Evaporating the myths

Wort boiling serves a number of vital process objectives, and is also the most energy intensive operation in a brewery. Putting to one side the various approaches to recovering the energy from the vapour produced, the heating up of wort and evaporation of water from it is typically half of the total energy consumed in brewing, excluding packaging. The sharp rise in the cost of energy over the recent past, in addition to a desire to minimise greenhouse gas emissions, has brought renewed interest in reducing the energy demand in boiling wort.

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Coors Shenandoah brewhouse showing one of the external wort heaters and 1000 US Barrel combined kettle/whirlpool. The large pump right of centre carries out the circulation for heating wort to boiling point but is sized for the much bigger duty of casting through wort cooling to the fermenters.

The process objectives can be categorised under a number of headings including flavour development, trub formation, stabilisation, and concentration. Figure 1 identifies the criteria which brewers expect to meet, but as some of the processes are not fully understood and cannot be quantified in specifying the performance of a wort boiling system, process specification is traditionally reduced to a target rate of evaporation of water over a fixed period of time. Thus, somewhat paradoxically with the evaporation of water being the least important issue, it is generally the control parameter.

Table 1 sets out the main functions of wort boiling together with the parameters believed to affect them. Considerable attention has been given to reducing primary energy consumption by using alternative technologies, such as mechanical or thermal vapour recompression, high temperature wort boiling, and volatile stripping using live steam[1] but adoption of these schemes often meets resistance due to lack of economic return or quality concerns. It is clear that most of the requirements shown in Table 1 require temperature and time, with no evaporation being needed for stabilisation, coagulation of proteins, extraction of hop compounds and isomerisation of hop acids, and the formation of flavour and aromatic compounds.

Since concentration is often not a substantial issue in many breweries, the only remaining function requiring evaporation is the removal of unwanted volatiles. So the key question is "How much evaporation is needed?", but unfortunately the answer is far from simple.

It is worthwhile to understand the fundamental relationship between water evaporation and volatile reduction and this is well covered by Sommer and Hertel[2,3] and is shown graphically in Figure 2. Of course this assumes equilibrium between the liquid and vapour and because of the batch nature of the process this will not be achieved in practice. However a large liquid/vapour interface is

Table 1. Wort Boiling Process Requirements

	REQUIREMENT	CONDITIONS
1.	Wort Sterilisation	Temperature/Time
2.	Inactivation of Enzymes	Temperature/Time
3.	Isomerisation of Hops	Temperature/Time
4.	Denaturation of Protein	Temperature/Time
5.	Coagulation of Protein	Turbulence/Vigour of Boil
6.	Formation of Flavour Compounds	Temperature/Time
7.	Formation of Colour Components	Temperature/Time
8.	Removal of Undesirable Volatiles	Temperature/Evaporation/Time
9.	Formation of Reducing Agents	Temperature/Time
10.	Concentration by Removal of Water	Temperature/Evaporation/Time

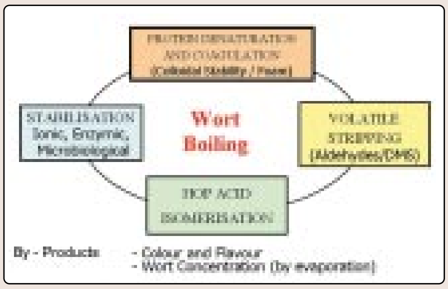

Figure 1: Evaporation tends to be the only process control parameter set by brewers to define effective boil – regardless of boiling technology.

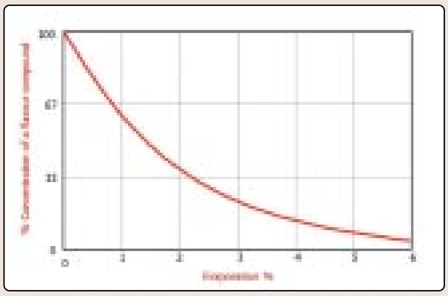

Figure 2: Reduction of a typical volatile by atmospheric boiling assuming liquid-vapour equilibrium which gives the best possible gradient.

Increased heater surface area and reduced evaporation

		7 % Evap.	4 % Evap.
Foam Nibem (sec/30mm)		267	265
DMS	ppb	30	17
Acetaldehyde	ppm	6.3	5.9
Colour	EBC	7.6	8.7
Bitterness	EBU	23.8	24.4
pH		4.18	4.27

Table 2: Lowering evaporation to 4% compared with 7% control in a 1000hl kettle.

	7% Evap.	4% Evap.
n-propanol	10	10
Ethyl acetate	18	15
Iso-butanol	11	11
3-methyl-butanol	43	42
2-methyl-butanol	15	15
i-butyl-acetate	0.05	0.06
Ethyl butanoate	0.07	0.07
i-amyl-acetate	1.9	1.6
Ethyl hexanoate	0.15	0.15
Ethyl octanoate	0.16	0.19

Table 3: Packaged beer head space analysis (mg/l) from 1000hl brewlength.

obviously desirable, together with good mixing of the wort, and open atmospheric boiling with these characteristics is likely to approach the equilibrium curve.

Some of the undesirable compounds possess high volatility which correlates with a low boiling point relative to water. So for instance dimethyl sulphide (DMS) has a relatively low boiling point (38ºC) at atmospheric pressure and its concentration in boiling wort therefore falls rapidly. However its taste threshold in finished beer is considered to be 30-50 ppb and its aroma of "vegetable", "cabbage", or "cooked corn", is generally considered undesirable, although there are some notable lager brands which have a specification of DMS concentration in the range 50–70 ppb in the finished beer (in other words above the taste threshold). On the other hand 2-methylbutanol and 3-methylbutanol boil at 90ºC–95ºC and their concentration in boiling wort changes only slowly. Their tastes are characterised as grainy or sweet at concentrations above their thresholds of 1200 and 600 ppb respectively.

Other compounds which have undesirable flavours, but with boiling points above that of water, and which therefore cannot be described as volatile, may actually be concentrated by the boiling process.

However, the central issue to grasp is that if we can identify each undesirable volatile, its starting concentration, and the desired concentration at the end of wort boiling, it is possible to calculate the minimum evaporation of water which is needed. This calculation applied to a range of volatiles with different boiling temperatures and concentrations gives rise to a different evaporation rate required in each case.

Fosters Brewing Group Yatala Brewhouse showing a top view of the two 800 hl kettles with the tangential entry from the top of the external wort heaters.

The consequence of this is that a change in the overall evaporation, by reference to the basic underlying principles of distillation and evaporation, must result in a change in the concentrations of all the components in the boiled wort.

How much evaporation is needed?

Different wort-boiling systems will produce results which diverge more or less from the liquid-vapour equilibrium, which would be provided by the best possible system characterised by the curve of Figure 2. The distilling industry uses a rectifying column, the purpose of which, besides raising the ethanol concentration, is to remove many of the same undesirable compounds, such as esters, aldehydes, and fusel-oils which occur in wash. However, this is not an approach which can be applied to beer which is made from the liquid left behind after evaporation, whereas rectification in distilling is applied to the product of evaporation.

Flash evaporation always requires more water evaporation than steady state open evaporation to achieve the same volatile reduction[2]. In practical batch systems the nearest approach to equilibrium is achieved by maximising two phase flow giving the maximum liquid-vapour interface and good mixing. Trials were carried out on a lager type beer at a production brewery with a 1000hl brewlength using a large surface area external wort heater circulating the contents of the wort kettle ten times per hour[4]. The evaporation rate was reduced from the standard 7% per hour to 4% per hour in trial brews and the trial batches were carefully tracked through the rest of the brewing process. No differences in fermentation or beer filtration were experienced, and the resulting beers were packaged normally and subjected to a range of analytical tests.

The trial beer showed no deterioration in colloidal stability and a 15% improvement in flavour stability measured by electron spin resonance. The taste panel rating was normal

Table 4 Analysis of wort and beer at different evaporation rates in 2hl kettle

Evaporation %	6	4.5	2
Imhoff	52	45	38
Ethanol			
OG	61.8	58.1	62.3
PG	8.5	9.9	9.2
%ABV before dilution	6.83	6.30	6.97
%ABV after dilution	5.10	4.70	5.20
DMS ppb			
Pre boil	192	115	227
End boil	13	22	12
Beer	43	44	53
DMS - degassed			
Pre boil	29	31	63
End boil	nd	nd	nd
Beer	13	12	14
DMS - from DMSp			
Pre boil	458	301	562
End boil	39	36	55
Beer	20	19	21
DMSp (DMS equivalents)			
Pre boil	429	269	499
End boil	39	55	36
Beer	7	7	7
Headspace analysis ppm			
Ethyl acetate	17.2	16.1	24.5
iso Butyl acetate	0.037	0.039	0.060
Ethyl butyrate	0.085	0.078	0.117
iso Amyl acetate	1.802	1.784	3.075
Ethyl Hexanoate	0.217	0.208	0.281
Ethyl Octanoate	0.595	0.587	0.94
Propan-1-ol	10.1	10.2	11.3
iso Butanol	9.8	8.8	14.3
2-Methyl Butanol	17.1	15.5	19.3
3-Methyl Butanol	44.8	47.7	51.1
Acetaldehyde	6.8	5.8	8.1
2,3 Butanedione	0.29	0.26	0.07
2,3 Pentanedione	0.23	0.23	0.07
Acetone	0.4	0.49	0.62
Head retention - Nibem	342	285	269
EBC Shelf Life			
Haze - initial	0.82	0.65	0.80
Haze - final			

Table 5 Blind tasting results

Wort Evaporation	6%	4.5%	2%
Flavour Descriptors	Diacetyl	Slight diacetyl	Estery
	Clean	Clean	Fruity
	Hoppy	Slight Dry	Clean
	Astringent	Astringent	Fresh
	Metallic	Worty	Perfume

and no significant differences were identified in the triangular taste tests. The beer analysis showed no significant change (Tables 2 and 3 on previous page). Somewhat paradoxically DMS is reduced from 30 ppb to 17 ppb at the lower evaporation rate. Both figures are very low and below the taste threshold but this reduction was not expected and may be explained possibly by a variation of the time for which the hot wort was held between the end of boiling and analysis, a period during which the remaining DMS precursor would continue to convert.

Subsequent trials[5] at large breweries in USA and Australia confirmed the findings that flavour stability is improved by using low temperature steam, and therefore a large heating surface area, for wort boiling. It is also apparent that delicate flavoured lager type beers can be made without detectable levels of unwanted volatiles at evaporation rates of 4–5%. A number of other workers have reported similar results. In the case of Bonacchelli *et al*[6] a classical wort boiling at 3% evaporation followed by wort stripping using steam at 0.5% to 1.5% of the wort i.e. 3.5% to 4.5% overall equivalent evaporation showed good volatiles reduction compared to normal wort boiling. Menger[7] showed comparisons of 7% overall evaporation in normal wort boiling with 3.5% evaporation in the wort kettle followed by 1.5% evaporation under vacuum after the whirlpool, with satisfactory results.

There is an over-emphasis on DMS which, with its low boiling temperature, is very easily removed at low evaporation rates, and unless the pre-boil concentration is very high which can be avoided by malt specification, is unlikely ever to give results above the taste threshold provided the precursor is given time to convert, typically requiring 60 to 70 minutes at 100ºC, and the evaporation rate is in the range 4% to 5%. However with volatiles with boiling temperatures nearer to that of water, including some of the aldehydes, the concentration in the wort changes only slowly, and overall evaporation rate has more impact.

Results of new trials

Trials were undertaken at the International Centre for Brewing and Distilling at Heriot-Watt University, Edinburgh in the 2hl experimental brewery using the brewing recipe for a well-known UK lager brand and a production lager yeast. Brews were mashed and separated identically and then boiled at three different evaporation rates for one hour by circulating through an external wort heater at a rate of seven times per hour. The overall evaporations were 6%, 4.5%, and 2%, and the results are shown in Table 4. The resulting beers were subjected to professional blind tasting at one month old and the descriptors are shown in Table 5.

The three professional beer tasters were of the view that all the beers would be commercially acceptable but they were different from each other. The difference between the 6% beer and the 4.5% beer was much less than that between the 4.5% and the

2% beer. The 2% beer could be characterised as estery, fruity, and perfumed.

The analytical results demonstrate a significant reduction in hot break as evaporation is reduced, indicating a reduction in physical stability (not yet apparent because the beers were only one month old when assessed) and also leading to a reduction in head retention. The importance of turbulence and two-phase flow in hot break formation is thus confirmed and it is necessary to provide these by some other means if the turbulence inherent in high evaporation is taken away. It is likely that high surface area heaters can provide the necessary conditions at lower evaporation rate than classical heaters.

The DMS removal is satisfactory at all evaporation rates confirming that this highly volatile compound is easily reduced below the taste threshold even at 2% evaporation rate. In all cases approximately 90% of the DMS precursor is converted to DMS during a one-hour boil.

The headspace analysis of the bottled beers generally exhibit the expected trends with many important flavour compounds in higher concentrations the lower the amount of evaporation. This complies with the underpinning basic science.

Conclusions

This article does not address the issues associated with high-temperature wort boiling which bring some different challenges, including a loss of head-retention in finished beer and a range of flavour and colour compounds resulting from the increased level of Maillard reactions.

In simple atmospheric wort-boiling it is impossible to produce finished beers with identical flavour profiles from different overall evaporation rates. As two-thirds of the energy consumed in wort-boiling is to provide evaporation (and one-third to heat the wort to boiling point), any atmospheric wort boiling system or technology which claims to reduce significantly the energy usage is invariably based on cutting the evaporation rate.

However, the brewer and his customer will ultimately determine whether the beer produced at evaporation rates which are low by normal standards is acceptable.

Evaporation rates of 4 to 5% overall are becoming increasingly common and the very small increase in undesirable volatiles, when compared to a more traditional 7 – 8%, is generally still below the taste threshold. Further reductions, significantly below 4%, lead to changes which would be more easily detected by the consumer. Also the question of whether 'drinkability' would suffer or be prejudiced at lower evaporation rates remains unanswered. ■

Acknowledgements

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