The 1st International Conference on Local Resource Exploitation
www.lorexp.org / info@lorexp.org
REF: LOREXP_2021_A1070 Pages: 939–956

LOCAL RESOURCE EXPLOITATION

The wort boiling techniques and energy requirements: A Review

Les techniques d'ébullition du moût et les besoins énergétiques : État des lieux

Desobgo Z. S. C.[1,*]

[1] Department of Food Processing and Quality Control of University Institute of Technology (UIT) of The University of Ngaoundéré, P.O. Box 455 UIT, Cameroon.

* Corresponding Author: desobgo.zangue@gmail.com ; +237 697 160 004

ABSTRACT:

For several decades, the developers of equipment and technologies intended for wort boiling have declared for commercial and technical reasons any kind of performance of their systems in order to interest the breweries. For most of them, there was not enough information in literature to verify their claim. Thus, the aim of this paper was to conduct a review of some of these technologies and estimate the specific energy requirements during wort boiling. The comparison between theoretical calculation results obtained and some manufacturer data for their wort boiling equipment has revealed a slight difference. Thus, at the end of this work, and under equal conditions (without taking into account the recovery of energy), Ecostripper Meura system could be considered to be the most economical in terms of energy requirements and considering only usual boiling equipment. More generally, the theory of the abolition of wort boiling could be considered to be the most economical and with some adjustments should be taken into account by manufacturers and brewers.

Keywords: Wort, Boiling, Stripping, Energy requirements, Calculation, Equipment.

RÉSUMÉ :

Depuis plusieurs décennies, les développeurs d'équipements et de technologies destinés à l'ébullition du moût ont déclaré pour des raisons commerciales et techniques tout type de performance de leurs systèmes afin d'intéresser les brasseries. Pour la plupart d'entre eux, il n'y avait pas suffisamment d'informations dans la littérature pour vérifier leur affirmation. Ainsi, le but de cet article était de mener une revue de certaines de ces technologies et d'estimer les besoins énergétiques spécifiques pendant l'ébullition du moût. La comparaison entre les résultats de calculs théoriques obtenus et certaines données des fabricants pour leur équipement d'ébullition du moût a révélé une légère différence. Ainsi, à l'issue de ces travaux, et à conditions égales (sans tenir compte de la récupération d'énergie), le système Ecostripper Meura pourrait être considéré comme le plus économique en termes de besoins énergétiques et en ne considérant que les équipements d'ébullition usuels. Plus généralement, la théorie de l'abolition de l'ébullition du moût pourrait être considérée comme la plus économique et avec quelques ajustements devrait être prise en compte par les fabricants et les brasseurs.

Mots clés : Moût, Ébullition, Volatilisation, Besoins énergétiques, Calcul, Équipement.

1. INTRODUCTION

Literature indicates that breweries are energy intensive industries and, during brewing, wort boiling consumes 33.7 % of the total energy consumption in brewery by itself (Scheller et al., 2008). In a general process of making efforts to reduce energy costs for brewing to be competitive in strict accordance with the environment, developers have thus proposed various equipment which they claim have better performance in terms of energy consumption reduction and increase the quality of the wort. Thus, different techniques of boiling wort have appeared on the market with different approaches. The purpose of these wort boiling techniques was also to fix the physicochemical profile of the wort to the desire of the brewer (Narziss, 1978; Hough, Briggs, Stevens, & Young, 1982; Miedaner, 1986; Willaert et al., 2001a; Wilkinson, 2003; Kunze et al., 2014). The equipment used for wort boiling was classified according to the heating techniques used. These heating techniques were classified into two classes. The first class is “usual boiling systems” and takes into consideration the equipment and techniques developed by the manufacturers like vacuum boiling, atmospheric pressure boiling, low pressure boiling, high temperature wort boiling, as well as combinations (Miedaner, 1986; Miedaner et al., 1986; Narziss, 1986; Narziss et al., 1992; Herrmann, 1998; Willaert et al., 2001b; Schwill-Miedaner et al., 2002; Bühler, Michel, Kantelberg, Baumgärtner, et al., 2003; Willaert et al., 2005) etc… The second class is “unusual boiling systems” and takes into consideration trials which were not developed on industrial scale like gas sparging and wort boiling abolition techniques (Mitani et al., 1999) and wort boiling abolition techniques (Maule et al., 1985). But more information which would permit better understanding of manufacturer’s contributions to technical knowledge are missing. Thus, the aim of this paper is to review some of these apparatus by providing a brief description of the boiling systems and a theoretical estimation of the energy consumed during the use of each of the boiling systems for comparison purposes i.e. comparing the boiling systems with the classical method.

2. WORT BOILING TECHNIQUES

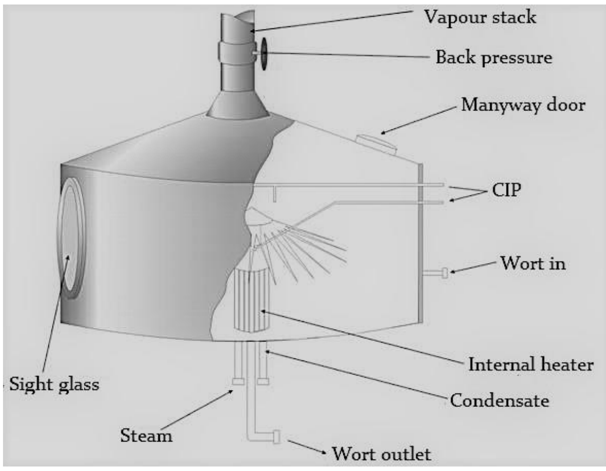
This part of the paper as stated in the introduction is concerned with a brief description of the boiling system and its theoretical energy estimations. It is classified as non-conventional and conventional systems.

2.1. Non-conventional system

2.1.1. Boiling with inert gas sparging

Inert gas sparging trials (Picture 1) used in wort boiling process was introduced by Mitani et al. in 1999. In that technique, the wort was boiled for 80 min using an internal heater and with the nitrogen gas jet portion mounted just beside it. Inert gas sparging (N2) at 41 L/min started 30 min after the boiling point is reached. This gas sparging allowed to gain 25 min (Mitani et al., 1999) of the remaining boiling time (50 min) to obtain the same wort quality than boiling without sparging. Knowing that the wort boiling conditions were 150 MJ/m3/h and 80 min (Mitani et al., 1999), the specific energy requirement without sparging is estimated at 31.8 MJ/hL. When using inert gas sparging, that specific energy requirement is estimated at 25.5 MJ/hL. Hence the energy reduction is estimated then at 6.3 MJ/hL as obtained by Mitani et al., in

1999. So, the sparging technique could permit an energy savings of 34.3 % (Table 1) compared to the classical boiling.



Picture 1: Gas sparging and boiling kettle (Mitani et al., 1999)

Table 1: Estimated heat requirements for non-conventional boiling system compared to classical wort boiling.

	non-conventional boiling system		**Classical wort boiling**
	Gas Sparging	**Wort boiling abolition**	
Kettle full amount (hL)	100.0	100.0	100.0
Estimated mass (kg)	10000.0	10000.0	10000.0
Temperature before heating (°C)	72.0	72.0	72.0
Temperature before boiling (°C)	100.0	93.0	100.0
ΔT (°C)	28.0	21.0	28.0
Heat capacity Cp (kJ/kg)	4.2	4.2	4.2
Calculated energy requirement heating up Q1 (MJ)	**1176.0**	**882.0**	**1176.0**
Evaporation related to kettle full (%)		6.0	12.0
Amount of total evaporation (kg)	150 MJ/m3/h with		1200.0
Boiling temperature (°C)	55 min boiling	No wort boiling	100.0
Enthalpie related to the boiling temperature (kJ/kg)	Mitani et al., 1999	Maule and Clark, 1985	2256.4
Calculated energy requirement for boiling Q2 (MJ)	**1375.0**	**0.0**	**2707.7**
Total calculated energy requirement Q (MJ)	**2551.0**	**882.0**	**3883.7**
Specific requirement Qs (MJ/hL)	**25.5**	**8.8**	**38.8**
Energy savings compared to conventional boiling	***34.3***	***77.3***	**/**

2.1.2. Abolition of wort boiling

Trials using boiling techniques that abolish wort boiling were introduced by Maule and Clark in 1985. In this technique, the wort was heated up to 93 °C. The heat of wort was used when doing recirculation through spray balls. This allowed to achieve 6 % evaporation and cool wort to 63 °C (Maule et al., 1985). With that technique, the energy spent should be for the heating up. The specific energy requirement in that case is estimated at 8.8 MJ/hL which could allow 77.3 % energy savings (Table 1).

2.2. Conventional boiling system

2.2.1. Vacuum boiling system

Schoko:

Schoko is a hybrid boiling system (Picture 2) using an atmospheric stripping combined with vacuum external boiler as flash evaporator for vacuum. It was introduced by the company Kaspar Schulz (www.kaspar-schulz.de) localized at Bamberg, Germany (Binkert et al., 2001). After the wort sparging, heating and resting for 1 h at 97.5 °C in the whirlpool, which period generates about 1 % of evaporation, the wort is pumped to the flash evaporator which steam pressure is at 300 mbar (69 °C) for stripping to achieve a total evaporation up to 8 % (Willaert et al., 2001b, 2005). The total energy required for wort heating is mentioned being 1919 Kwh for 225 hL (Binkert et al., 2002), thus 30.7 MJ/hL. That energy value is similar to the estimated one which is 29.3 MJ/hL (Table 2). The use of Schoko could effect a 24.5 % energy savings (Table 2).

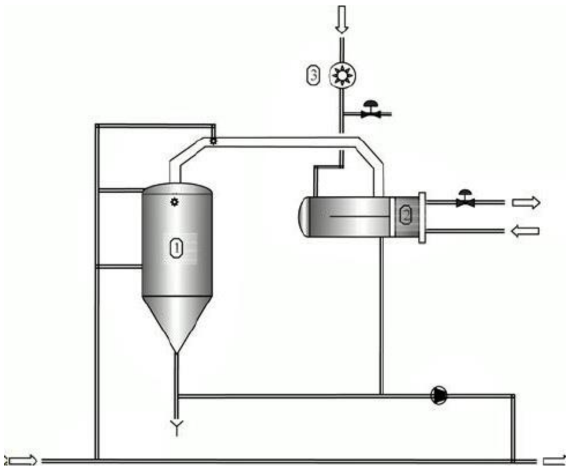
Picture 2: Schoko wort boiling system (source: Kaspar Schulz Brauereimaschinenfabrik, Bamberg, Germany)

Table 2: Estimated heat requirements for vacuum boiling system compared to classical wort boiling.

	conventional boiling system : *Vacuum boiling*			**Classical wort boiling**
	Schoko	**Ziemann**	**Varioboil**	
Kettle full amount (hL)	100.0	100.0	100.0	100.0
Estimated mass (kg)	10000.0	10000.0	10000.0	10000.0
Temperature before heating (°C)	72.0	72.0	72.0	72.0
Temperature before boiling (°C)	97.5	100.0	99.0	100.0
ΔT (°C)	25.5	28.0	27.0	28.0
Heat capacity Cp (kJ/kg)	4.2	4.2	4.2	4.2
Calculated energy requirement heating up Q1 (MJ)	**1071.0**	**1176.0**	**1134.0**	**1176.0**
Evaporation related to kettle full (%)	8.0	6.0	4.7	12.0
Amount of total evaporation (kg)	800.0	600.0	470.0	1200.0
Boiling temperature (°C)	97.5 °C for 1 % 300 mbar (69 °C) for 7 %	100 °C for 4 % 0.4 bar (75.9 °C) for 2 %	99 °C for 2.9 % 88 °C for 1.8 %	100.0
Enthalpie related to the boiling temperature (kJ/kg)	2263.6 kJ/kg for 1 % 2335.5 kJ/kg for 7 %	2256.4 kJ/kg for 4 % 2319.2 kJ/kg for 2 %	2259 kJ/kg for 2.9 % 2287.6 kJ/kg for 1.8 %	2256.4
Calculated energy requirement for boiling Q2 (MJ)	**1861.2**	**1366.4**	**1066.9**	**2707.7**
Total calculated energy requirement Q (MJ)	**2932.2**	**2542.4**	**2200.9**	**3883.7**
Specific requirement Qs (MJ/hL)	**29.3**	**25.4**	**22.0**	**38.8**
Energy savings compared to conventional boiling	***24.5***	***34.5***	***43.3***	*/*

Ziemann:

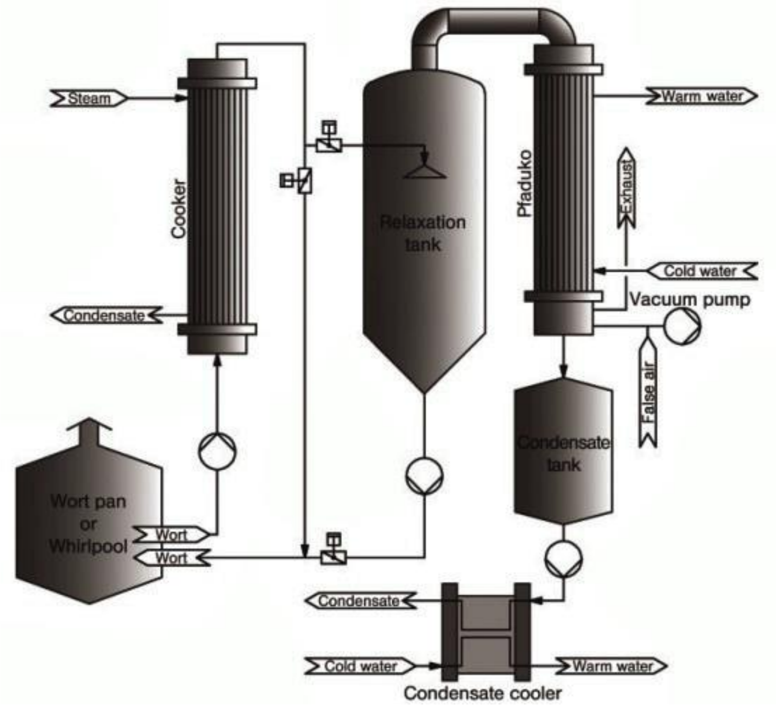
Vacuum wort stripping (Picture 3) is a system introduced by Ziemann (www.ziemann.com) situated at Ludwigsburg, Germany and, it is flexible for use (Fohr, 2000; Krottenthaler et al., 2003). After boiling the wort (up to 100 °C) to achieve 4 % evaporation (Willaert et al., 2001b, 2005) and allowing it to rest in whirlpool for trub separation in the existing system, it is pumped as a thin film tangentially in a vacuum vessel which is an additional kettle where, it is boiled again at 0.4 bar (75.9 °C) to effect a 2 % evaporation (Willaert et al., 2001b, 2005). The energy spent in that heating process is estimated at 25.4 MJ/hL that means a 34.5 % energy savings (Table 2).



Picture 3: Ziemann evaporation system. 1, vacuum vessel; 2, vapour condenser; 3, vacuum pump (Willaert et al., 2005)

Nerb Varioboil:

The Nerb Varioboil is a vacuum boiling system (Picture 4) by Esau & Hueber (www.esau-hueber.de) company located in Schrobenhausen since 1981 and which acquired the know-how of Nerb, Freising since 2011. It is a recent boiling system (Krottenthaler et al., 2001). To realize the wort boiling process, the wort is preheated then allowed to flow tangentially as a thin film in an expansion vessel where it is boiled at 99 °C which has permitted a 2.9 % evaporation. Thereafter, the wort is pumped to the whirlpool for a vacuum boiling at 88 °C (Willaert et al., 2001a, 2005) with a 1.8 % evaporation (Krottenthaler et al., 2001). The total evaporation is therefore estimated at 4.7 % and the total boiling time 50 min. All these conditions permitted to estimate the specific energy requirement of this system at 22.0 MJ/hL which constituted a 43.3 % energy savings (Table 2).



Picture 4: Process scheme of the Varioboil system (Willaert et al., 2005).

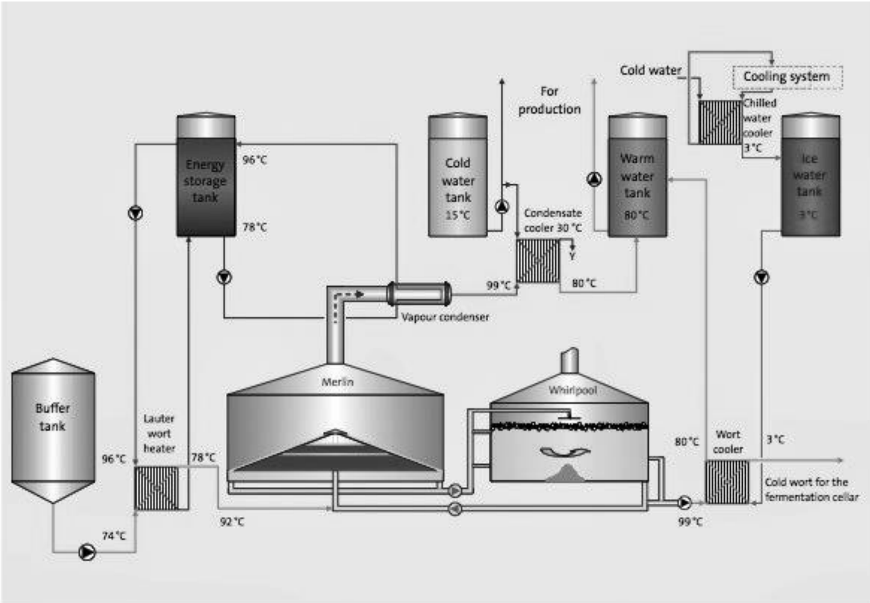
2.2.2. Atmospheric boiling system

Merlin:

Merlin was introduced in 1998 by Anton Steinecker Maschinenfabrik GmbH (Stippler et al., 1998). Instead of the almost universal shell-and-tube calandria design a conical, steam heated surface is utilized (Picture 5) over which pre-heated wort from 72 °C to 99 °C (Wilkinson, 2003) is recirculated as a thin layer, via a holding tank to achieve a 35 min boil duration with a 1 - 2 % evaporation (Buttrick, 2006). Following this period the wort is held hot in the pre-run vessel (designed as a whirlpool) for a 10-30 min period (Stippler et al., 1998; Jacob et al., 2001) followed by a single-pass across the heated cone for 35 min (Willaert et al., 2001b, 2005) to effect volatile stripping to achieve a total evaporation of 4 to 4.5 % (Weinzierl et al., 2000; Jacob et al., 2001; Schwill-Miedaner et al., 2002). The estimated value on energy spent using Merlin is 19.4 MJ/hL (table 1) and that value is similar to industrial trial which is 16.7 MJ/hL (Weinzierl et al., 2000) and supplier's claims which was 19.93 MJ/hL. Compared to the classical boiling, energy savings could be about 59.9 % (Table 3).

Table 3: Estimated heat requirements for atmospheric boiling system compared to classical wort boiling.

	Conventional boiling system : *Atmospheric boiling*				**Classical boiling**
	Merlin	**Meura (two level wort spreader)**	**Stromboli**	**Ecostripper Meura**	
Kettle full amount (hL)	100.0	100.0	100.0	100.0	100.0
Estimated mass (kg)	10000.0	10000.0	10000.0	10000.0	10000.0
Temperature before heating (°C)	72.0	72.0	72.0	72.0	72.0
Temperature before boiling (°C)	99.0	100.0	99.0	100.0	100.0
ΔT (°C)	27.0	28.0	27.0	28.0	28.0
Heat capacity Cp (kJ/kg)	4.2	4.2	4.2	4.2	4.2
Calculated energy requirement heating up Q1 (MJ)	**1134.0**	**1176.0**	**1134.0**	**1176.0**	**1176.0**
Evaporation related to kettle full (%)	3.6	6.0	3.0	2.0	12.0
Amount of total evaporation (kg)	355.0	600.0	300.0	200.0	1200.0
Boiling temperature (°C)	99.0	100.0	99.0	100.0	100.0
Enthalpie related to the boiling temperature (kJ/kg)	2259.0	2256.4	2259.0	2256.4	2256.4
Calculated energy requirement for boiling Q2 (MJ)	**801.9**	**1353.8**	**677.7**	**451.3**	**2707.7**
Total calculated energy requirement Q (MJ)	**1935.9**	**2529.8**	**1811.7**	**1627.3**	**3883.7**
Specific requirement Qs (MJ/hL)	**19.4**	**25.3**	**18.1**	**16.3**	**38.8**
Energy savings compared to conventional boiling	***50.2***	***34.9***	***53.4***	***58.1***	***/***



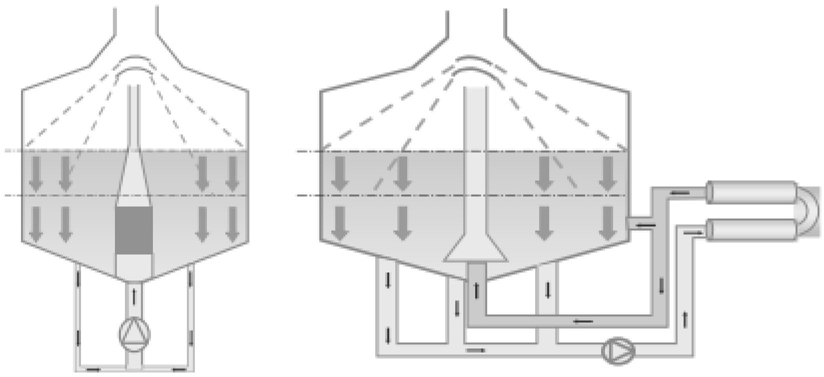
Picture 5: Process diagram of Merlin wort boiling system (Weinzierl et al., 2000).

Meura (two level wort spreader:

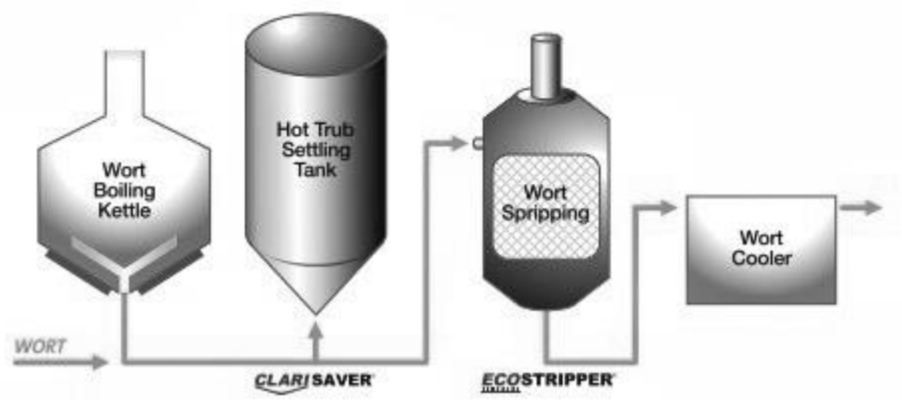
Meura (two-level wort spreader) is a natural thermosyphon boiling system (Picture 6) with a recirculation pump which was introduced by Meura company (Meura, 2013). This system can have either internal or external boiler technologies for the same target. In fact, the use of this type of atmospheric boiling system has established that the wort is preheated from 72 °C to 100 °C. After preheating, the wort is recirculated through the heater via natural thermosyphon and pump and, allowed to effect 4 % to 6 % evaporation (Meura, 2013). The specific energy requirement of those working conditions is estimated at 25.3 MJ/hL, hence an energy saving of 34.9 % (Table 3).

Ecostripper Meura:

Ecostripper is a wort stripping column system (Picture 7) developed by Meura (Meura, 2013). It has specific steps. After preheating up to 100 °C (Krottenthaler et al., 2009) in a boiling kettle and allowing trub separation in a Clarisaver (settling tank) for 30-50 min (Krottenthaler et al., 2009), the wort (100°C) is pumped into an external packed column where stripping is done using injected countercurrent flow steam to desorb unwanted compounds (Seldeslachts et al., 1997; Willaert et al., 2001b, 2005). This process runs to achieve 2 % evaporation (Willaert et al., 2001b, 2005). The specific energy requirement when using this technology is estimated at 16.3 MJ/hL and with a 58.1 % energy savings (Table 3).



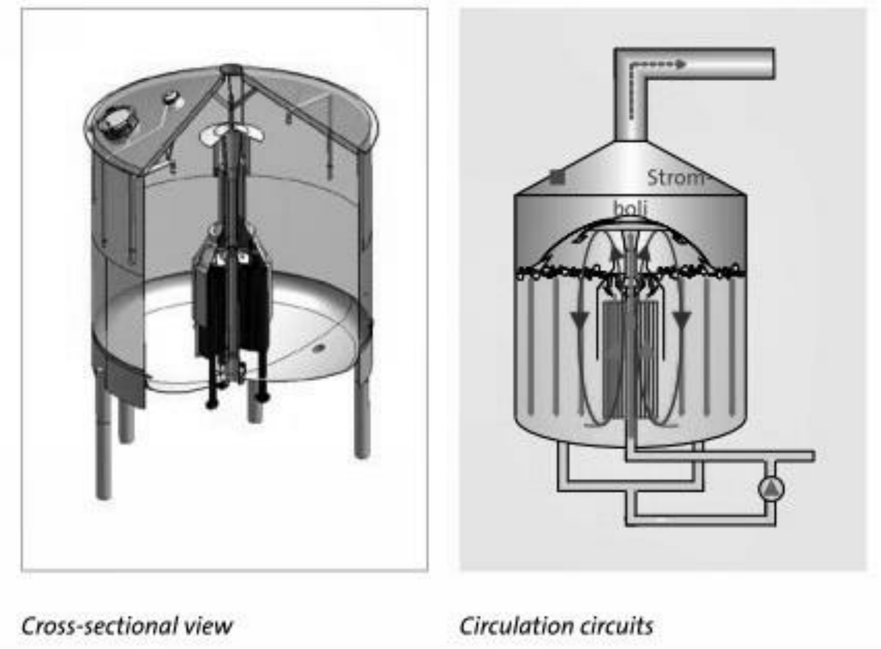
Picture 6: Process diagram of Meura (two level wort spreader) wort boiling system (Meura, 2013).



Picture 7: Flow diagram of the Ecostripper system (Meura, 2013).

Stromboli:

Stromboli is an atmospheric boiling system (Picture 8) introduced by Steineker Krones AG (Krones, 2013). It is constituted by a kettle which is supplied with wort by a pump and an internal heater which has a double wort spreader. The venturi nozzle over the pipe bundle heat exchanger is the principal component of the Stromboli technology. The wort was put into circulation by the use of the pump and thermosyphon (natural circulation), and preheated for 30 min up to 100 °C. After preheating, the wort is boiled at that temperature (100 °C) for about 65 min (from 30 min to about 95 min). This is done with a 3 - 4 % total evaporation (Krones, 2013). The supplier claimed about 4.5 Kwh/hL (Krones, 2010) which is between 16.2 MJ/hL and 18.9 MJ/hL (Krones, 2013). These values are similar to the theoretical one estimated at 18.1 MJ/hL with energy savings up to 53.4 % (Table 3).



Picture 8: Stromboli internal wort boiling system (Krones, 2013)

2.2.3. Low temperature wort boiling

Symphony Briggs:

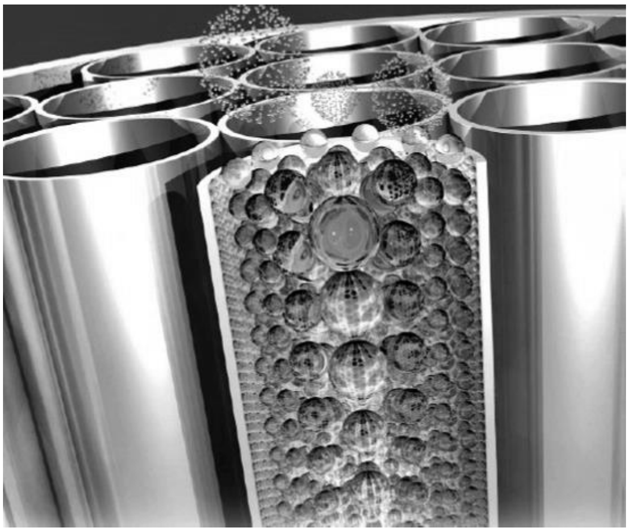
Symphony is an external wort boiling system (Pictue 9) from Briggs (www.briggsplc.co.uk) that was introduced more than 20 years ago (Hough, Briggs, Stevens, Young, et al., 1982). It is a development of Ecotherm system and, it uses a thermosyphon principle where a single phase (liquid) flows from the bottom of the tubes and two-phase (liquid plus vapour) flows out of the top, generating a difference of density which is its driving force. The symphony is constituted by long heater tubes where the preheated wort (99 - 100 °C) is pumped and heated at around 103 °C (Wilkinson, 2003; Andrews et al., 2006) with a total evaporation of 4 %. The energy used for heating is estimated at 20.8 MJ/hL so, symphony could permit a 46.6 % energy savings (Table 4).

Table 4: Estimated heat requirements for low temperature wort boiling system compared to classical wort boiling.

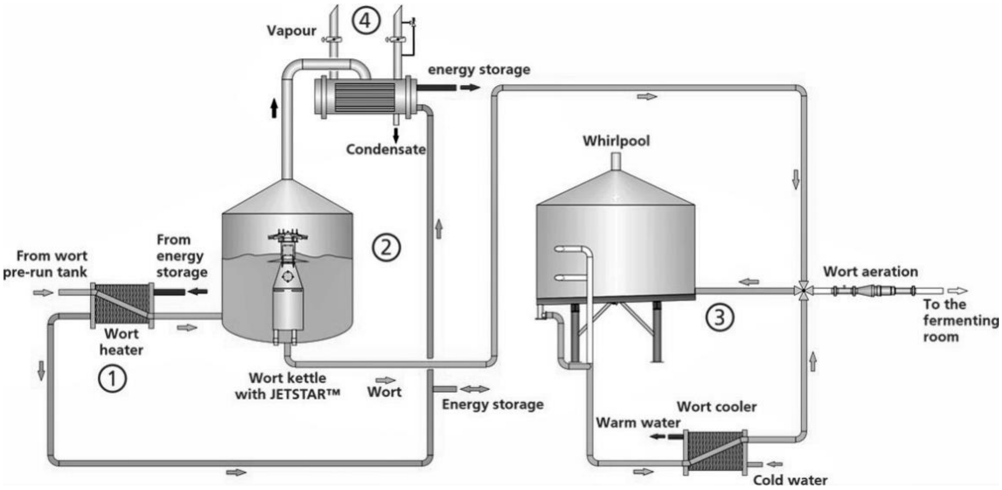
	Conventional boiling system : *Low temperature wort boiling*		**Classical boiling**
	Symphony Briggs	**Jetstar**	
Kettle full amount (hL)	100.0	100.0	100.0
Estimated mass (kg)	10000.0	10000.0	10000.0
Temperature before heating (°C)	72.0	72.0	72.0
Temperature before boiling (°C)	100.0	100.0	100.0
ΔT (°C)	28.0	28.0	28.0
Heat capacity Cp (kJ/kg)	4.2	4.2	4.2
Calculated energy requirement heating up Q1 (MJ)	**1176.0**	**1176.0**	**1176.0**
Evaporation related to kettle full (%)	4.0	4.5	12.0
Amount of total evaporation (kg)	400.0	450.0	1200.0
Boiling temperature (°C)	103.0	102 °C average	100.0
Enthalpie related to the boiling temperature (kJ/kg)	2248.4	2251.1	2256.4
Calculated energy requirement for boiling Q2 (MJ)	**899.4**	**1013.0**	**2707.7**
Total calculated energy requirement Q (MJ)	**2075.4**	**2189.0**	**3883.7**
Specific requirement Qs (MJ/hL)	**20.8**	**21.9**	**38.8**
Energy savings compared to conventional boiling	***46.6***	***43.6***	/

Jetstar:

Jetstar is a dynamic low-pressure boiling system that uses internal boiler with natural thermosyphon (Picture 10) where multiple short phases of pressure build up and get released (Hackensellner, 2001; Kantelberg et al., 2001; Schwill-Miedaner et al., 2001; Huppmann, 2013). It was developed by GEA Brewery Systems GmbH, Huppmann (www.geabrewery.com) and introduced to the market in September 2005 (Buttrick, 2006). Concerning the use of the technology, the wort is preheated up to 100 °C. After preheating the wort is allowed to be boiled up to 25 min and during the boiling period, pressure is built up till 1.17 bar and released till 1.05 bar is realized for about 30 min with a total evaporation of up to 4 % - 6 % (Hackensellner, 2001; Bühler, Michel, Kantelberg, & Baumgärtner, 2003; Galitsky et al., 2003; Huppmann, 2006, 2013). The specific energy requirement is then estimated at 21.9 MJ/hL meaning 43.6 % of energy savings (Table 4).



Picture 9: Process diagram of Symphony external wort boiling system.



Picture 10: Jetstar during heating up (phase 1) and discharging via the two-level wort spreader (source: GEA, kitsingen, Germany).

2.2.4. Hot temperature wort boiling

Classical:

High wort boiling temperature-induced that wort was carried out at temperatures of 128 to 140 °C in three steps for about 5 min (Narziss et al., 1982, 1983; Willaert et al., 2001b). Subsequently, two steps were remaining to lower the temperature of the wort. Wort during resting, evaporation of aroma substance to occurred. The energy of the resulting vapor was recovered and used for heating in stages of the wort. In the first two wort boilers, the wort was heated with vapors at 87 and 107 °C, respectively. Heating at 130 °C occurred in primary energy. This temperature was maintained for 2.5 to 3.0 min and then cooled to steam two - vessels at 117 °C and finally to 100 °C by resting. The hot trub was separated in a whirlpool. The evaporation rated by 6 to 8 %. During this process, the main part of the energy was recovered so that the system was part of boiling more energy-efficient systems. The best results were performed at 130 °C and hot - the holding time of 3 min and then 140 °C for 2 min (Narziss et al., 1991). The specific energy requirement of this system was estimated at 28.9 MJ/hL, hence the energy savings percentage is about 25.5 % (Table 5)

Table 5: Estimated heat requirements for high-pressure wort boiling system compared to conventional wort boiling.

	Conventional boiling system : *High pressure wort boiling*		**Classical boiling**
	HTWB	**Ecotherm**	
Kettle full amount (hL)	100.0	100.0	100.0
Estimated mass (kg)	10000.0	10000.0	10000.0
Temperature before heating (°C)	72.0	72.0	72.0
Temperature before boiling (°C)	100.0	100.0	100.0
ΔT (°C)	28.0	28.0	28.0
Heat capacity Cp (kJ/kg)	4.2	4.2	4.2
Calculated energy requirement heating up Q1 (MJ)	**1176.0**	**1176.0**	**1176.0**
Evaporation related to kettle full (%)	8.0	2.5	12.0
Amount of total evaporation (kg)	800.0	250.0	1200.0
Boiling temperature (°C)	140.0	135.0	100.0
Enthalpie related to the boiling temperature (kJ/kg)	2144.3	2159.1	2256.4
Calculated energy requirement for boiling Q2 (MJ)	**1715.4**	**539.8**	**2707.7**
Total calculated energy requirement Q (MJ)	**2891.4**	**1715.8**	**3883.7**
Specific requirement Qs (MJ/hL)	**28.9**	**17.2**	**38.8**
Energy savings compared to conventional boiling	***25.5***	***55.8***	***0.0***

Ecotherm:

Ecotherm boiling system is a wort kettle with an internal boiler but which wort flow rates are accelerated by a pump below the heating chamber. It was developed by the Steineker Company. During its uses, the wort is heated up till 100°C for about 20 min (Stippler et al., 1997) and it circulated inside the kettle using the pump. After that, the wort is boiled in steps with a 2.5 % evaporation using different temperatures, as 141 °C for 20 min, 130 °C for 30 min, and 138 °C for 20 min (Stippler et al., 1997). This allowed a 1036 Kwh heating energy (Stippler et al., 1997) meaning a specific energy requirement of 18.6 MJ/hL since the wort volume is 200 hL. That value is similar to the theoretical one estimated at 17.2 MJ/hL. Therefore, energy savings could be 55.8 % (Table 5).

3. CONCLUSION

The article highlighted the various boiling techniques of the wort concerning the quantity of energy implemented using different equipment utilized in the brewing industries. After having discussed the basic principles of energy calculation, to confirm or invalidate the values announced by the manufacturers, the article presents different techniques for boiling wort while comparing the energy consumption for each technique with the conventional boiling.

4. AUTHOR CONTRIBUTIONS

Desobgo designed and wrote the article.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

6. FUNDING

This work was supported by funds from the University of Johannesburg.

7. ACKNOWLEDGEMENT

Our acknowledgements go to the location of the University of Johannesburg via the Faculty of Science (Food Technology department), the faculty of engineering and built environment (School of mining, metallurgy and chemical engineering – brewing & beverage engineering initiative) and the NRF for facilitating the completion of this work.

8. APPENDIX: BASIC CONCEPT OF ENERGY CALCULATION

The wort heating process is generally divided into two phases. The first phase is the preheating of the wort where it is heated from an initial temperature and then brought to a higher temperature. After the first stage, the wort is boiled at a specific temperature with a specific percentage of evaporation. Since literature on the efficiencies is not available for all the systems, it is assumed that preheating and boiling efficiencies are 100 % and no recovery energy system is taken into consideration. The reason of avoiding energy recovery system is based on the fact that we could effectively see the individual contribution of each technology since the recovery energy system does not have the same efficiency and all the information are not known. Since during mashing, the higher temperature is at 72 °C, it is assumed that 1 hL of wort is equal to 100 kg and that wort is taken at the same initial temperature 72 °C. The total theoretical energy used in the heating process is simply the sum of the preheating energy and the energy used for boiling.

For the first stage where preheating takes place, the energy Q_1 is obtained by the formula:

$$Q_1 = m_w \times C_p \times \Delta T \quad (1)$$

Where $\Delta T = \left| T_i - T_f \right|$

With, m_w: wort mass to be preheated (kg); C_p: heat capacity (kJ/kg/°C); T_i: initial wort temperature (°C); T_f: final wort temperature (°C); Q1: calculated preheating energy (kJ)

For the second stage, the boiling energy calculation Q_2 is obtained by the formula:

$$Q_2 = m_{evap} \times H_{evap,T} \quad (2)$$

Where $m_{evap} = \eta \times m_w$ (3)

With, m_{evap}: evaporated wort mass (kg); $H_{evap,T}$: latent heat of evaporation of water at temperature T (kJ/kg); η: evaporation percentage (%)

The total theoretical energy calculation Q (kJ) is then given by the formula:

$$Q = Q_1 + Q_2 \quad (4)$$

Then

$$Q = m_w \times \left(\left(C_p \times \Delta T \right) + \left(\eta \times H_{evap,T} \right) \right) \quad (5)$$

The specific energy requirement Qs is given by the formula:

$$Q_S = \frac{Q}{1000 \times V_w} \quad (6)$$

With Qs: specific energy requirement (MJ/hL); V_w: Initial wort volume (hL); 1000 is the conversion factor from kJ to MJ.

9. REFERENCES

Andrews J.M.H. & Dowd P., 2006. Thermosyphon wort boiling–new plants and their impact on flavour stability. *World Grains Summit*. Briggs of Burton PLC, San Francisco, California, 5–10.

Binkert J. & Bamberg H.D., 2002. New wort boiling system using flash evaporation. *Brauwelt Int.* **1**, 31–38.

Binkert J. & Haertl D., 2001. Würzekochsystem mittels Expansionverdampfung. *Brauwelt* **37**, 1494–1503.

Bühler T., Michel R., Kantelberg B. & Baumgärtner Y., 2003. Die dynamische Niederdruckkochung – systematisch qualitätsoptimiert. *Brauwelt*, **38**, 1173–1178.

Bühler T.H., Michel R., Kantelberg B., Baumgärtner Y. & Kitzingen, 2003. Dynamic low-pressure boiling–systematically optimized for top quality. *Brauwelt Int.*, 306–313.

Buttrick P., 2006. A brewer's view on a modern brewhouse project, *Brew. Distill.* **2**, 1–7.

Fohr M., 2000. Höhepunkte der Sudhaustechnik auf der Brau 2000. *Brauwelt,* **48**, 2090–2092.

Galitsky C., Martin N., Worrell E. & Lehman B., 2003. Energy Efficiency Improvement and Cost Saving Opportunities for Breweries: An ENERGY STAR Guide for Energy and Plant Managers, California, USA, 1–8.

Hackensellner T., 2001. Würzebereitung mit dynamischer Niederdruckkochung: Energie - und Anlagentechnik. *Brauindustrie,* **3**, 14–16.

Herrmann H., 1998. Wort Boiling – Innovations with impact on product quality and plant efficiency. *MBAA Tech. Quart*, **35**, 84–89.

Hough J.S., Briggs D.E., Stevens R. & Young T.W., 1982, *Malting and Brewing Science: volume II hopped wort and beer,* Springer, 528.

Hough J.S., Briggs D.E., Stevens R., Young T.W., Hough J.S., Briggs D.E., Stevens R. & Young T.W., 1982. Methods of Wort Boiling and Hop Extraction. *Malting and Brewing Science*. Springer US, 499–526.

Huppmann, 2006. The new generation of internal boilers from Huppmann: the Jetstar. *In*: *Newsletter*. Huppmann AG, 1–5.

Huppmann, 2013. Jetstar: the new generation of internal boilers. *In*: *Technology Paper*. GEA process engineering division, Kitzingen, Germany, 1–4.

Jacob F., Krieger R. & Wahl R., 2001. "Würze-Stripping" Auswirkungen auf die Würze-Bierqualität, *Brauwelt,* **141**, 166–170.

Kantelberg B. & Hackensellner T., 2001. Zeitgemäße Würzekochung. *Brauwelt* **34/35**, 1290–1303.

Krones A., 2010. Stromboli wort boiler throws up major energy savings for brewers. *Food Vision*. William Reed Business Media Ltd, Cannes, France, 1–5.

Krones A., 2013. Steinecker Stromboli wort boiling system Perfect in every brewing process. *In*: *Wort Boiler*. Krones AG, Böhmerwaldstraße 5, 93073 Neutraubling, Germany, 5.

Krottenthaler M., Back W. & Zarnkow M., 2009. Wort Production. *In*: Eßlinger, H.M. ed. *Handbook of Brewing*. Wiley-VCH, Weinheim, Federal Republic of Germany, 165–206.

Krottenthaler M., Hartmann K. & Back W., 2001. Einsatz eines Entspannungsverdampfers zur Wurzebehandelung. *Brauwelt,* **39**, 1690–1693.

Krottenthaler M., Lehmann J. & Mieth R., 2003. Use of a vacuum evaporator unit in gilde Brauerei AG. *Brauwelt Int.,* **21**, 382–387.

Kunze W. & Hans-J M., 2014, *Technology brewing and malting*, Berlin : VLB, Berlin, 968.

Maule D.R. & Clark B.E., 1985. A step towards the abolition of wort boiling. *EBC Congress*, 379–386.

Meura, 2013. Internal and External boiler. *In*: Meura ed. *Meura Traditionally Pioneers since 1845*. Péruwelz, Belgium.

Miedaner H., 1986. Wort boiling today-old and new aspects. *J. Inst. Brew.,* **92**(4), 330–335.

Miedaner H. & Narziss L., 1986. Volatiles during wort boiling: General considerations and a comparison of various boiling systems. *EBC Symposium*, Maffliers, France, 80–97.

Mitani Y., Suzuki H., Abe T., Nomura M. & Shinotsuka K., 1999. Performance of wort boiling with inert gas sparging for the energy reduction. *EBC Congress*, 619–626.

Narziss L., 1978. Progress in wort boiling. *Cerevisia,* **4**, 161–173.

Narziss L., 1986. Modern wort boiling techniques; technological and analytical data, comprising the ensuing process of wort cooling. *EBC Symposium*, Maffliers, France, 98–109.

Narziss L., Miedaner H., Kattein U. & Schwill A., 1983. Versuche zur optimierung der Hochtemperatur-Würzekochung. *Monatschr Brauwiss,* **11**, 424–431.

Narziss L., Miedaner H., Kattein U., Schwill A., Hofmann W., Kain F. & Schropp P.H., 1982. Moderne Würzekochung (Teil 2). *Brauwelt,* **4**, 118–123.

Narziss L., Miedaner H. & Schneider F.P., 1991. Weiterführende Untersuchungen zur Technologie der Würzekochung unter besonderer Berücksichtigung energiesparender Maßnahmen (Teil 3). *Monatsschrift für Brauwiss. H.*, **9**, 304.

Narziss L., Miedaner H. & Schneider F.P., 1992. Some aspects of the technology of wort boiling today. *Brauwelt Int.,* **4**, 346–355.

Scheller L., Michel R. & Funk U., 2008. Efficient use of energy in the brewhouse, *Tech. Q. MBAA Commun.,* **45**(3), 263–267.

Schwill-Miedaner A. & Miedaner H., 2001. Würzekochung—heutige stand der technologie und technik. *Brauwelt,* **18**, 670–673.

Schwill-Miedaner A., Miedaner H. & Freising-Weihenstephan, 2002. Wort boilingcurrent state-of-the-art. *Brauwelt,* **1**, 19–23.

Seldeslachts D., Van-den-Eynde E. & Degelin L., 1997. Wort stripping. *Proceedings of the European Brewery Convention Congress,* 323–332.

Stippler K. & Wasmuht K.-K., 1998. Vessel and wort processing method for producing beer, United States Patent, Patent No.: US 6,968,773 B1, 10p.

Stippler K., Wasmuht K., Gattermeyer P. & Freising, 1997. Generation change in internal boilers. Part 1: Temperature distribution in the boiler and in the kettle and its effects. *Brauwelt Int.*, **137**, 1–8.

Weinzierl M., Miedaner H., Stippler K., Wasmuht K. & Englmann J., 2000. Merlin – A new wort boiling system. *MBAA Tech. Quart.,* **37**, 383–391.

Wilkinson R., 2003. Wort boiling technology. *Brew. Guard.,* 22–28.

Willaert R.G. & Baron G. V., 2001a. Wort Boiling Today – Boiling Systems with Low Thermal Stressin Combination with Volatile Stripping. *Cerevisia,* **26**(4), 1–15.

Willaert R.G. & Baron G. V., 2001b. Wort boiling today-boiling systems with low thermal stress in combination with volatile stripping. *Cerevisia,* **26**, 217–230.

Willaert R.G. & Baron G. V., 2005. Applying sustainable technology for saving primary energy in the brewhouse during beer brewing. *Clean Techn. Environ. Policy,* **7**, 15–32.