Review of Literature about DMS and Whirlpool

L1 Note on Collection of Knowledge about DMS and Whirlpool

L1: Notat om videnindsamling omkring DMS

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1. Introduction

This report contains a literature review on DMS and whirlpool as part of the MUDP project “Climate Friendly Handling of Wort in Breweries”.

1.1 Dansk indledning

Denne rapport udgør aktivitet 1.1 Videnindsamling omkring DMS i arbejdspakke 1 af MUDP projektet ”Klimavenlig Urthåndtering i Bryggerier”.
I denne aktivitet gennemføres et litteraturstudie omkring, hvordan DMS genereres under brygning, og hvordan det fjernes. Det belyses, hvordan fysiske og kemiske parametre påvirker processerne. Der gives anvisninger for analyser af DMS, herunder anvisninger om mulige hurtigmetoder. Resultatet bringes på en samlet form for at skabe et solidt grundlag for det senere forsøgsarbejde.
Rapporten indeholder desuden et litteraturstudie om funktion og design af whirlpool for bedre at kunne udvikle en model for en whirlpool og konstruere en forsøgswhirlpool i arbejdspakke 2.

Rapporten er skrevet på engelsk således, at den vil kunne bruges i undervisningen på Den Skandinaviske Bryggerhøjskole og Københavns Universitet, hvor kandidatstuderende i bryggerividenskab og teknologi undervises. Desuden vil det gøre en evt. publicering i et engelsksproget tidsskrift lettere.

2. DMS – Dimethyl Sulphide

2.1 Flavour and chemistry of DMS

Dimethyl sulphide (DMS) has an aroma of cooked vegetable, by most people described as sweetcorn from a tin can or tomato sauce or concentrate. Sometimes also described as celery, cabbage, or beet. DMS is normally considered an off-flavour in beer. Compounds like phenyl ethanol and phenyl ethyl acetate tend to mask the perception of DMS. Also, linalool, ethyl acetate and isoamyl acetate are found to influence the perceived intensity of DMS (Hanke et al., 2010). The flavour threshold is found in several literature sources to be in the range 25-90 µg/l (Meilgaard, 1981, FlavourActive, Aroxa). The typical concentration in beer is 10 – 150 µg/l. In the internationally recognized flavour wheel DMS has flavour No. 0732 (Meilgaard, 1981).

Dimethyl sulfide (DMS, CAS No. 75–18–3) is a colourless and flammable liquid with a molar mass of 62.134 g/mol, a density of 0.846 g/cm^3, a melting point at −98 °C and a boiling point between 35 and 41 °C (Fig. 1). The solubility in wort is 300 mM (Anness & Bamforth, 1982). Henry's constant is $5.6 \cdot 10^{-3}$ mol/(m^3*Pa) (enthalpy of solubilization of -29.1 kJ/mol) making DMS highly volatile. The preferred IUPAC name is Methylsulfanylmethane.

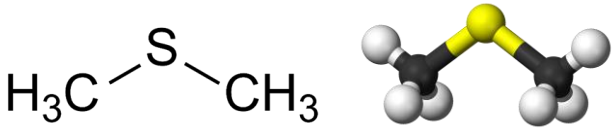


Fig. 1: Chemical structure of dimethyl sulphide (DMS), Wikipedia.org

DMS (Fig. 1) is formed during production of malt from the DMS pre-cursor (DMS-P) S-methyl methionine (SMM, Fig. 2). DMS is removed during kilning and wort boiling. At the same time, the oxidation product dimethyl sulfoxide (DMSO, Fig. 3) is produced. DMSO can be enzymatically reduced by wort bacteria and by yeast to DMS.

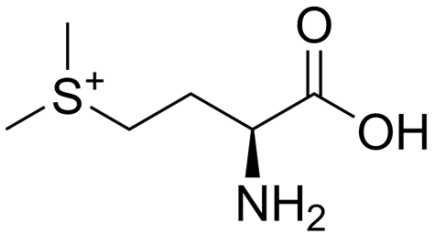


Fig. 2: Chemical structure of S-methyl methionine (SMM) also called DMS precursor (DMS-P), Wikipedia.org

SMM has a high solubility in water and is not volatile (Anness & Bamforth, 1982), and does not evaporate during wort boiling.

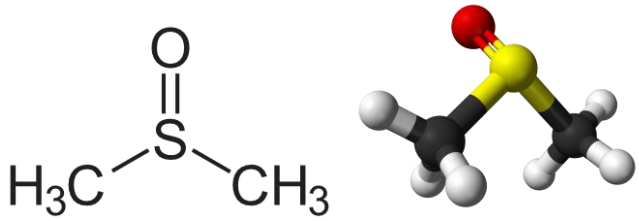


Fig. 3: Chemical structure of Dimethyl sulfoxide (DMSO), Wikipedia.org

DMSO is extremely soluble in water (Anness & Bamforth, 1982), and the Henry constant is $9.8 \cdot 10^2$ mol/(m^3*Pa) (enthalpy of solubilization of -10.8 kJ/mol) (Sander, 2015) making it non-volatile. The boiling point of DMSO is 189°C (Anness & Bamforth, 1982), i.e. DMSO is not lost in wort boiling.

SMM breaks down into DMS at temperatures above 70-75°C according to the reactions in Fig. 4 and Fig. 5.

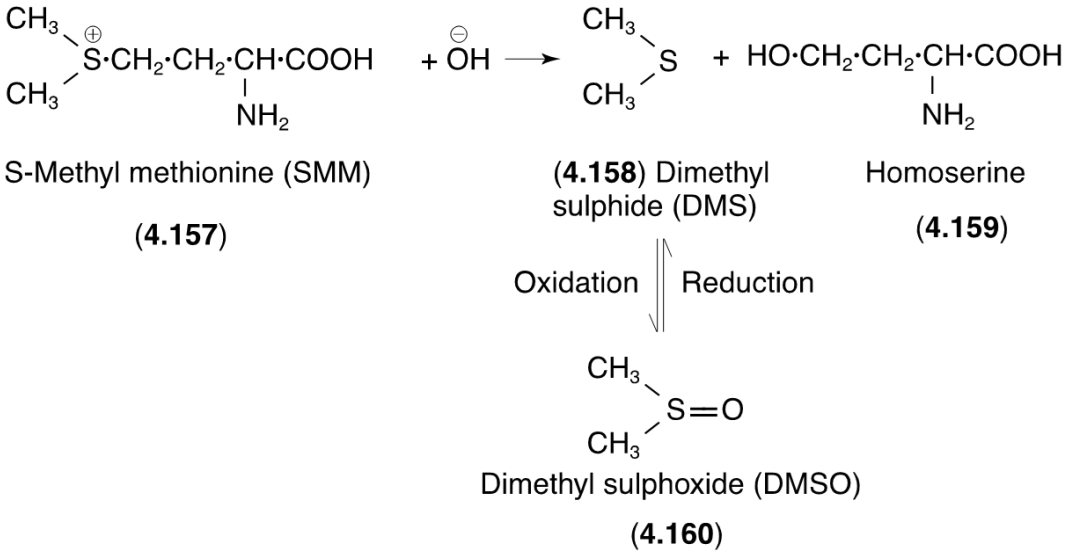


Fig. 4: Formation of DMS from SMM and DMSO

There is an equilibrium between DMS and DMSO.

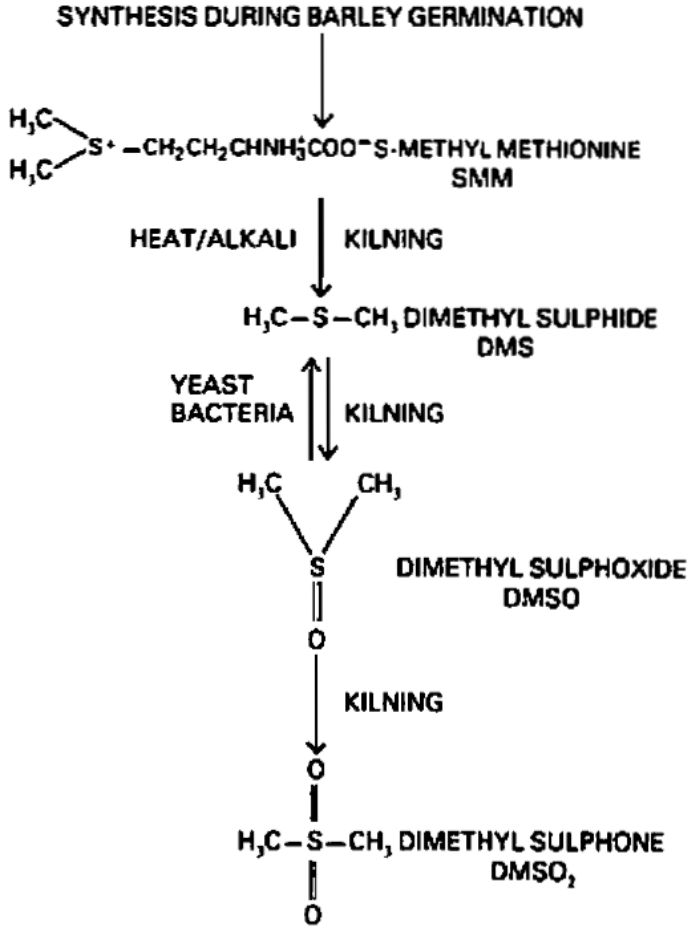


Fig. 5: Pathways of DMS formation and conversion (Anness & Bamforth, 1982)

Baldus et al., 2017, have proposed a reaction mechanism for the oxidation of DMS to DMSO in malt by hydrogen peroxide, the amino acid Cysteine (Cys) and Copper Cu(II) as shown in Fig. 6. Baldus et al., 2018, suggested a kinetic model for the oxidation.

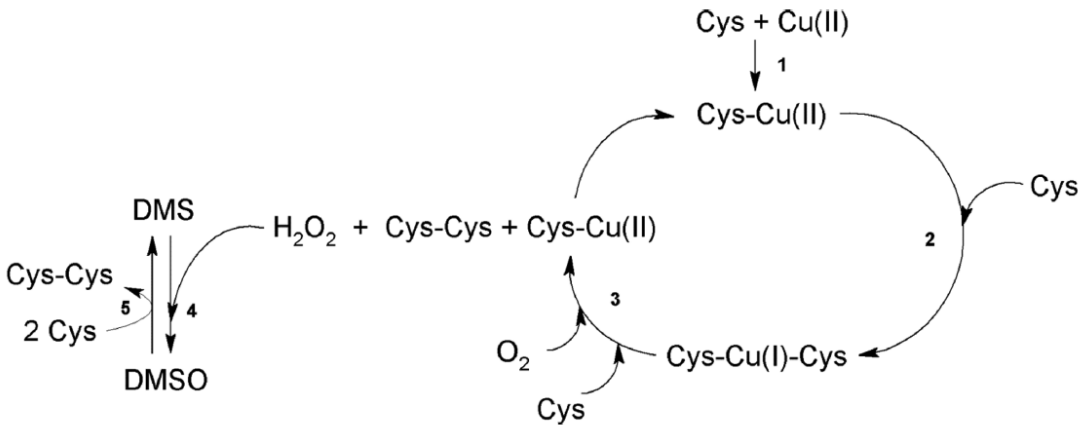


Fig.6: Proposed reaction mechanism of the effect of Cysteine (Cys) and Cu(II) on DMS oxidation (Baldus et al., 2017).

Another possible way of formation of DMS is from the Maillard reactions between glucose and the sulphur containing amino acids cysteine and methionine.

2.2 Production during malting

SMM is synthesized in the barley embryo during germination by the enzyme L-Methionine S-methyltransferase (SMM synthetase, Yang et al., 1998). The extent of SMM synthesized depends on the barley variety, the nitrogen content and the vigour of the seed. Kavanagh et al., 1976, found higher DMS production with increase in protein modification. Increased temperature during steeping and germination promotes SMM synthesis (Yang et al., 1998). During kilning SMM is broken down at temperatures greater than 70°C to DMS, which evaporates. This is especially taking place during curing phase of kilning, where the bound water is evaporated. SMM is almost completely removed at 110°C (Yang et al., 1998). DMSO is also produced from DMS during kilning. At higher temperature during kilning more DMSO and DMS are formed. The free DMS in malt is lost in the brewhouse during mashing and boiling.

Fig. 7 illustrate the development of DMS and DMSP during commercial malting (Hysert et al., 1980).

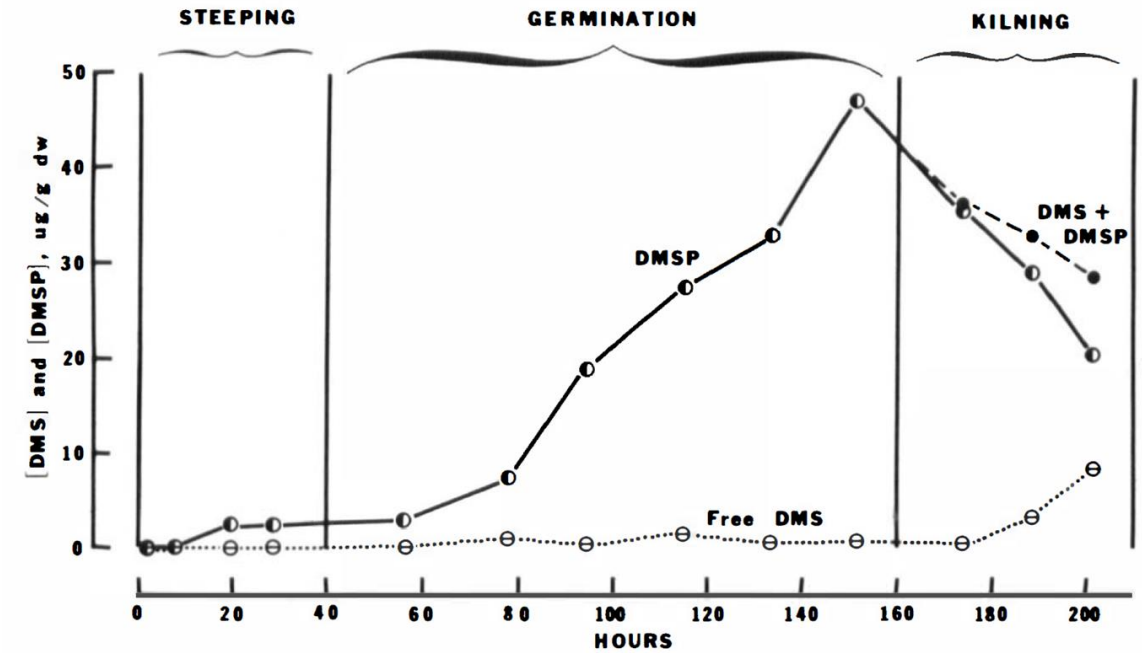


Fig. 7: Development of DMS and DMSP during commercial malting (Hysert et al., 1980)

The typical content of SMM in malt is 10-30 µg DMS equivalents per g dry weight malt. Fig. 8 shows the content of SMM, DMS and DMSO during a kilning program (Anness & Bamforth, 1982).

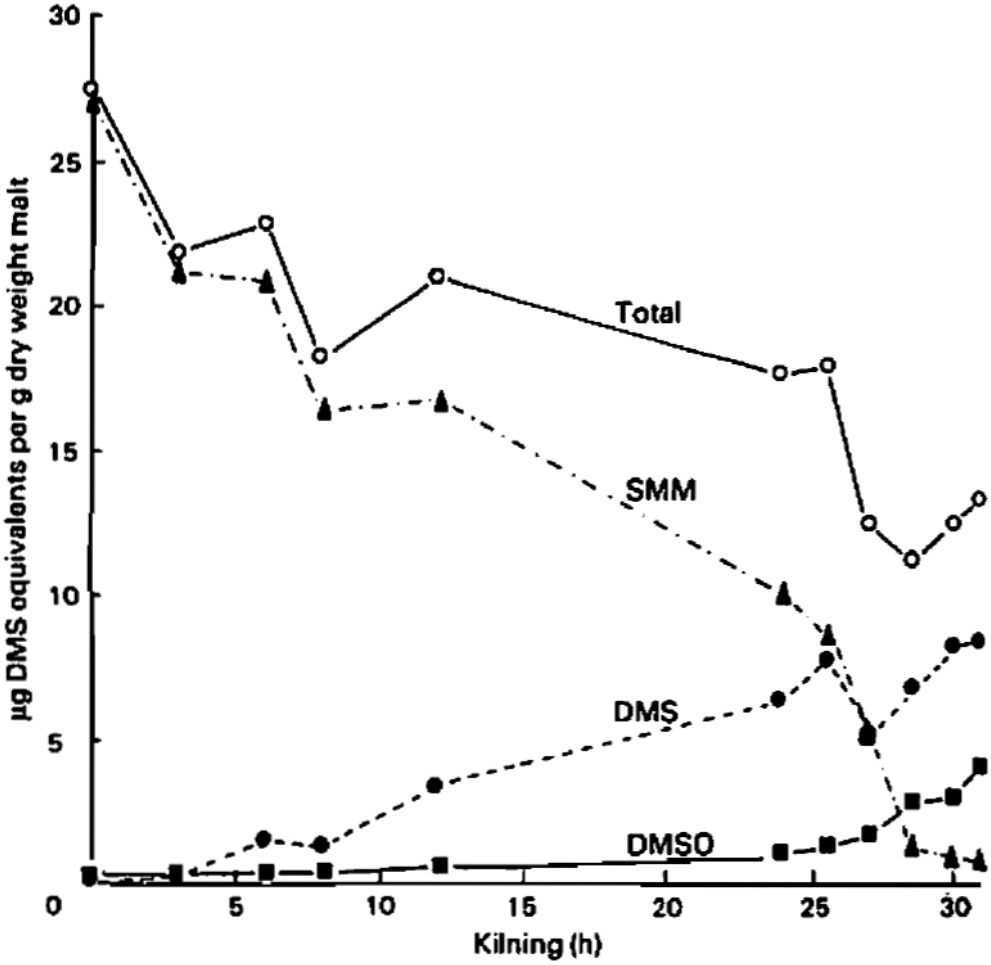


Fig. 8: The effect of kilning on the levels of SMM, DMS and DMSO in malt. Kilning schedule: 24 h at 65°C; 3 h at 85°C; 3 h at 95°C; 1 h at 105°C. ▲ SMM; ● DMS; ○ SMM+DMSO; ■ DMSO (Anness & Bamforth, 1982)

Baldus et al., 2018, found no antioxidant effect on the oxidation of DMS to DMSO by sulfite, ascorbic acid, gallic acid, L-cysteine or L-glutathione.

Dugulin et al., 2020, found increased levels of SMM in wort and beer made from green malt, but DMS was not different from reference beer made from kilned malt.

At Carlsberg Research Laboratory a new barley variety Null-DMS has been developed by breeding techniques. This variety do not produce DMS pre-cursor as shown in Fig. 9.

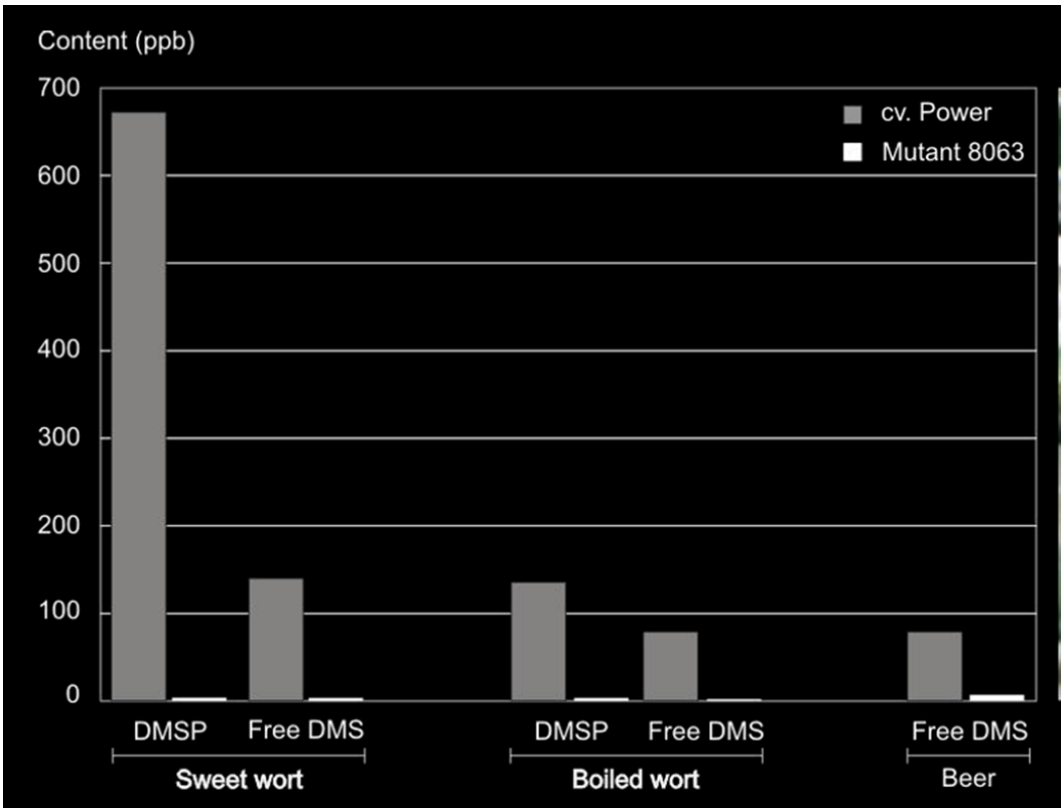


Fig. 9: Production of DMS-P and free DMS in barley variety Power and mutant 8063 in sweet wort, boiled wort and beer (Carlsberg)

2.3 DMS in Hops

DMS has also been found in hops (Lermusieau, 2003) together with dimethyl disulfide (DMDS) and dimethyltrisulfide (DMTS). After 60 minutes boil, these compounds cannot be detected, but after late hopping an increase in the three compounds are detected.

2.4 Extraction and evaporation during mashing

SMM and DMSO are found to be extracted during mashing due to their high water solubility. DMS is found to evaporate during mashing and not oxidise to DMSO (Baldus et al., 2018). However, Scheuren, Sommer and Dillenburger, 2015, found that the volatility of DMS decrease in the range 60-80°C, so that evaporation is decreasing with temperature increase due to condensation in the mash kettle.

2.5 Formation and evaporation of DMS during wort boiling and whirlpool stand

DMS is very volatile and is lost during wort boiling due to thermal break down of SMM. Fig. 10 (Wilson & Booer, 1979) shows an example of the degradation of SMM during wort boiling. It is seen that DMS is evaporated during the breakdown of SMM.

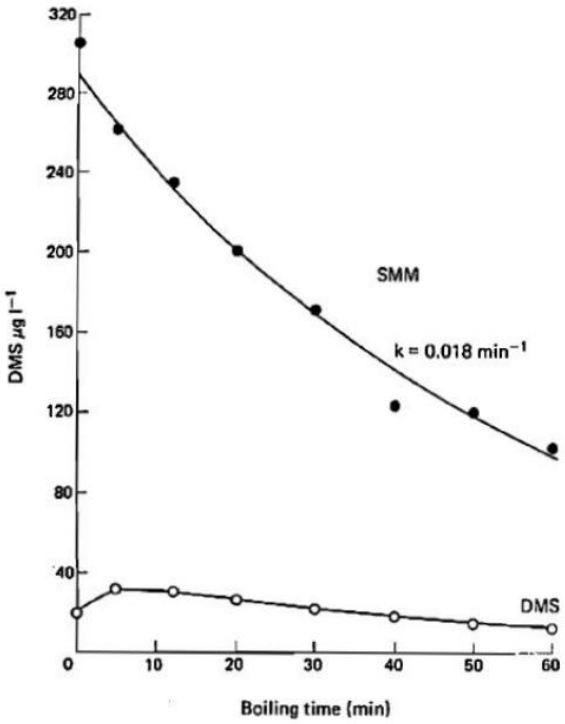


Fig. 10: The effect of boiling time on the levels of DMS and SMM in an imitation sweet wort to which SMM has been added (Wilson & Booer, 1979)

Scheuren, Dillenburger, et al., 2014, have measured the volatility of DMS at different temperatures.

Fig. 11 illustrates the change in DMS-P and DMS from heating the wort in a pre-heater, during low pressure boiling (LPB), whirlpool rest and cooling. It can be seen, that DMS-P is decrease through the entire process, whereas DMS starts to increase in the whirlpool, when the temperature decreases. It emphasize the importance of limiting the whirlpool stand.

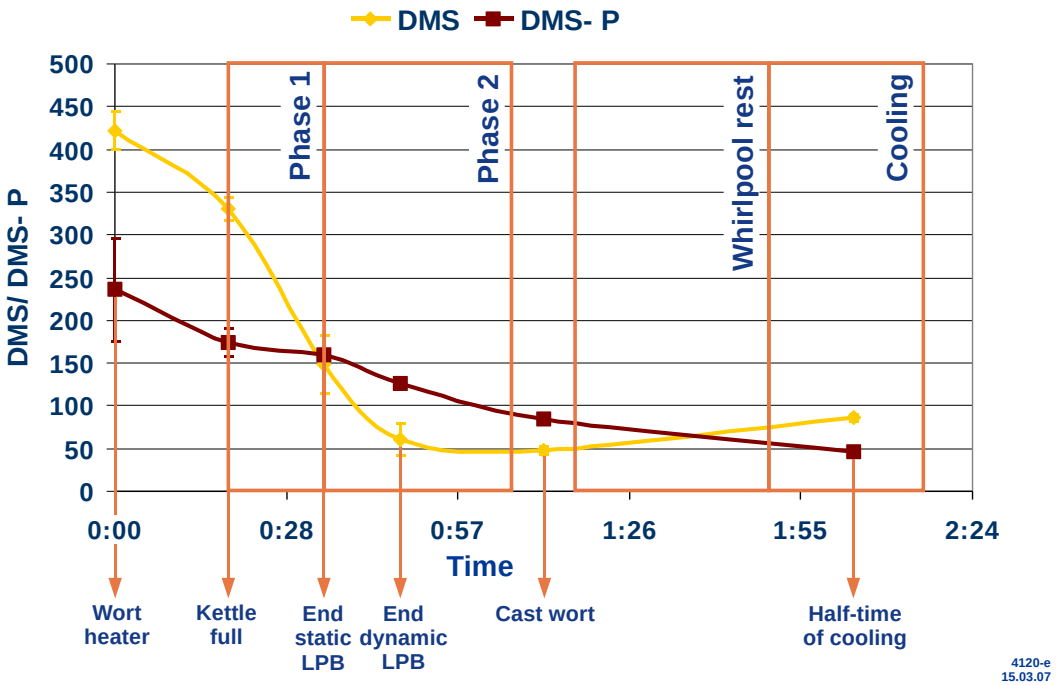


Fig. 11: Content of DMS-P and DMS during wort boiling, whirlpool and wort cooling (GEA Huppmann)

According to Bamforth, 2014, the following can be done to minimise DMS. During boiling in the wort kettle more DMS is evaporated in a vigorous 'rolling' boil and for a long time, i.e. one hour. Furthermore, at pH 5 there are lower formation of DMS vs. at pH 5.5 – 5.8.

In the whirlpool, the rate of formation of DMS exceeds the rate of evaporation of DMS, i.e., there will be an accumulation of DMS. To keep the DMS at a minimum the stand time must be limited to 15-20 minutes and cooling time must be limited to 45-60 minutes. The temperature should be kept below 85°C to obtain an evaporation higher than the formation.

Alternatively, a wort stripper or rectification column can be used (Dillenburger et al., 2017).

Fig. 12 illustrates the decrease in DMS-P and Fig. 13 illustrates the decrease and increase in free DMS during boiling, whirlpool and cooling (Rübsam et al., 2010).

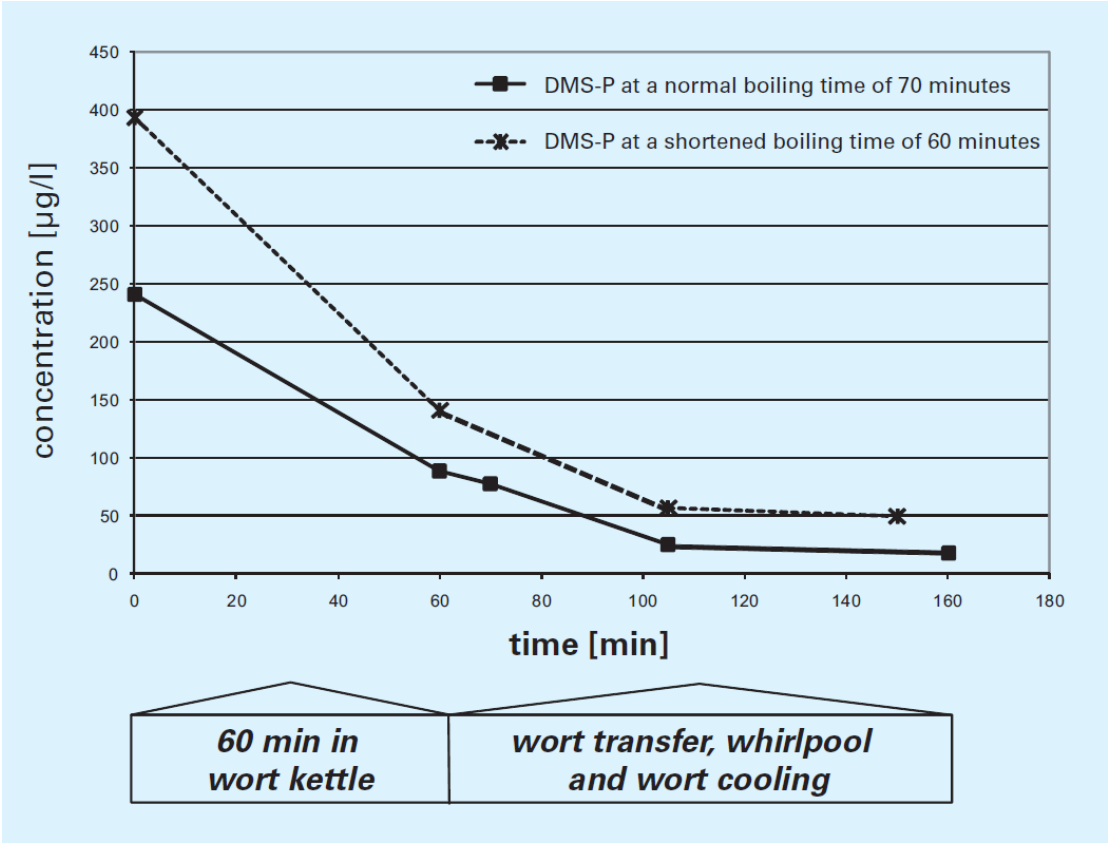


Fig. 12: Decrease in DMS-P during boiling (Rübsam et al., 2010)

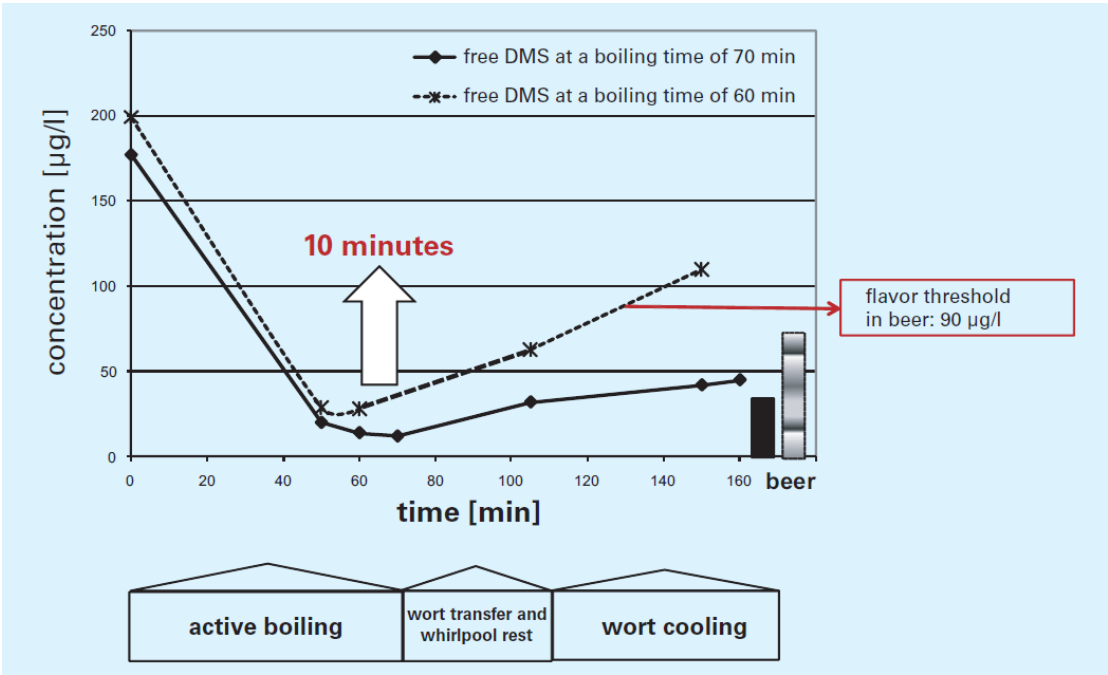


Fig. 13: Free DMS during boiling, whirlpool and cooling (Rübsam et al., 2010)

During wort boiling, no significant changes in DMSO is observed and a typical boiled wort contains 200-400 µg DMSO/l (Anness & Bamforth, 1982).

Scheuren et al., 2015, found that the volatility and quality of evaporation is independent of the surface area from which the evaporation takes place.

Desobgo et al., 2017, injected CO_2 between heating and boiling in the wort kettle and achieved stripping of DMS and possible energy savings by shortening boiling time and hence use less boiling energy.

Different technical solutions in wort boiling systems have been investigated for the production and evaporation of DMS. Weinzierl et al., 2000, found almost complete evaporation of DMS in the Merlin wort boiling system (Krones Steinecker). Michel, R.A. and Vollhals, 2002 and 2003, investigated how DMS evaporation is affected in the dynamic low-pressure boiling (GEA Huppmann, Fig. 11). Samp and Foster, 2002, optimised wort boiling in a low pressure system to maximize evaporation of DMS. Bonacchelli et al., 2006, found the stripping column (Meura) to be efficient in removing free DMS. Kattein and Herrmann, 2009, compared several wort boiling systems of which all resulted in acceptable levels of DMS after boiling. Feilner, 2011, and Feilner et al., 2013, found efficient evaporation of DMS for a wort stripping column (Krones) after the whirlpool. Holmes et al., 2014, found that DMS in wort and beer after the Steam Injection Technology (Pursuit Dynamics, PDX) were at level or slightly higher than conventional methods.

2.6 Kinetics of Decomposition of DMS-P to DMS

The thermal decomposition of DMS-P to DMS is a first-order reaction (Rübsam et al., 2010, and Krottenthaler et al., 2010, Fig. 14), where the concentration can be described

$$\boldsymbol{A_t = A_0 * e^{-kt}}$$

Velocity

$$\boldsymbol{v = \frac{dA}{dt} = k * A}$$

$$\boldsymbol{k = -\ln\left(\frac{A_t}{A_0}\right) * \frac{1}{t} = \frac{lnA_0 - lnA_t}{t}}$$

Half time

$$\boldsymbol{\tau_{1/2} = \frac{ln2}{k}}$$

where A_t is the concentration at time t, A_0 is the initial concentration, k is the 1st order velocity constant, t is the time and v is the velocity

The reaction is dependent on temperature and pH of the wort

The temperature dependency of the rate constant can be described using the Arrhenius equation:

$$\boldsymbol{k = A * e^{\left(-\frac{E_A}{RT}\right)}}$$

where A is the Arrhenius factor, E_A the activation energy, R the gas constant and T the temperature.

Several studies have reported values for the rate constant and its temperature dependency. Table 1 summarizes the reported values.

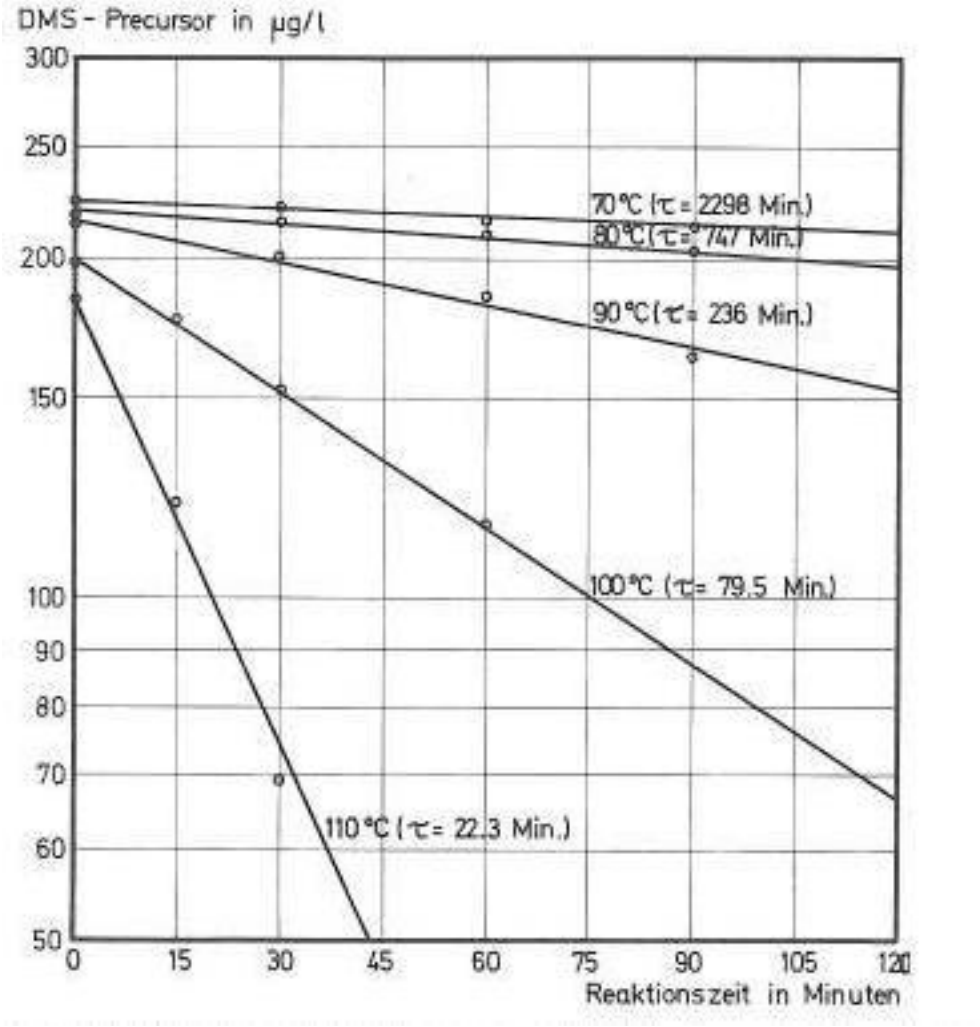


Fig. 14: Decomposition of DMS-P to DMS (Krottenthaler et al., 2010)

Reference	Rate constant k_1 [min^{-1}]	Activation Energy E_A [kJ/mol]	Arrhenius Factor A [min^{-1}]	Reference temperature [°C]	pH
Anness & Bamforth, 1982	0.0198	-	-	-	5.4
Desobgo et al, 2017 (4)	0.0099	-	-	97	5.4
Desobgo et al, 2017 (3)	0.0054	-	-	95	5.4
Dickenson, 1979	0.0180	-	-	100	4.9
	0.01824	138	-	100	5.2
	0.0213	-	-	100	5.5
Wilson & Booer, 1979	0.018	-	-	100	-
	0.022	-	-	100	-
ZÜRCHER et al., 1979 [1]	0.0258	121.779	$2.88 \cdot 10^{15}$	100	-
RÜBSAM, & KROTTENTHALER, 2010 [1]	0.0245	115.015	$3.09 \cdot 10^{14}$	100	-
SCHEUREN, 2010 [1]	0.0367	182	$4 \cdot 10^{24}$	100	-
HERTEL et al., 2006 [1]	0.0231	-	-	-	-
SCHWILL-MIEDANER, 2002 [1]	0.0165	-	-	-	-
FELGENTRÄGER, 1993 [1]	0.115	-	-	-	-
Huang et al, 2016 [2]	0.0116	81.3	$2.79 \cdot 10^{9}$	100	-
Baldus et al., 2018	0.021				

Table 1: Kinetic constants for the degradation of SMM to DMS. [1] Values are referred by Huang et al, 2016, [2] Data are obtained using the Coats–Redfern method

The reported values vary substantially, and in particular the rate constant of 0.115 min^{-1} reported by Huang et al, 2016, is much higher than the rest. Disregarding this value, the average value of the rate constant is 0.0193 min^{-1} with a standard deviation of 0.0076 min^{-1}. Less data is available on the temperature dependence of the rate constant. The average value of the reported activation energies is 128 kJ/mol ± 37 kJ/mol. It should be noted that the data from Dickenson, 1979, demonstrates a pH dependence of the rate constant as it increases with pH. Thus, decreasing the pH by CO_2 sparging will reduce the formation rate of DMS.

Rate constants (k_2) for the removal of DMS due to volatilization are reported in the literature and they depend on the geometry of the wort boiler, the power input and the composition of the wort as seen from Table 2.

Reference	Rate constant k_2 [min^{-1}]	Measurement
Desobgo et al, 2017 (4)	0.02049 - 0.07882	varying power input and CO_2 stripping gas flow
Desobgo et al, 2017 (3)	0.0151 - 0.407	
Desobgo et al, 2015	0.0202 - 0.0436	a DMS/water mixture with variable power input
	0.0143 - 0.036	a DMS/sugar/water mixture with variable power input

Table 2: Rate constants (k_2) for the removal of DMS

Provided knowledge of k_1, k_2 and the initial SMM concentration, the Mitani model (Desobgo et al, 2017 (4)) below can be used to predict the evolution of DMS during the wort boil and subsequent treatment(s) at known temperature(s):

$$[DMS] = \frac{k_1[SMM]_0}{k_2 - k_1} * [e^{-k_1 t} - e^{-k_2 t}] + [DMS]_0 * e^{-k_2 t}$$

A model for the evaporation of DMS during wort boiling has been further developed by Scheuren and co-workers, 2014-2017, and by Desobgo and co-workers, 2015-2017. Furthermore, Scheuren, H. and Dillenburger, 2015, made a model for evaporation of DMS during dealcoholization of beer.

2.7 Reduction of DMSO to DMS by wort bacteria

Wort spoilage bacteria like *Hafnea protea, Zymomonas* sp. and *Enterobacter* sp. are reported to reduce DMSO to DMS (Ingledew, 1979 and Spedding et al., 2016).

2.8 Reduction of DMSO to DMS by yeast

During fermentation lager as well as ale yeast can reduce DMSO to DMS (Bamforth, 2014) by the enzyme methionine sulfoxide reductase (Hansen, 1999, Hansen et al., 2002). Thus methionine sulfoxide is inhibitor to this enzyme competing with DMSO. Some studies have shown that 80% of DMS present in beer originated from DMSO (Bamforth, 2014). A typical formation rate of DMS during fermentation is 20-60 ng DMS/min per g wet yeast grown on wort. Approximately 5% of the DMSO present in the wort is converted into DMS during fermentation (Anness & Bamforth, 1982). It is reported that reduction of DMSO is higher in ale yeast *Saccharomyces cerevisiae* than in lager yeast *Saccharomyces pastorianus* (Baldus et al., 2018).

SMM is not metabolised by yeast, so little SMM will survive into the finished beer. However, wine yeast *Saccharomyces cerevisiae* has been reported to metabolise SMM into DMS (Eder et al., 2022).

Reduction of DMSO to DMS during fermentation is reported to depend upon several factors. More DMS is produced at lower fermentation temperature, at higher gravity, at low FAN and at increased pH. More DMS is produced from maltose rich adjuncts

than from glucose rich adjuncts. Closed vessels are reported to give more DMS than open vessels. DMS is the largest contaminant in recovered CO_2.
DMS is decreasing early in fermentation and increasing late in fermentation (Fig. 17).

Samp et al., 2010, suggest, that the lipid cardiolipin in yeast mitochondria is involved in the DMSO reduction to DMS. Low level of cardiolipin is found to reduce DMS formation and glucose is found to reduce cardiolipin.

Baldus and Methner, 2019, found reduction of DMSO to DMS by antioxidants sulphite, L-cysteine and L-glutathione, whereas ascorbic acid and gallic acid were not able to reduce DMSO. The proposed mechanisms are shown in Fig. 15 and 16.

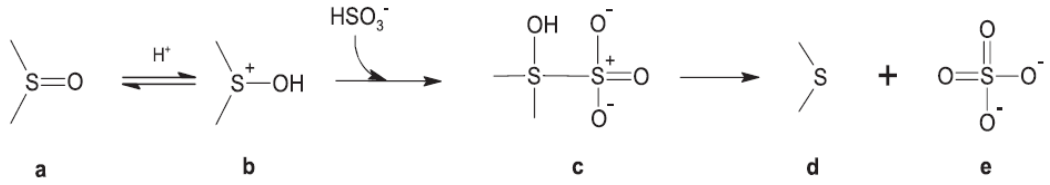


Fig. 15: Proposed mechanism of the reduction of DMSO by sulphite in beer. (a) DMSO; (b) protonated DMSO; (c) DMSO sulphite adduct; (d) DMS; and (e) sulphate (Baldus and Methner, 2019).

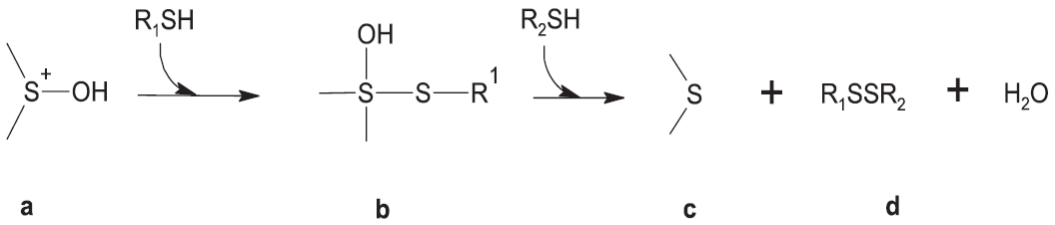


Fig.16: Proposed mechanism of the reduction of DMSO by thiols in beer. (a) Protonated DMSO; (b) DMSO–thiol adduct; (c) DMS; and (d) disulphide (Baldus and Methner, 2019).

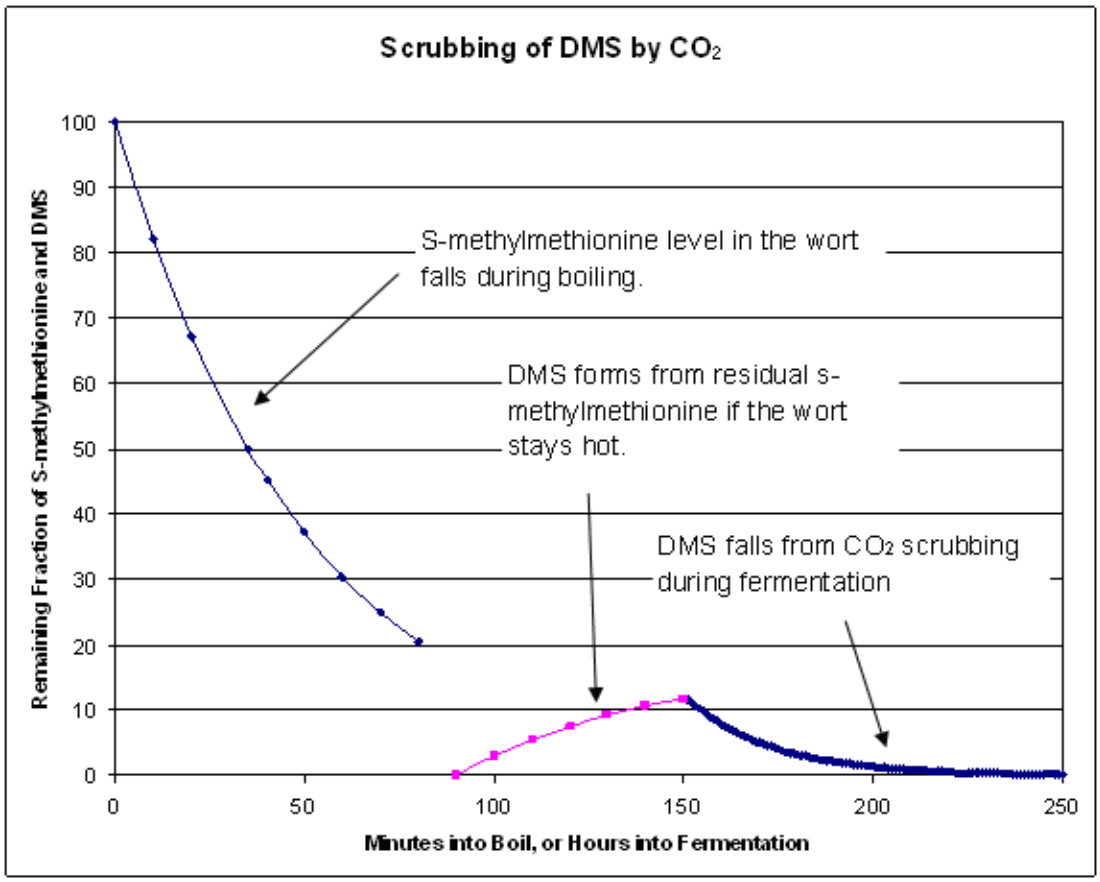


Fig. 17: Scrubbing of DMS by CO_2 during fermentation

2.9 Summary – Control of DMS in beer

Table 3 (from Bamforth, 2014) summarize how you can decrease the level of DMS in beer.

TABLE II
The Control of DMS Levels in Beer (9)

Approaches to *decreasing* DMS levels	Be mindful of…
Decrease the SMM level in the grist (replacement of malt with adjuncts, decreased modification of malt, use of rootlet inhibitor, increased intensity of kilning, select a 2-row as opposed to 6-row variety)	Obvious impacts of changing the grist. Less modification and more kilning means, for example, increased β-glucan risks
Increased duration and vigor of the kettle boil	Some concern about increased cooked character
Reduced residence time in hot wort receiver (whirlpool), including faster cast out from kettle	Impact on wort clarity. If trub is not efficiently removed then the increased turbidity can impact yeast metabolism and production of other flavor volatiles
Use of wort stripper	Will also purge other volatiles
Use of open shallow fermenters	Greater hygiene concerns
Increase in fermentation temperature	Will impact other aroma substances
Ensure an absence of DMS-producing wort spoilage microorganisms in the brew house	Will also lessen risk from non-volatile nitrosamines

Table 3: How to decrease DMS levels (Bamforth, 2014)

At the end of the shelf life in the container, DMS is found to be significantly lower in PET bottles compared to glass bottles, aluminium cans and kegs (Gagula et al., 2020).

3. Analytical methods

Methods to analyse DMS by Gas Chromatography has been described by EBC in Analytica-EBC Method 9.39. Gas Chromatography methods have also been published by American Society of Brewing Chemists (ASBC): Dupire, 1999, Miracle et al., 2005 and Li et al., 2008.

Membrane Inlet Mass Spectrometry (MIMS) is a method used by DHI. Evidence of using this method to analyse DMS in beer or wort has not been found in the literature, but Nemcek et al., 2009, used MIMS to measure DMS in sea water.

The following laboratories are offering analyses of DMS:

- VLB Berlin – https://www.vlb-berlin.org/en/beer
- Institut Romeis – https://www.institut-romeis.de/cta
- Campden BRI – https://www.campdenbri.co.uk/services/beer-barley-malt-analysis.php

4. Whirlpool

4.1 Introduction

The whirlpool was developed and introduced at the Molson's Brewery in Montreal in 1960 (Hudston, 1969). Since then, it has been the dominating unit operation to separate the hot trub from the wort. Recently the whirlpool has been used by craft brewers for adding aroma hops instead of late hopping in the wort kettle. The whirlpool substituted the wort settling tank, which is now being introduced again by at least one supplier (Meura).

In older times the coolship was used to separate the trub. The coolship had several functions: cooling down the wort, taking up and dissolving oxygen from the air, inoculating with microorganisms for the spontaneous fermentation and settling of particles (trub). Some craft brewers are even reintroducing the coolship for the above reasons.

4.2 Hot trub

The remains of the hops together with the precipitations formed during wort boiling are called hot trub or hot break and can be easily separated in the whirlpool. We distinguish between the hot trub and the cold trub, which sediment after wort cooling in the fermentation tank and is more difficult to separate. The hot trub consists of much larger particles and has a different composition than the cold trub as shown in Table 4 below.

	Hot break/trub	**Cold break/trub**
Dry matter content	40-80 g/hl	20-30 g/hl
Particle size	20-80 μm	0.5 μm
Composition	50-60% proteins 20-30% polyphenols and other organic materials 15-20% bittering substances 3-30% minerals	50-60% proteins 15-30% polyphenols and other organic materials 20-30% carbohydrates primarily β-glucans
Particles settle and suspend in wort	During boiling	During cooling
Separation	Easy	Difficult

Table 4: Hot versus cold break/trub

Hot trub or hot break can be increased by several factors:

- Under-modified malts with high content of protein and β-glucans and relatively low content of polyphenols
- Infusion mashing (no boiling/decoction of mash)
- Low pH during wort boiling
- Long wort boiling time
- Wort boiling at higher temperature
- Increased hop dosing

Trub formation can be measured by an Imhoff cone.

4.3 Whirlpool design

The whirlpool is the most common method of wort clarification used throughout the brewing industry. The boiled wort is pumped tangentially into the whirlpool at a high velocity of around 3 – 3.5 m/s along the inner circumference of the kettle creating a circular rotation of the wort. The precipitated trub will after a rest of 20–30 minutes collect in the centre of the whirlpool bottom. This is also referred to as the tea-cup effect (Hudston, 1969) (try to circulate tea with small leaves in the cup and the leaves with gather in the centre of the bottom). Emptying of the whirlpool through the wort cooler normally takes 45–60 minutes.

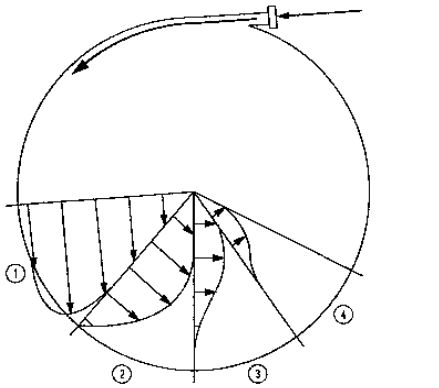


Figure 48 Vector depiction of wort velocity during filling of a whirlpool.

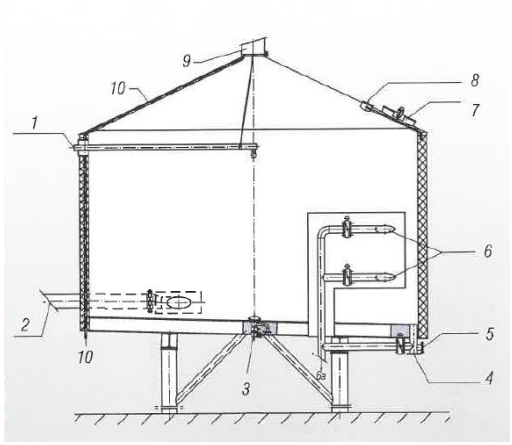


Fig. 18: Flow of wort into the whirlpool
Fig. 19: Typical design of a whirlpool (Kunze, 2019)

1. *CIP inlet*
2. *Wort inlet*
3. *Trub spraying*
4. *Trub outlet*
5. *CIP outlet*
6. *Wort outlet*
7. *Manhole*
8. *Lighting*
9. *Vapor funnel (stack)*
10. *Condensate*

Whirlpools are usually insulated, and neither heated nor cooled.

Sterczyńska and Jakubowski, 2017 and Sterczyńska, 2021, found that a baffle mounted on the bottom of the whirlpool could improve trub settlement.



Fig. 20: Tangential wort inlet in lower third of the vessel, typically about 1 metre above the floor.

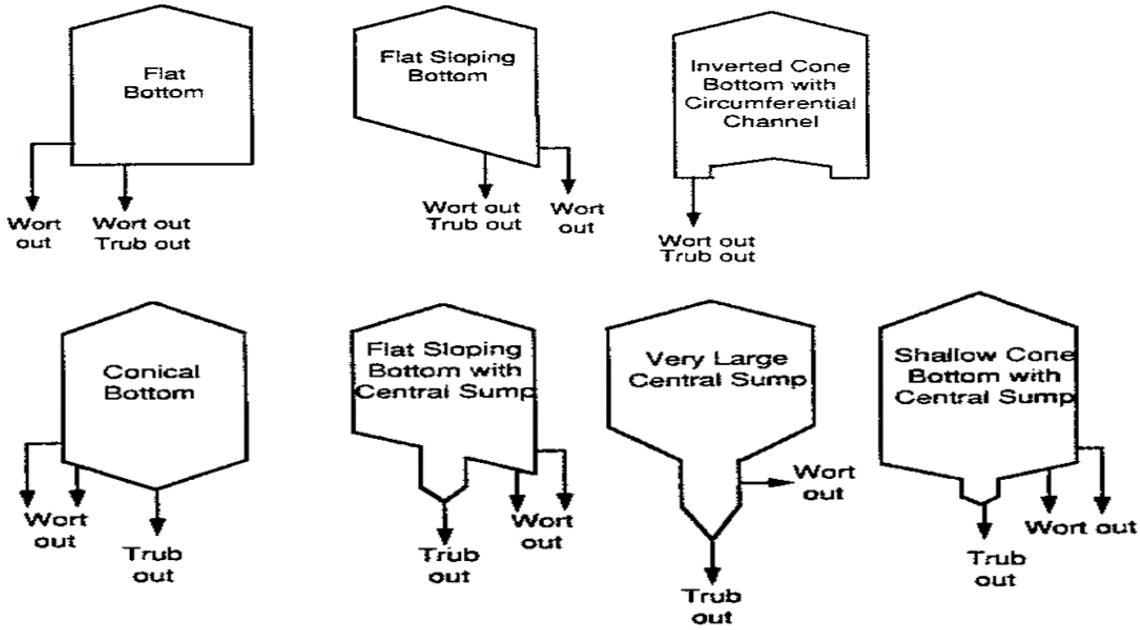


Fig. 21: Different designs of whirlpool bottoms.

A flat bottom design with a 1% slope towards a circumferential mounted outlet is the preferred design today (Hudston, 1969).

Modern whirlpools are cylindrical kettles with a smooth internal surface. The height to diameter ratio is 0.4:1 – 1:1 with optimal ratio of 0.7:1 – 0.8:1. In taller kettles the trub has a longer distance to settle (Hudston, 1969).
The tangential wort inlet should flow at a velocity of 3 – 3.5 m/s. The inlet pipe should be pointing into the kettle at an angle of approx. 17° and positioned about 1/3rd of the way up the vessel (working capacity).
There are one to two outlets above the trub cone and a third outlet in the bottom.

Poor whirlpool performance is rarely due to the design of the kettle itself. It is more often a combination of faults in the whole operation, e.g.: low clarity in the wort run-off from the lauter tun or mash filter, lack of vigour during the wort boiling, need for

optimisation of the addition of fining agents in the wort kettle and general poor quality of brewing raw materials.

Many breweries in the UK have whirlpools with a central sump in the bottom. This has the advantage of working as a simple sedimentation tank if the trub compaction is poor, but the sump leaves more wort with the trub, which then requires further processing to maximise the extract recovery. Up to 1% yield can be gained by recovering the wort in the trub by transferring it to the spent grains before sparging.

4.4 Flow pattern

When the whirlpool has been filled, the speed of wort gradually decreases from the circumference to the centre. At the same time a circular flow pattern perpendicular to the circular inlet flow starts.
The wort moves down the side walls as the liquid is cooled down and the density increases. The wort moves towards the centre, where it will rise upwards again. The trub particles will meet and coalesce at the bottom of the rising column. The size of trub particles will increase, which means the rate of sedimentation will increase. When the rate of sedimentation is higher than the rate of the up-going wort flow, the trub will sediment in the centre of the bottom.

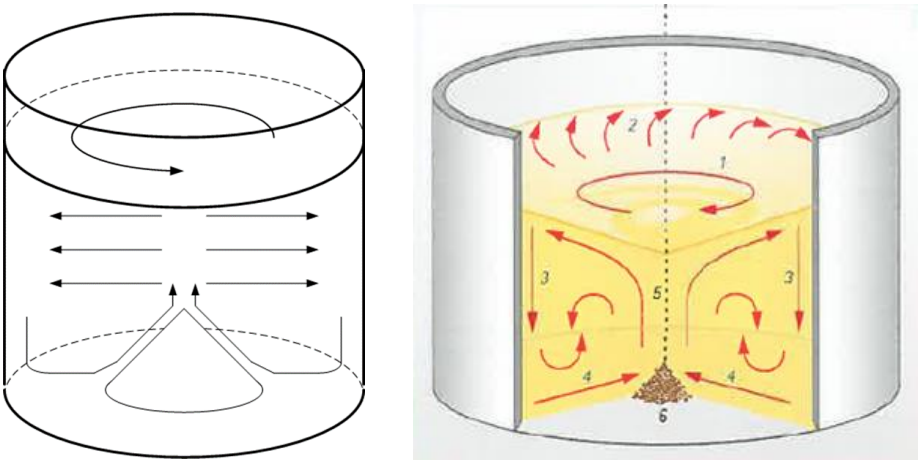
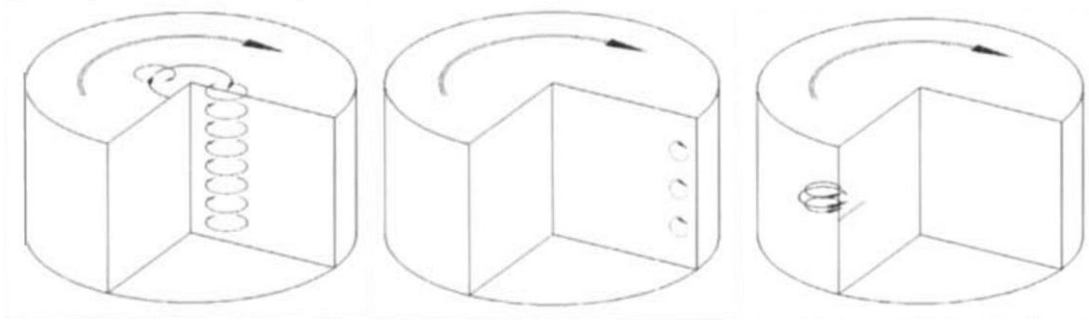
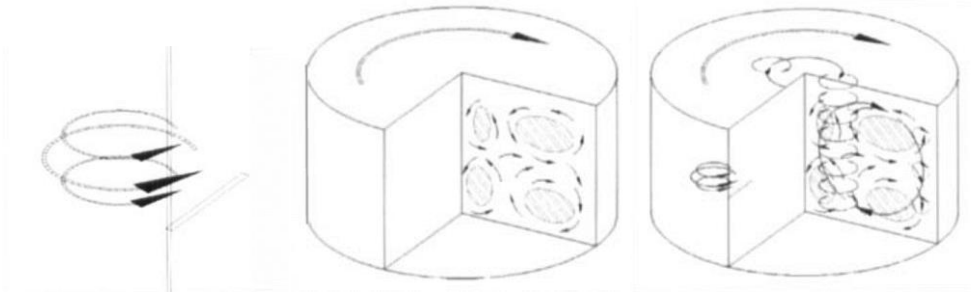


Fig. 22: Circulation flow pattern in the whirlpool (Kunze, 2019)

In Fig. 23 there are examples of disturbing eddies from Mallett, 1999.



Planetary eddies, Taylor eddies and Torus eddies.



Stationary eddies, Torus eddies and a combination of these forces.
Fig. 23: Examples of disturbing eddies (Mallett, 1999)

Jakubowski and co-workers, 2010, 2013, 2014, 2015, 2017, 2019 and 2020, developed a simulation model for the flow in the whirlpool.

4.5 Trub removal

When the trub cone has formed after 20-30 minutes, the whirlpool will be emptied by transferring the wort through the wort cooler to the cellars. The wort is taken out through the upper-most outlet first and then through the second outlet on the side. Only in the end of the transfer the bottom outlet is used and a reduced speed at end of wort casting will maintain a more stable trub cone. This entire procedure will prevent the trub cone from collapsing. At constant speed towards the end trub will be flushed out together with the last wort as illustrated on Fig. 24.

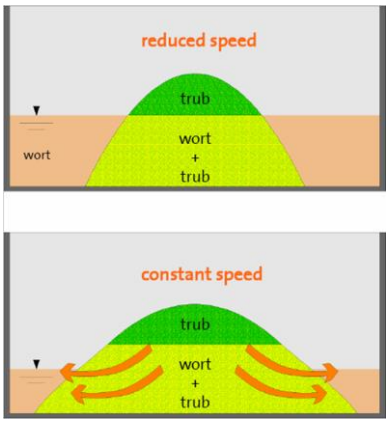


Fig. 24: Trub cone with reduced and constant speed at the end of emptying the whirlpool (Krones, 2006)

The trub cone can be flushed out by a spraying device mounted in the bottom as shown on fig. 25.

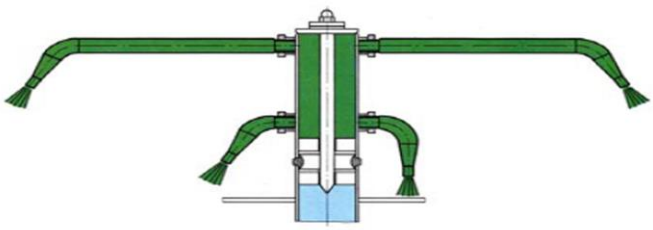


Fig. 25: Device for flushing out the trub to the trub tank (Krones, 2006)



Fig. 26: Stable trub cone formation.

4.6 Efficiency of operation

The following factors are affecting the operation and efficiency of the whirlpool:

- The raw materials (malt, hops) used in the wort production
- The clarity of the wort run-off from the lauter tun
- The intensity and vigour of wort boiling
- The use of finings
- The distance from wort kettle to the whirlpool
- The velocity of the wort and degree of filling of the whirlpool
- The shape and dimension of the whirlpool (incl. the bottom)
- The surface finish and obstructions inside the whirlpool (Hudston, 1969)
- The shape and location of outlets
- The outlet velocity
- The wort transfer pump – avoid cavitation
- Cleanability of the whirlpool and transfer systems
- Shear forces will break up trub particles in bends and obstructions, if pipe velocity is too high.

The advantages of the whirlpool are:

- A simple design and construction – there are no moving parts
- Relatively low investment (CAPEX)
- Relatively low maintenance costs
- Easy to operate
- Easy to clean
- Low labour intensity

The disadvantages of the whirlpool are:

- Limited flexibility with regard to the brew size
- Relatively low effectiveness and efficiency
- There will be losses if the whirlpool is not equipped with a decanter or system to return trub to lauter tun / mash filter
- There are no removal of cold break/trub

In some brewing plants the wort kettle and the whirlpool is one common kettle, where the wort is circulated back into the wort kettle to obtain the circular movement of the whirlpool.

Coors et al., 2003, reported less thermal stress, if the wort is cooled to 89°C before the whirlpool.

4.7 Sedimentation theory

In the whirlpool, a sedimentation of the trub particles takes place in the center of the bottom.
Sedimentation is the settling of particles in suspension to rest against a barrier or at the bottom of a tank. Sedimentation is described by Stokes law:

$$\boldsymbol{V = \frac{D^2 * g * (\rho_P - \rho)}{18\eta}}$$

where:
V = settling velocity of the spherical particle (m/s)
D = diameter of the spherical particle (m)
g = gravitational acceleration (m/s^2)
ρ_p = density of the spherical particle (kg/m^3)
ρ = density of the liquid (kg/m^3)
η = dynamic viscosity of the liquid (Pa*s)

In the centrifugal field in the whirlpool the gravitational acceleration is substituted by the centrifugal acceleration in Stokes equation:

$$\boldsymbol{V = \frac{D^2 * (\rho_P - \rho) * r * \omega^2}{18\eta}}$$

where:
r = radius of rotation = radius of whirlpool (m)
ω = angular velocity (radians/s)

4.8 Alternative designs

The 'Whirlship Calypso' from Steinecker (Krones, Schwill-Miedaner, 2006) is a whirlpool and a coolship in one vessel. It consists of two vessels inside each other. The inner vessel works as a whirlpool filled through an inlet slot and with separation of hot trub. The outer vessel works as a coolship with evaporation by stripping off volatiles from a thin layer over a large surface area and by cooling the wort. With reference to Fig. 27, the transfer from the wort kettle (1) goes through a wort inlet slot (2) to the inner of two vessels. The whirlpool rest with hot trub separation (3) works as in a normal whirlpool. The wort is drawn from an outlet (4) to a wort ring line (5) in the outer kettle, where atmospheric wort stripping takes place. From here the wort is transferred through an outlet (6) to the wort cooler (7).

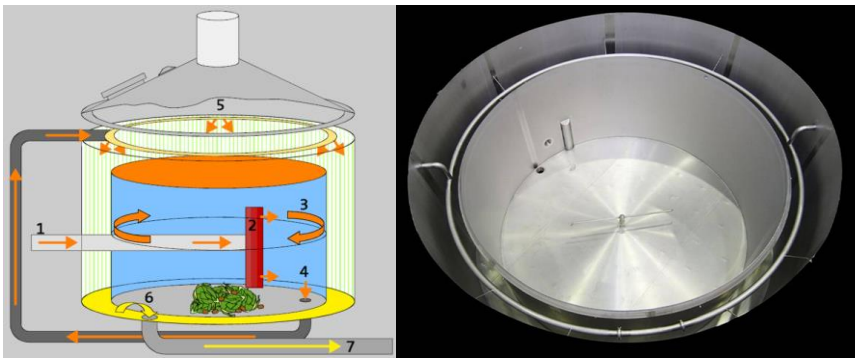


Fig. 27: 'Whirlship Calypso' from Steinecker (Schwill-Miedaner, 2007)

According to Steinecker, the advantages of 'Whirlship Calypso' is a better control of the DMS (45% less free DMS), opportunity for shorter boiling times and hence lower energy consumption, separate energy storage, better hot trub separation and no changes in oxygen indicators and wort colour were observed.

Another alternative to the whirlpool is the wort settling tank from Meura. The tank is gently filled from the bottom resulting in low shear forces and less oxygen is taken up compared to the whirlpool.

Hambach et al., 2015, described a centrifuge used in combination with a whirlpool as being an efficient system to separate hot trub.

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