



Hydrodynamic cavitation-assisted wort boiling: energy savings without compromising beer quality

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Abstract

From both environmental and economic perspectives, it is desirable to minimize energy consumption during brewing while maximizing raw material utilization. One of the most energy-intensive steps in brewing is wort boiling, which can be intensified through the application of hydrodynamic cavitation. This study compares two beer production processes that differ in wort treatment/boiling: one using hydrodynamic cavitation-assisted (HC-assisted) treatment at 90 °C for 80 min, followed by short wort boiling for 15 min, and the other using a conventional wort boiling process for 90 min. The resulting worts and lager beers showed very similar key parameters in terms of analytical composition, sensory evaluation, and colloidal stability. Notably, the HC-assisted process reduced energy consumption during wort boiling by approximately 30%. These findings demonstrate the potential of hydrodynamic cavitation as an effective approach for improving the sustainability and efficiency of beer production without compromising product quality.

Keywords: hydrodynamic cavitation; sensory; analysis; wort; beer; energy consumption

1 Introduction

The increasing demand for sustainable and energy-efficient industrial processes has stimulated the search for alternative technologies to achieve reducing energy consumption. Higher energy costs have intensified the need for process optimization across the food and beer brewing processing (Sturm et al., 2012). Among the various process intensification strategies, hydrodynamic cavitation has recently attracted considerable attention as a promising approach to enhancing chemical and physical transformations while potentially reducing overall energy demand (Arya et al., 2019).

Hydrodynamic cavitation (HC) is the phenomenon of vapor bubble formation in a liquid induced by rapid pressure changes at a given temperature during high-velocity flow (Arya et al., 2019). It occurs when local hydrodynamic pressure drops below the vapor pressure of the liquid (Carpenter et al., 2017). In practice, HC is generated by flow restrictions, such as a Venturi nozzle, which accel-

erates the liquid velocity (reducing pressure) followed by a sudden pressure recovery and bubble implosion. The subsequent collapse of the formed bubbles produces intense localized pressure and temperature hotspots, leading to material or cell disruption, further enhanced by strong velocity gradients in the flow (Carpenter et al., 2017; Vajnhandl and Majcen Le Marechal, 2005).

Cavitation intensity can be expressed by the cavitation number (CN), derived from Bernoulli's equation, with lower CN values indicating more intense cavitation (Štěrba et al., 2024; Šarc et al., 2017). Bubble implosions are also caused by overall differences in the flow velocity gradients (Carpenter et al., 2017). The intensity of cavitation can be expressed as cavitation number (CN), derived from the Bernoulli's equation (Šarc et al., 2017) as:

$$CN = (P_{out} - P_v) / (0.5 \cdot \rho \cdot u^2) \quad (1)$$

Where P_{out} (N/m²) is the average pressure downstream of the cavitation reactor, where collapse of the bubbles occurs, P_v (N/m²) is the liquid vapor pressure specific for the given liquid at the given temperature (calculated according to Antoine equation – 70 113.59 Pa at 90 °C), ρ (kg/m³) is the liquid density and u (m/s) is the velocity of the flow through the cavitation reactor. Therefore, a low CN value means intense cavitation. Cavitation bubbles were originally generated using ultrasound; however, Venturi nozzles later became the preferred alternative because of their scalability, lower equipment cost, and, most importantly, superior energy efficiency (Gogate et al., 2001). HC has been used in the food processing industry to reduce the size of particles, improve the mixing of ingredients and increase the rate of chemical reactions (Asaithambi et al., 2019).

According to findings reported in the scientific literature, hydrodynamic cavitation may provide several beneficial effects in the brewing process. These effects include the isomerization of α -acids (AA) into iso- α -acids (IAA), which are responsible for beer bitterness (Meneguzzo and Zabini, 2025; Štěrba et al., 2024), gluten reduction (Meneguzzo and Zabini, 2025; Albanese et al., 2017), increased levels of xanthohumol and hop prenylflavonoids in beer (Ciriminna et al., 2018), and the inactivation of food-spoilage microorganisms (Milly et al., 2007).

In our previous study, the effect of hydrodynamic cavitation on the isomerization of alpha-acids during wort processing was evaluated with respect to two main parameters: temperature and cavitation number. This parametric evaluation demonstrated that HC significantly accelerates AA isomerization at temperatures below the atmospheric boiling point (70–90 °C) (Štěrba et al., 2024). The results obtained in the previous study are consistent with those of other studies showing that alpha-acid isomerization follows first-order kinetics; consequently, an increase in temperature leads to a higher rate of isomerization (Malowicki and

Shellhammer, 2005). Conversely, excessively high temperatures may reduce the isomerization rate and promote the formation of undesirable off-flavors and aromas (Olaniran et al., 2017). In our previous study, the highest HC-assisted yields were achieved at 90 °C. No statistically significant correlation was found between CN and the yield of hop α -acid isomerization. These findings suggest that, within the investigated range of CN, the extent of iso- α -acid formation was governed primarily by cavitation exposure time rather than by cavitation intensity itself. However, some of the monitored wort quality parameters, particularly dimethyl sulphide (DMS) content and hot break formation, were not fully satisfactory when HC treatment was carried out exclusively under sub-boiling conditions. When a 10-minute boiling step was included, the resulting wort was comparable to that produced by traditional 90-minute wort boiling. Moreover, a significant 33% reduction in energy consumption was achieved (Štěrba et al., 2024).

This study builds on the previous one by using hop pellets instead of hop extract and by investigating the effect of HC on the entire brewing process as well as on the finished beer. The final lager beer produced by HC-assisted wort treatment was analyzed both chemically and sensorially and compared to lager beer produced by traditional technology.

2 Materials and methods

2.1 Brewing unit and cavitation components

The wort boiling kettle (50 L, Pacovské strojírný, Czech Republic) used an external heat exchanger through which the wort circulated in a closed circuit. During the experiments with cavitation, an additional closed circuit for wort circulation was added. Flow in the cavitation circuit was powered by a horizontal multistage pump (E-Tech EH3/8, 1.39 kW, Franklin Electric, Germany). A circular-section Venturi tube was used as a cavitation nozzle (Štěrba et al., 2024), while flow and pressure were monitored (Figure 1). P_{out} was measured as was recommended in previous studies (Šarc et al., 2017). P_v was calculated from the flow velocity (u), and u was computed from Venturi tube characteristics. Temperature was measured by an onboard thermometer.

2.2 Brewing ingredients

Pilsner-type malt (Beerex Malt, Czech Republic) was used to prepare each wort batch (10.2 kg/60 L of water). Hop pel-

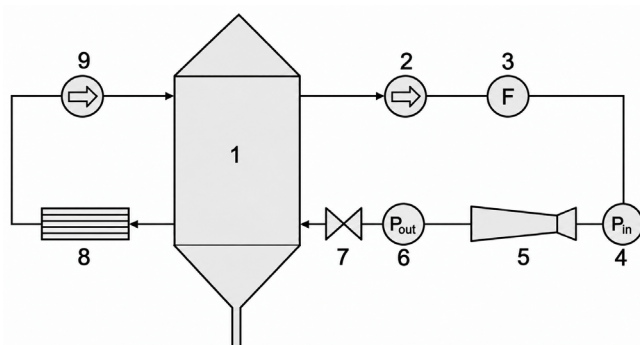


Figure 1 Scheme of the brewing apparatus: 1 – Wort kettle, 2 – Horizontal pump, 3 – Flow meter, 4 – Pressure sensor P_{in} , 5 – Venturi tube, 6 – Pressure sensor P_{out} , 7 – Pressure release valve, 8 – Heat exchanger, 9 – Horizontal pump.

lets (T90, variety URAN, Svoboda – Fraňková s. r. o., Czech Republic) had an alpha-acid (AA) content of 8.94%. Into each wort batch, 60 g of hop pellets were added at the beginning of the wort boiling. For the fermentation of the wort, 50 g of lyophilized yeasts (Fermentis Saflager W-34/70, France) was added to each batch.

2.3 Brewing process

Due to their high cost, the pilot-scale experiments involving the complete beer production process were performed only once. Mashing-in was performed in the main mash vessel using 37 L of water and 10.2 kg of Pilsner malt at 37 °C, followed by a 10 min rest. The mash was then heated to 52 °C and held for 30 min for the protein rest. Subsequently, the temperature was raised to the first saccharification rest at 62 °C, where the mash was maintained for 20 min. After this period, 26 L of mash were removed as the decoction to the mash converter. The decoction was heated to the second saccharification temperature of 72 °C and held for 20 min, then brought to the boil and boiled for 15 min. The boiled decoction was subsequently returned to the main mash vessel, resulting in a final mash temperature of approximately 72 °C. This temperature was maintained for an additional 20 min. The mash was then transferred to the lautering stage, including sparging of the spent grains. The resulting sweet wort volume was 60 L, with an extract content of $11.25 \pm 0.1\%$ (w/w).

Conventional wort boiling was conducted at 100 °C for 90 min without application of cavitation. In the hydrodynamic cavitation-assisted variant, wort treatment was carried out at 90 °C for 80 min, with the cavitation nozzle operated at CN = 0.1. This was followed by a 15 min heating step from 90 °C to 100 °C and a final 15 min boiling step without cavitation. In both process variants, the full hop dose was added at the beginning of wort boiling or treatment. After hot trub separation in a whirlpool, the wort was cooled to the fermentation temperature of 10 °C, aerated and inoculated with yeasts at a pitching rate of 8.6×10^6 cells/mL. The primary fermentation was carried out in cylindrical-conical vessels under identical conditions at 10–13 °C for 7 days, followed by maturation of the young beer at 2 °C for 22 days. After maturation, the beers were filtered, bottled, and subjected to chemical and sensory analyses in order to assess potential differences between the hydrodynamic cavitation-assisted and conventionally produced batches.

2.4 Quality Analysis

Total AA concentration (humulone, co-humulone, ad-humulone) and total IAA concentration (iso-humulone, iso-co-humulone, iso-ad-humulone) were measured simultaneously (EBC 8.20, uncertainty of measurement (u.m.) $\pm 10\%$) on HPLC (Agilent 1260 Infinity II instru-

ment, United States). The yield of isomerization (Y) was calculated as the ratio of total IAA to the sum of AA and IAA at the end of wort boiling/treatment.

All measured wort and beer parameters were determined according to EBC or MEBAK analytical methods: dimethyl sulphide and its precursors (DMS-P) by gas chromatography (EBC 9.39, u.m. $\pm 20\%$), polyphenols by spectrophotometer (EBC 9.11, u.m. $\pm 3\%$), thiobarbituric acid (TBA) index spectrophotometrically (MEBAK 2.4, u.m. $\pm 3\%$), color of wort and beer with spectrophotometric method (EBC 8.5, u.m. $\pm 1\%$), original wort extract by densitometer (EBC 8.3, u.m. $\pm 1\%$), sensitive proteins (EBC 9.40, u.m. $\pm 5\%$) by nephelometer, and pH (EBC 9.35, u.m. $\pm 1\%$).

2.5 Sensory analysis

Sensory analysis of the beer was performed by a permanent panel of 10 trained evaluators. The panelists were gender balanced aged between 25 and 50 years. Sensory evaluation followed ISO 5492, which defines the fundamental terminology of sensory analysis (CSN EN ISO 5492, 2009), together with ISO 8586, which provides general guidance for monitoring the performance of a quantitative sensory panel (CSN EN ISO 8586, 2023). The beers were assessed using quantitative descriptive analysis, including carbonation, body/fullness, overall bitterness intensity, peak bitterness intensity, bitterness aftertaste, and the qualitative character of bitterness. In addition, specific sensory descriptors, including astringency, sweetness, sourness, hoppiness, fruitiness, yeastiness, and maltiness, were evaluated. Attention was paid to the detection and characterization of off-flavors, as well as to the assessment of the sample's conformity with the defined beer style, namely a pale lager. Furthermore, the overall balance of sensory attributes, perceived acceptability, and the overall sensory impression were critically assessed to provide a comprehensive evaluation of the beers.

The sensory evaluation was conducted using structured sensory evaluation. The intensity of selected sensory descriptors was rated on a 0–5 scale, where 0 indicated the absence of the attribute and 5 indicated very high intensity. The assessed descriptors comprised carbonation, body/fullness, bitterness, bitterness peak, bitterness aftertaste, astringency, sweetness, sourness, hoppiness, fruitiness, yeastiness, and maltiness. In addition, the character of bitterness was evaluated on a separate 1–5 scale, where 1 indicated a very soft bitterness and 5 indicated a very harsh and lingering bitterness. Both core and optional parameters were scored using whole-number values only. Balance was also assessed on a 3-point scale (1 = balanced; 3 = unbalanced). Preference and overall impression were assessed on a 1–7 scale, where 1 corresponded to an excellent beer and 7 to the worst possible

rating. Style appropriateness was scored on a 3-point scale (1 = appropriate for the declared style; 2 = serious doubts regarding style conformity; 3 = clearly representative of a different style). The results are presented as arithmetic means of the evaluations of all panelists.

2.6 Calculation of energy consumption

The total energy demand associated with beer production comprises a broad range of components. The main energy-consuming operations in the brewing process include wort production, wort boiling, wort cooling, and temperature control during both primary and secondary fermentation. In the present study, all process steps except wort boiling were identical for both brewing methods. Energy consumption during wort boiling consists of three main components: energy required to heat the wort to the boiling temperature, heat losses to the surrounding environment, and energy required for water evaporation from the wort (Kunze, 2004). The method used to calculate energy consumption during wort boiling/treatment was described by Štěrba et al. (2024). Because the same experimental setup was used in the present study, the same calculation method was applied.

3 Results and discussion

3.1 Isomerization of hop alpha acid

The time course of the isomerization of total AA to total IAA during traditional wort boiling at 100 °C and during wort treatment at 90 °C with HC (CN 0.1), followed by boiling for 15 min, is shown in Figure 2. Taking into account the uncertainty of the total AA and IAA measurements ($\pm 10\%$), the following results were obtained. Differences in both total AA and total IAA were statistically significant up to 60 min. At 80 min, only the difference in total IAA remained statistically significant, whereas the

difference in total AA was not significant. The differences in the final contents of total AA and total IAA between traditional wort boiling at 100 °C and wort treatment at 90 °C with HC, followed by boiling for 15 min, were not statistically significant (Figure 2). The observations related to the final contents of total AA and total IAA are further supported by the isomerization yields (Y) obtained during traditional wort boiling at 100 °C and during wort treatment at 90 °C with HC (CN 0.1), followed by boiling for 15 min, which were 61.2% and 62.3%, respectively.

3.2 Other wort parameters

The concentration of polyphenols was lower in the HC-assisted batch, whereas the TBI value and color were markedly higher in the conventionally boiled wort (100 °C) than in the HC-treated wort, consistent with the lower thermal load in the HC-assisted process (Table 1). Although the final boiling step applied after HC treatment increased the TBI, the values remained lower than those observed in traditionally boiled wort (100 °C). The original wort extracts were very similar in both batches, indicating comparable mashing and wort treatment processes. The concentrations of dimethyl sulfide (DMS) and its precursors (DMS-P) were monitored at the beginning and end of the wort boiling/treatment processes. Initial concentrations of both DMS and DMS-P were higher in the wort treated at 90 °C (Table 1). However, due to the final boiling step applied to the HC-assisted batch, DMS and DMS-P concentrations decreased by 71.5% and 79.5%, respectively. By comparison, during traditional wort boiling, DMS and DMS-P concentrations decreased by 58.3% and 86.6%, respectively.

The energy balance calculations were based on a wort density of 1044 kg/m³, a specific heat capacity of water of 4202.96 J/kg/K at 90 °C and 4214.75 J/kg/K at 100 °C, and an enthalpy of vaporization of water of 2283 kJ/kg at 90 °C and 2257 kJ/kg at 100 °C (Jahoda et al., n.d.)

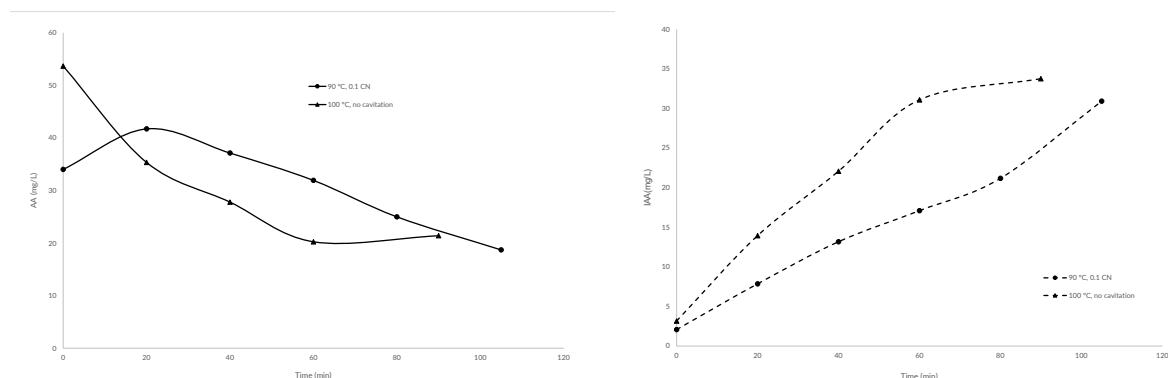


Figure 2 A – concentration of total alpha-acids (AA); B – total iso-alpha-acids (IAA) in wort during wort boiling (100 °C) without hydrodynamic cavitation and wort treatment (90 °C) with hydrodynamic cavitation (CN = 0.1) at 90 °C.

Table 1 Qualitative parameters of wort as affected by different treatments: wort boiling at 100 °C (90 min) and hydrodynamic cavitation (HC) assisted treatment: 80 min at 90 °C with HC (CN = 0.1) followed by boiling (100 °C) for 15 min. TBI – thiobarbituric acid index, OWE – original wort extract, DMS – dimethylsulfide, DMS-P – dimethylsulfide precursors, Y – isomerization yield

Wort parameter		HC-assisted treatment			Wort boiling	
		90 °C, 0.1 CN		100 °C, no CN	100 °C, no CN	
		0 min	80 min	15 min	0 min	90 min
OWE	(w/w %)	11.4	11.4	11.6	11.1	11.3
Y	(%)	-	45.8	62.3	-	61.2
Polyphenols	(mg/L)	166	166	167	173	200
TBI		21	28	33	22	38
Color	(EBC)	-	-	8.0	-	8.7
DMS	(µg/L)	130	-	37	36	15
DMS-P	(µg/L)	331	-	68	186	25

3.3 Beer parameters

The original wort extract (OWE) and pH values were very similar in both beer samples (Table 2). The beer produced using HC-assisted wort treatment showed a higher ethanol content as well as a higher real degree of attenuation. A darker color was observed in the beer produced by conventional boiling at 100 °C (Table 2), consistent with the higher temperature and TBI during wort boiling (Table 1). The concentrations of dimethyl sulfide (DMS) and its precursor (DMS-P) were higher in the hydrodynamic cavitation-assisted batch (Table 2). Although DMS levels were close to the sensory threshold 30–40 µg/L (Basarova et al., 2017; Bamforth, 2014), none of the trained sensory evaluators detected DMS during the sensory evaluation. The concentration of iso-α-acids (IAA) was found to be higher in the reference batch (Table 2), despite a comparable isomerization yield during wort boiling (Table 1). Given the uncertainty of the IAA measurements ($\pm 10\%$), the difference between the two analyzed beers was not statistically significant. The content of haze-active sensitive proteins was very similar in both beers (Table 2), being 7% lower in the HC-assisted beer, which indicates comparable colloidal stability in the two samples.

Colloidal stability measured as haze of bottled beers was monitored at regular one-month intervals throughout the storage period (Table 3). Haze values measured at a scattering angle of 15° remained consistently within the range of 0.4–0.6 for both beer batches, indicating very good colloidal stability and no significant haze formation. A similar trend was observed at a scattering angle of 90°, where only a slight increase in turbidity was detected over time.

Table 2 Qualitative parameters of filtered and bottled beers brewed by different wort treatments: wort boiling at 100 °C (90 min) and hydrodynamic cavitation (HC) assisted treatment: 80 min at 90 °C with HC (CN = 0.1) followed by boiling (100 °C) for 15 min. OWE – original wort extract, DMS – dimethylsulfide, DMS-P – dimethylsulfide precursors

Beer parameters		HC-assisted treatment	Wort boiling
OWE	(w/w %)	4.21	4.37
Real attenuation	%	63.4	61.3
Ethanol	% vol.	4.80	4.55
iso-α acids	(mg/L)	29	34
Color	(EBC)	6.3	7.0
DMS	(µg/L)	55	34
DMS-P	(µg/L)	65	36
Polyphenols	(mg/L)	126	150
Sensitive proteins	(EBC)	8.4	9.1
pH		4.42	4.44

Table 3 Changes in haze of bottled beer over time as affected by different wort treatments: wort boiling at 100 °C (90 min) and hydrodynamic cavitation (HC) assisted treatment: 80 min at 90 °C with HC (CN = 0.1) followed by boiling (100 °C) for 15 min. DMS-P – dimethylsulfide precursors

Haze (EBC)	HC-assisted treatment		Wort boiling	
	90°	15°	90°	15°
0 day	1.58	0.47	1.79	0.44
30 days	1.66	0.54	1.54	0.56
60 days	1.72	0.42	1.68	0.47
90 days	1.77	0.57	1.66	0.52
120 days	1.83	0.61	1.80	0.59

3.4 Beer sensorial analysis

Both beer batches were evaluated consistently by the sensory panel (Table 4). The samples were perceived as comparable in terms of bitterness, although all monitored bitterness attributes were slightly more intense in the beer

produced by the traditional wort-boiling process. Their overall body and fullness profiles were also similar. In addition, the beers showed closely aligned sensory attributes, including astringency, sweetness, hoppiness, fruitiness, yeastiness, and maltiness. Both samples were considered consistent with the sensory profile of a pale lager and were characterized as well balanced in flavor. Overall impression reflects the overall balance and the degree to which off-flavors are present, whereas preference also includes a subjective factor, namely individual liking. The tasting panel expressed a greater preference for the beer produced using HC; however, the overall impression of both beers was identical (Table 4). A very faint cereal off-flavor was identified in both beers, whereas the beer produced using the traditional wort boiling also exhibited very faint diacetyl and burnt off-flavors.

Differences between the HC-assisted and conventionally boiled beer for each sensory attribute were evaluated using a paired two-tailed t-test ($n = 10$ panelists), reflecting the repeated-measures design in which the same panel assessed both beer samples. A significance level of $\alpha = 0.05$ was applied.

3.5 Energy consumption

The energy consumption of the tested processes was calculated by including the energy required to raise the wort temperature from the mashing temperature (78 °C) to 90 or 100 °C (Table 5). Heat losses to the surroundings were estimated experimentally from the wort cooling curve in the kettle, while the heat required to compensate for evaporation losses was quantified separately. The energy required for pumping to drive HC was calculated from the specifications of the multistage pump used. The total energy consumption of HC-assisted wort treatment (90 °C, 80 min, CN 0.1) was only 31% (9 483 kJ) of that of traditional wort boiling (44 426 kJ). When the HC-assisted treatment was extended by heating to boiling temper-

Table 4 Sensory evaluation results (arithmetic means with standard deviation) of filtered and bottled beers brewed by different wort treatments: wort boiling at 100 °C (90 min) and hydrodynamic cavitation (HC) assisted treatment: 80 min at 90 °C with HC (CN = 0.1) followed by boiling (100 °C) for 15 min.

Sensory parameters	HC-assisted treatment	Wort boiling
Carbonation	1.9 ± 0.9	2.4 ± 0.5 ^s
Body/Fullness	2.6 ± 0.6	2.8 ± 0.5 ^{ns}
Bitterness	1.4 ± 0.6	1.8 ± 0.7 ^s
Bitterness – Peak	2.5 ± 0.9	2.9 ± 0.5 ^s
Bitterness – Aftertaste	2.1 ± 1	2.3 ± 0.7 ^{ns}
Character of bitterness	2.8 ± 0.5	2.9 ± 0.9 ^s
Astringent	1.9 ± 0.9	1.9 ± 0.7 ^{ns}
Sweet	2.6 ± 0.7	1.9 ± 0.7 ^s
Sour	1.6 ± 1.0	2.5 ± 1 ^s
Hoppy	1.3 ± 1.0	1.8 ± 1.3 ^{ns}
Fruity	1.6 ± 0.9	1.4 ± 0.9 ^s
Yeasty	1.2 ± 0.9	0.9 ± 0.7 ^s
Malty	1.5 ± 1.0	1.8 ± 1.3 ^{ns}
Balance	1.4 ± 0.7	1.3 ± 0.5 ^s
Preference	3.4 ± 1.1	4.1 ± 1.1 ^s
Overall impression	3.5 ± 0.6	3.5 ± 0.9 ^s

s = statistically significant difference, ns = not significant

ature for 15 min and subsequent boiling for 15 min, the energy consumption remained only 70% (31 458 kJ) of that of the traditional boiling process (Table 5).

3.6 Discussion

Hydrodynamic cavitation (HC) is an effective process-intensification strategy for wort treatment, allowing operation at reduced temperatures (90 °C) during wort preparation while maintaining comparable final beer quality. The isomerization of α -acids during wort boiling is strongly influenced by pressure and temperature (Malowicki and Shellhammer, 2005; Fischer, 2002). The collapse of cavitation bubbles produces localized hot-spots of high temperature and pressure, which enhance chemical reactions and mass transfer (Chuah et al.,

Table 5 Comparison of the energy consumption during different wort treatment processes in a pilot scale (50 L) wort kettle: boiling at 100 °C (90 min) and hydrodynamic cavitation (HC) assisted treatment: 80 min at 90 °C with HC (CN = 0.1) followed by heating to 100 °C (15 min) and boiling (100 °C) for 15 min.

	Wort boiling	HC-assisted treatment		
	100 °C, 90 min	90 °C, 80 min, CN 0.1	90–100 °C, 15 min	100 °C, 15 min
Heating (kJ)	4 825	2 629	2 197	0
Losses (kJ)	30 175	9 483	1 953	5 029
Evaporation (kJ)	9 426	1 178	1 178	1 178
Pumping (kJ)	0	6 240	0	0
Total (kJ)	44 426	19 530	5 328	6 600

2017). As demonstrated previously (Štěřba et al., 2024), this HC effect enables efficient isomerization of hop α -acids even at sub-boiling temperatures. Pressurized wort boiling systems operating above 100 °C are also used in breweries as energy-saving technologies, but they may reduce sensory stability by increasing the formation of aldehydes that contribute to stale flavor (Mikyška and Štěřba, 2023).

The basic parameters of both beers, such as original wort extract, real attenuation, and alcohol content, were comparable, although slightly higher in the HC-assisted version. The reduced thermal load associated with HC-assisted processing is reflected in lower TBI values, which are generally linked to improved flavor and colloidal stability of beer (Malfliet, 2008). Likewise, the lower color intensity observed in HC-treated wort prior to the final boiling step confirms the reduced progression of Maillard reactions at lower temperatures (Basarova et al., 2017). The color of the final beer can be readily adjusted by the addition of coloring malts.

DMS is sensorially important because it has a low sensory threshold of approximately at 30 $\mu\text{g/L}$ (Bamforth, 2014). Other sources report that, in Czech lagers, concentrations of 35–40 $\mu\text{g/L}$ may already have an adverse sensory effect, while a concentration of 100 $\mu\text{g/L}$ has a demonstrably negative effect on flavor (Basarova et al., 2017). The DMS content in wort, and subsequently in beer, depends both on the amount of precursors (DMS-P) present in the malt and on its formation and subsequent evaporation during wort boiling. The substantially higher initial concentrations of DMS(–P) in the wort of the HC-assisted batch suggest that a different batch of malt was used during mashing, even though Pilsner malt with the same commercial designation was purchased from the supplier. For these two brews, it is therefore more appropriate to evaluate the trends in the decrease of DMS(–P) rather than their absolute values. Part of the observed difference in initial DMS concentrations may also be attributable to DMS volatilization during the heat-up period before the target temperature was reached, as the heating rate and duration differed between the HC-assisted and conventional processes.

The behavior of DMS(–P) represents a critical limitation of sub-boiling wort treatment. As previously reported, most DMS is volatilized during conventional boiling (Bamforth, 2014), whereas insufficient removal at lower temperatures can lead to concentrations exceeding the sensory threshold (Kucharczyk, 2020). However, the inclusion of a short final boiling step proved to be an effective mitigation strategy, reducing DMS concentrations close the sensory threshold. This finding is consistent with previous studies demonstrating that even short

thermal treatments can significantly enhance DMS stripping. Alternatively, additional gas–liquid separation technologies could be implemented at the industrial scale to further improve DMS removal efficiency (Dai et al., 2022; Desobgo et al., 2015).

The colloidal stability of both beers was fully comparable. An increase in beer haze of only approximately 0.2 EBC over 4 months indicates excellent stability (Kühbeck et al., 2006; Briggs et al., 2004). Despite minor differences in analytical parameters, sensory analysis revealed no significant differences between beers produced by HC-assisted and traditional wort-boiling processes. This suggests that the overall flavor profile is preserved under HC-assisted conditions, even when slight variations in iso- α -acid concentration or minor compounds are present. It also highlights the complex relationship between analytical composition and sensory perception, in which multiple factors contribute to the final taste profile. From the perspective of the new technology, it was encouraging to find that the sensory panel showed a slight preference for the beer produced using HC technology.

From an energy perspective, the results clearly demonstrate the advantages of HC-assisted wort processing. Traditional atmospheric wort boiling is highly energy intensive, typically requiring 24–84 MJ/hL, depending mainly on process scale (Weinzierl et al., 1999). In the present study, the conventional process required approximately 88.8 MJ/hL at the pilot scale, whereas HC-assisted processing reduced the energy demand to 60 MJ/hL. Even with the inclusion of a short final boiling step, energy savings of approximately 30% were achieved. These savings were primarily due to reduced heating requirements and lower evaporation losses. Importantly, the additional energy demand associated with pumping in the cavitation loop did not offset these benefits.

The scalability of HC technology is also promising for industrial application. As reported, the energy consumption of the cavitation system is relatively independent of scale, suggesting that larger brewing systems could achieve even greater relative energy savings. In addition to energy efficiency, HC may offer further technological benefits, such as microbial inactivation (Milly et al., 2007), although this effect was not specifically investigated in the present study.

Nevertheless, several limitations should be acknowledged. The experiments were conducted at the pilot scale, and further validation under industrial conditions is necessary to confirm process robustness and reproducibility. Overall, the results demonstrate that hydrodynamic cavitation can serve as a viable alternative to conventional wort boiling, enabling substantial energy savings while preserving the key quality attributes of beer.

4 Conclusion

Raw material consumption and energy demand are critical factors in most industrial processes, including beer production. In our previous work, a parametric study identified conditions for intensifying hop α -acid isomerization during wort boiling while minimizing undesirable effects. In the present study, these findings were applied in practice through the production of a hydrodynamic cavitation (HC)-assisted pilot-scale beer, resulting in a final product with analytical, sensory and colloidal properties highly comparable to those of a conventionally produced beer. In addition, the HC-assisted process enabled an approximately 30% reduction in energy consumption during wort boiling, which could be the main driving force for the large-scale application of this technology. For future process scale-up, the use of infusion mashing could be considered, while attention should be paid to the risk of β -glucan gel formation during cavitation, which may cause membrane fouling during beer filtration.

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