials were avoided because previous results showed its efficiency drops sharply at lower rates, increasing the risk of exceeding critical wort DMS levels. The resulting low number of repetitions did not allow for a separate statistical evaluation and is therefore not reported independently.

The degradation of DMSP during wort boiling followed first-order kinetics, consistent with previous studies on volatile formation and removal during boiling [2, 7]. For each trial, the reaction rate constant k was calculated based on measured DMSP concentrations at the start and end of boiling. Using these empirically derived constants, the expected DMSP concentration after 60 minutes of boiling was modelled, assuming an initial concentration of 300 $\mu\text{g/L}$, to avoid the influence of rawmaterial variability on the initial DMSP levels.

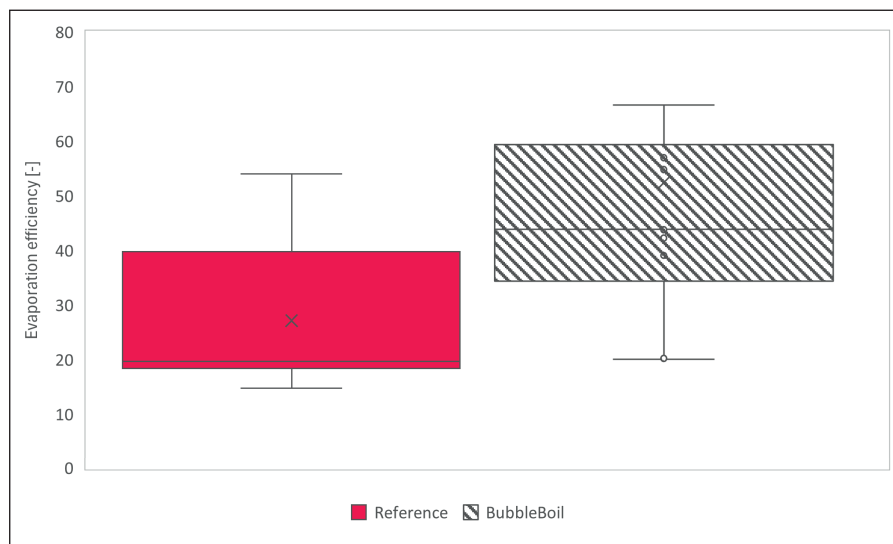


Fig. 2: DMS evaporation efficiency of wort produced with the reference system at around 4 % evaporation rate or *BubbleBoil* at around 2% evaporation rate

Table 2 Calculated DMSP concentrations (\pm SD) at the end of wort boiling for the reference system and the *BubbleBoil* system at their respective evaporation rates assuming an initial DMSP concentration of 300 $\mu\text{g/L}$

Boiling System	Reference	BubbleBoil	BubbleBoil
Measured Evaporation Rate	4 %	3.8 %	1.8 % \pm 0.1
k-value [1/min]	0.0178	0.0246 \pm 0.0007	0.0201 \pm 0.0016
Concentration of DMSP at end of boil [$\mu\text{g/L}$]	103	83 \pm 3.5	90 \pm 8.4

Table 2 compares the expected DMSP content at end of boiling of both boiling system and their respective evaporation rates.

The reference boiling system with an evaporation rate of 4%, the k value was 0.0178 min^{-1} , resulting in a final DMSP concentration of 103 $\mu\text{g/L}$. When the *BubbleBoil* system was operated with the same process settings, a higher degradation rate was observed ($k = 0.0246 \pm 0.0007 \text{ min}^{-1}$). This

corresponds to an increase in DMSP conversion compared to the reference system and yielded a lower final concentration of $83 \pm 3.5 \mu\text{g/L}$.

When the evaporation rate in the *BubbleBoil* system was reduced to 1.8%, the degradation rate decreased accordingly ($k = 0.0201 \pm 0.0016 \text{ min}^{-1}$). Nevertheless, that constant remained higher than that of the reference system at 4% evaporation. The final DMSP concentration of $90 \pm 8.4 \text{ mg/L}$ confirms that the system facilitates more efficient DMSP degradation despite reduced thermal load.

The *BubbleBoil* trials consistently showed higher k values. This finding suggests that the process of DMSP cleavage becomes more efficient. The observed faster decrease in DMSP concentration might primarily be due to intensified stripping rather than accelerated precursor cleavage. *BubbleBoil* enhances gas-liquid mass transfer, and shifting the equilibrium, which indirectly supports precursor conversion by continuous removal of the reaction product [1, 2, 5]. Therefore, *BubbleBoil* achieves higher evaporation efficiency by combining intensified stripping with accelerated DMSP degradation, enabling energy savings while maintaining wort quality.

4.2 Foam formation

Consistent with results from previous pilot-scale trials, a foam layer formed above the wort surface during boiling in the industrial-scale setup using the ring-shaped nozzle. Foam height correlated positively with the number of circulations and the external boiler temperature ($R^2 = 0.715$; $p\text{-value} < 0.05$). At $>> 3\%$, foam formation becomes critically high and required redirecting the flow via the spreader to mechanically destroy the foam which had to be performed roughly every 5 minutes for about 10 seconds.

Within the target range of $< 3\%$ evaporation rate, a stable and controllable foam layer of approximately 50 cm was observed. No additional measures such as foam breakers, pressure regulation, or flow redirection were required.

4.3 Coagulated Nitrogen

Figure 3 shows the coag. N content normalised to 12°Plato, grouped by boiling system. Wort brewed with *BubbleBoil* exhibited a median coag. N content approximately 0.3 mg/L higher than the reference.

Figure 4 further differentiates coag. N values by malt batch, revealing that raw material composition had a stronger influence than the boiling system itself. To facilitate comparison, blocks represent datasets produced with the same raw material batch. Within identical malt batches, *BubbleBoil* consistently yielded higher coag. N values.

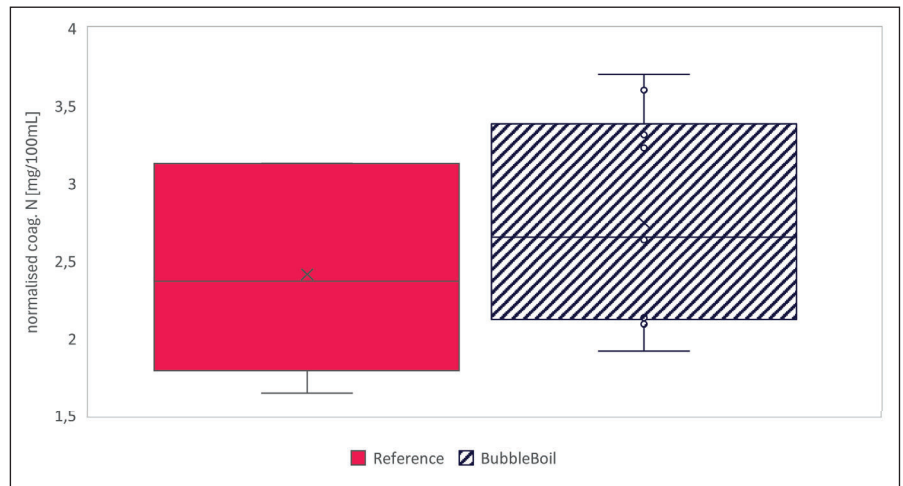


Fig. 3 Normalised coag. N values at end of boiling of wort produced with the reference system or *BubbleBoil*

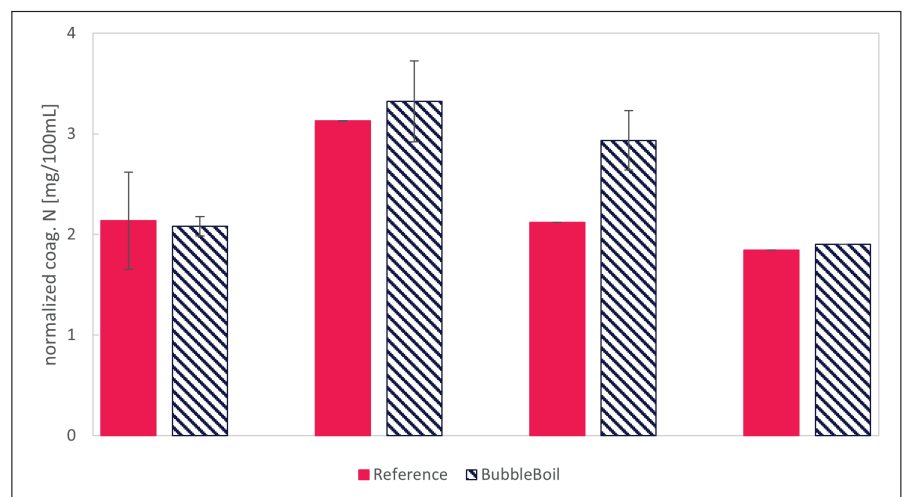


Fig. 4 Normalised coag. N values measured at end of boiling from boiling trials using either the reference system or *BubbleBoil*. Data points are grouped in blocks indicating the respective raw material batch

The higher coag. N value for wort produced with *BubbleBoil* can be attributed to the gentler boiling conditions, particularly the reduced number of recirculations and the lower external boiler temperature, which result in less protein denaturation [8].

For breweries using malt with low protein content or facing variability due to future harvests, coag. N levels can be adjusted by modifying recipe parameters such as temperature or recirculation rate. However, potential interactions with bubble formation must be considered, as these may affect evaporation efficiency and DMS removal.

4.4 Thermal Load

The thermal impact of the boiling systems was assessed based on colour and TBI. Figures 5 and 6 show the corresponding end-of-boil values for both systems, colour-coded by raw material batch.

Consistent with previous pilotscale findings, variations in colour and TBI were driven primarily by differences between malt batches,

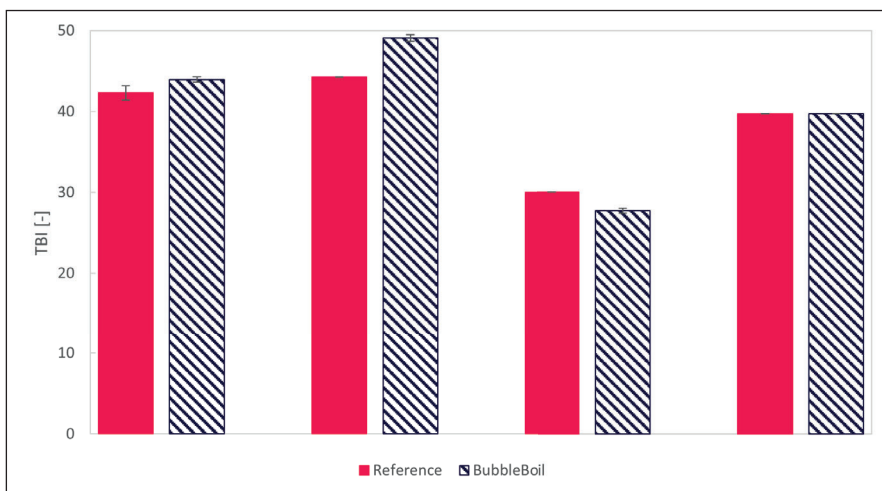


Fig. 5 TBI values measured at end of boiling from boiling trials using either the reference system or *BubbleBoil*. Data points are grouped in blocks indicating the respective raw material batch

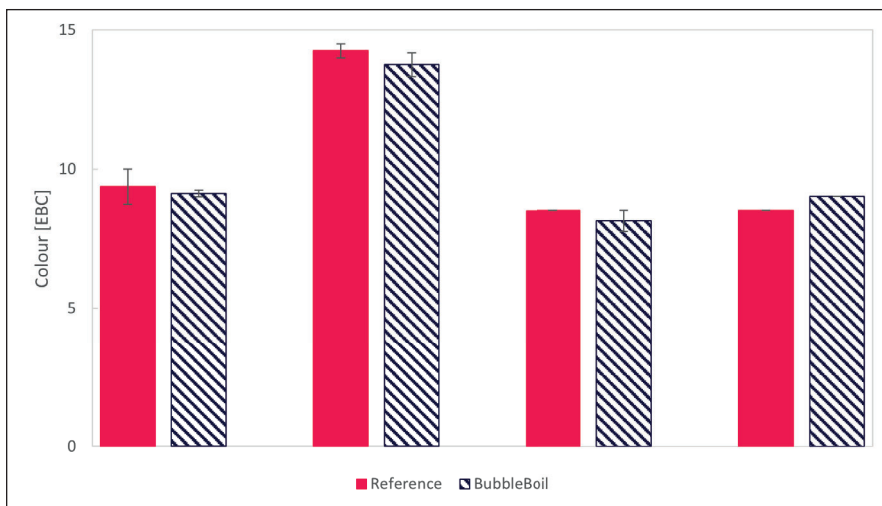


Fig. 6 Colour measured at end of boiling from boiling trials using either the reference system or *BubbleBoil*. Data points are grouped in blocks indicating the respective raw material batch

whereas the choice of boiling system showed no significant influence on these parameters [6].

4.5 Beer: Foam stability and Sensory

Following recipe optimisation, beers brewed with *BubbleBoil* were fermented under identical conditions to the reference brews. Foam stability is shown in Table 3.

Despite higher coag. N values in *BubbleBoil* wort, no significant change in foam stability was observed. This suggests that the reduced protein denaturation did not translate into measurable foam quality.

Fully randomized triangle test ($\alpha = 0.05$) was conducted with 22 untrained panellists to evaluate perceptible sensory differences between beers produced with the *BubbleBoil* and the reference boiling system. Of the 22 panellists, 8 correctly identified the odd sample, which is below the critical number of 10 correct responses required at this significance level. Therefore, no statistically significant difference could be demonstrated.

Table 4 summarizes the comments from panellists who correctly identified the differing sample.

No consistent sensory attributes were associated with either boiling system, indicating that any potential differences remained below the perception threshold or were individually interpreted. These observations align with the analytical data, confirming the sensory equivalence of *BubbleBoil*. Both beers showed DMS-free levels below the sensory threshold at the end of boiling, excluding any flavour impact [9]. Their TBI and coag. N values were similarly comparable (*BubbleBoil*: TBI = 39.7, Coag. N = 1.9 mg/100mL ; Reference: TBI=39.7, Coag. N=1.8 mg/100mL). This analytical similarity was further supported by the sensory evaluation, as panellists did not perceive visual differences in colour or foam stability.

4.6 Energy saving potential

Figure 7 illustrates the primary energy demand per brew for both the reference system (R) and *BubbleBoil* (BB). The energy requirement is divided into i) heating the wort from the Lauter Tun to the boiling temperature and ii) evaporation at the respective evaporation rates. Additionally, the recovered energy from the vapour condenser is considered and assumed to be reused for heating the subsequent brew. The second bar assumes that *BubbleBoil* is integrated into the existing energy system without further modifications, while the third bar additionally accounts for potential optimisation of other energy flows.

Compared to the reference system, *BubbleBoil* recovers less energy in the vapour condenser, resulting in a higher primary energy demand for the heat-up phase. However, *BubbleBoil* requires substantially less energy for evaporation due to its reduced evaporation rate. As a result, the energy savings during the phase transition outweigh the additional heat-up demand, leading to an overall primary energy reduction of approximately 10%.

However, brewery energy systems operate as interconnected thermal networks, so modifying wort boiling without adjusting adjacent heat flows leaves efficiency potential unused. *BubbleBoil*'s lower evaporation rate reduces heat input and yields a smaller, more temperaturealigned surplus, which can be integrated into multistage heatrecovery cascades. Twostage wort cooling enables

Table 3 Foam stability of Pilsner beers brewed with the reference system and *BubbleBoil* under comparable fermentation conditions

	Reference	BubbleBoil
Foam Stability [-]	112	110
Foam stability HLT [s]	94	92

the utilisation of progressively lower energy levels, reducing ΔT losses and increasing overall efficiency. In contrast, the larger surplus of reference systems often exceeds demand. By lowering primary energy needs first and recovering residual heat more effectively, total primary energy savings can reach up to 40 %.

5 Conclusion and Outlook

This study confirms that *BubbleBoil* enables a substantial reduction in evaporation rate from approximately 4% to around 1.5% in a largescale industrial brewery - without compromising wort quality, foam stability, or sensory characteristics of the final beer. The improved evaporation efficiency, demonstrated through kinetic analysis of DMS expulsion, highlights the system's capability to maintain volatile compound removal at lower thermal input.

The gentle boiling conditions of *BubbleBoil* resulted in higher coagulable nitrogen levels, which may be particularly beneficial when using low-protein malt. Despite this, no measurable improvement in beer foam stability and no sensory effects were detected. This confirms that *BubbleBoil* does not negatively influence foam-related quality parameters nor the sensory profile of the beer.

The retrofit integration of *BubbleBoil* via an existing tangential inlet proved technically feasible and required minimal structural modifications. The system offers a particularly attractive alternative to traditional energy recovery technologies, which often involve higher investment costs and more complex installation. Due to its significantly improved return on investment, *BubbleBoil* can therefore represent a more economical and sustainable option for breweries seeking to modernise their boiling processes.

Acknowledgments

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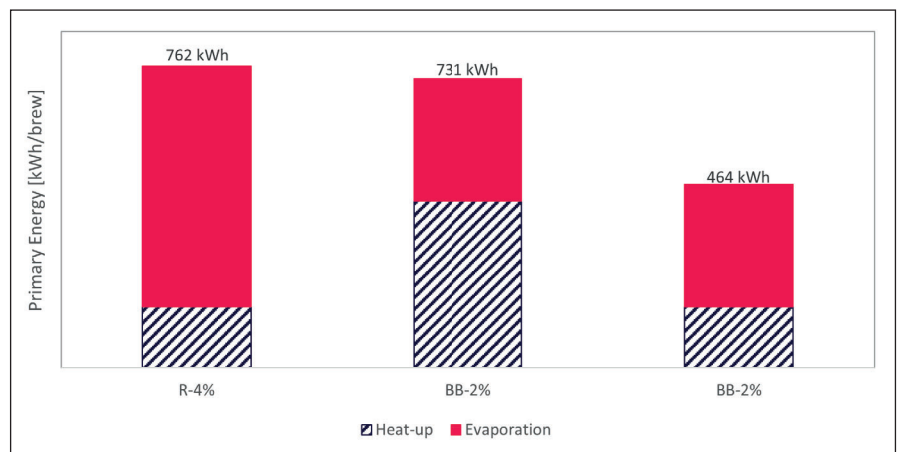


Fig. 7 Primary energy input required for the heat-up and evaporation steps of the reference system (R) and *BubbleBoil* (BB) at their total evaporation rates, assuming an additional heat recovery from e.g. wort cooling (right bar).

Table 4 Summary of comments from panellists who correctly identified the differing sample in a triangle test (n = 22, untrained)

	Reference	BubbleBoil
Comments from correct answers how samples differed	• Slightly sour note	• Less bitter
	• Lingering bitterness	• Slightly more bitter
	• Deviation in aroma, taste is identical	• Milder in taste, smoother finish
	• More pronounced bitterness in the aftertaste	• Flavour slightly milder

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