- Without sufficient oxygen, respiration is inhibited and the grain essentially drowns in the steep liquor.
- If respiration is allowed to increase beyond desirable levels then the grain will hydrate rapidly and unevenly producing non-homogenous, unevenly modified malt.

Steeping is conducted in conical or flat-bottomed vessels, usually with a capacity between 60 and 500 tonnes and a capability of being hygienically cleaned. Combined steep/germination vessels (SGV's) and steep/germination/kilning vessels (SGKV's) are available. After the steep liquor is added, keeping the grain suspended will ensure hydration occurs evenly. Most steep vessels are equipped to bubble air through the grain slurry, which has the added benefit of providing oxygen for respiration. Flat-bottomed vessels allow better mixing of the grain slurry and can be equipped with rotating arms to enhance mixing. Some conical vessels are designed with central circulation or a circulation pump and loop to keep the grain slurry moving.

The steeping process involves a combination of "steeps", where the grain is immersed in steep liquor for hydration, and "air rests", where the grain is drained and exposed to the air. During the steep stages, husk and grain constituents, including sugars and amino acids, leach into the steep liquor. These materials support the growth of microbial populations that compete and deprive the grain of oxygen (inhibiting germination), degrade the outer layers of the grain and potentially produce metabolites, which can be toxic (eg. mycotoxins), inhibitive of grain germination or deleterious to malt quality (flavour taints, gushing initiators etc). During the steep the grain will also produce CO_2 from respiration and as anaerobic conditions develop this will be accompanied with the production of ethanol. Both CO_2 and ethanol at sufficient levels will inhibit grain germination. Therefore steeping regimes will often incorporate air rests where the steep liquor is drained away and discarded, air is sucked downward through the grain bed to remove carbon dioxide (conical vessels only) and the grain is allowed to rest before fresh steep liquor is added. This process:

- Removes dust, dirt and leached grain components, which are suspended in the steep liquor
- Removes microorganisms suspended in the steep liquor
- Removes metabolites produced by the grain or microbial populations
- Discharges excess heat allowing greater temperature control, and
- Replenishes oxygen

The regime of steeps and air rests is dictated by laboratory testing of the grain, data collected from previous batches and economic factors such as efficiency and water usage. Important laboratory tests include:

- Variety – varieties that have loose husks or tend to split during wet growing conditions will absorb water faster
- Moisture content – the initial moisture content of the grain will help determine the duration of the first steep
- Dormancy (Germinative Energy) - water uptake increases significantly once germination begins
- Water Sensitivity - water sensitive grains require shorter steeps and more frequent air rests
- Total nitrogen – high protein (steely) grains exhibit reduced water uptake
- Grain Size (TCW & Screenings) – smaller grains exhibit increased water uptake

Temperature and moisture are critical parameters during steeping and are maintained by controlling the temperature of the fresh steep liquor, the mixing of the grain slurry during steeps, the temperature of the air sucked through the resting grain bed and spraying the grain with water during air rests. These controls in combination with monitoring the temperature and moisture content of the grain are important to:

- Ensure respiration and hydration are occurring at the desired levels,
- Prevent dehydration of the grain,
- Prevent heat damage to the grain embryo,
- Prevent excessive rootlet growth and subsequent malting losses,
- Prevent the inhibition of proteases and other enzymes, and
- Control the growth of microbial populations.

Steep liquor additives may be used to improve the steeping process. Sterilants or populations of harmless microorganisms may be added to control the populations of damaging microorganisms. Alkaline chemicals may be added to assist cleaning of the grain, remove musty odours and extract phenolic compounds, which cause astringency in beer if they persist in the malt. Hydrogen peroxide, lime, sodium hydroxide and mineral acids may be used to overcome dormancy to ensure consistent germination of all the grains. Despite the advantages of steep liquor additives, they are not widely adopted due to the costs involved and the concerns of residual chemical levels in the malt. Similarly, steep liquor in general must be of potable quality and free of taints otherwise the impurities will potentially be passed on through the malt to the wort.

ADJUNCTS, ENZYMES, WATER & HOPS

Details: *Brewhouse adjuncts*

An adjunct is usually defined as “any carbohydrate source other than malted barley that contributes sugars to the wort”. Adjuncts are used in brewing as cheaper sources of extract to partially replace or supplement malted barley and often to impart desirable characteristics on the wort and beer.

Solid adjuncts are manufactured from cereal grains such as barley, wheat, maize, rice, sorghum, oats and rye. Solid adjuncts are generally added to the grist or mash and contribute extract in the form of starch. Starch granules from maize, rice and sorghum and some of the smaller starch granules of barley have higher gelatinisation temperatures than those achievable during mashing due to the denaturation temperatures of malt amylolytic enzymes. Therefore, adjuncts from these cereals will require prior processing to gelatinise the starch granules such as pressure-cooking, roasting, torrification or micronisation, in order for the amylolytic enzymes to liquefy and saccharify the starch effectively. If raw cereal adjuncts are to be used they are usually put through rollers to produce coarse grits of endosperm or milled to produce fine flours.

Liquid adjuncts are highly processed and often purified syrups including hydrolysed starch syrups, sucrose syrups, malt extracts and caramel. They only need to dissolve in the wort or beer and therefore their use is much more simple and reliable than solid adjuncts. Hydrolysed starch syrups are produced from maize or wheat by acid or enzyme hydrolysis (or a combination of both). Current technology means that hydrolysed starch syrups can be produced with virtually any carbohydrate profile desired. Sucrose syrups are derived from sugar cane or sugar beet and can come in invert form, where the disaccharide sucrose molecules have been hydrolysed into discrete monosaccharide units to maximise product volume. Malt extracts are concentrated syrups of wort, which can be prepared from any range of grist components to achieve the required specifications. Brewing caramel is produced by heating glucose syrup with ammonia to promote colour formation by maillard reactions.

Solid adjuncts rely on malt or commercial enzymes to convert their starch into available extract. If enzyme levels are too diluted or the grist contains raw maize, rice or sorghum adjuncts then undegraded starch will remain at the end of mashing causing extract losses, haze issues, increased wort viscosity and impaired wort separation. Similarly, the use of high volumes of flour adjuncts can cause set mashes where they become too thick to allow enzyme mixing and conversion of the starch is impaired. The levels of β-glucan in cereal adjuncts are typically lower than barley; however, the absence of a malting process means that the adjuncts may contribute increased levels of β-glucan to the mash, which will retard wort separation, leave sticky spent grain, reduce filtration efficiency and lead to colloidal instability and haze formation. Therefore, the use of some cereal adjuncts may need to be accompanied by the use of commercial enzymes such as β-glucanases.

Different solid adjuncts will impart distinctive flavours on the beer, for example roasted barley will contribute sharp, astringent, burnt flavours, while rice adjuncts will give beer a light, dry, crisp flavour. Some cereal adjuncts containing increased levels of non-fermentable carbohydrates will also enhance mouthfeel of the fermented beer. Compared to liquid adjuncts, the composition of solid adjuncts is relatively uncontrolled and their use will often have more implications on wort and beer quality. Adjuncts from different cereals will have varying influences on foam stability, for example wheat adjuncts are rich in glycoproteins & peptides that improve foam stability, while maize adjuncts are rich in foam-negative lipids and deficient in nitrogen. The low levels of nitrogen of maize and rice are deleterious in some respects but advantageous in others. Low nitrogen levels will decrease foam stability, decrease free amino nitrogen (for yeast performance) and decrease the ester formation (due to an increased carbon to nitrogen ratio); however, the low nitrogen levels will also increase beer stability by diluting the proteins and polypeptides involved in the formation of chill and permanent hazes.

Hydrolysed starch and sucrose syrups offer a simple and reliable means of increasing wort gravity, and as such increasing brewhouse capacity. Liquid adjuncts will also improve brewhouse capacity by allowing faster lauter run-off, shorter brewing cycles and reduced raw material storage. Liquid adjuncts also provide a simple means of altering the fermentability of the wort in order to manipulate the sweetness, mouthfeel, alcohol level and carbohydrate content of the fermented beer. They can also be utilised as primings in the production of bottle or cask conditioned ales The main implication with these syrups is that they are relatively flavour neutral and deficient in nitrogen. This can be beneficial if the brewer is intending to produce lighter, smoother beers with increased stability and shelf life; however, the reduced nitrogen is could result in reduced foam stability, poor yeast performance and an altered ester profile. The brewer will also encounter critical levels of adjunct syrups where the uptake of other sugars by the yeast is suppressed causing stuck or hanging fermentations. Concentrated malt extracts can also be used to alter wort gravity, fermentability and flavour; however, their cost means that dark malt extracts are most commonly used as an alternative to caramel, where they are used diluted to fine tune the colour of the wort or fermented beer.

Solid adjuncts can be dangerous to store due to the risk of dust explosions, particularly in the case of flours, which also require pneumatic conveyors and can cause issues by blocking vessel outlets. The storage of liquid adjuncts can also be problematic as they must be stored warm to prevent crystallisation and to minimise

Permanent hardness does have some drawbacks, particularly reduced α-acid isomerization and therefore poor hop utilisation, and the presence of magnesium salts will contribute a sour, slightly bitter taste to beer and if present at sufficient concentrations can cause flatulence and induce laxative effects.

Water hardness can be measured by titration methods involving EDTA or HCl. The hardness of water is measured as total hardness, calcium hardness, magnesium hardness or total alkalinity, all of which are expressed as mg of $CaCO_3$. Water can be treated to remove or reduce water hardness. Temporary hardness can be removed by simply boiling the water and removing the carbonate precipitate. Permanent hardness can be reduced by treating the water with lime to precipitate and remove any dissolved calcium or magnesium salts as calcium carbonate and magnesium hydroxide. Water hardness can also be treated with sulphuric, hydrochloric and phosphoric acids, to remove carbonates. Other methods of reducing water hardness include distillation, ion exchange, de-mineralization, de-ionisation and reverse osmosis.

Details: ***Composition of brewing liquor and significance in brewing***

The composition of brewing water, particularly brewing liquor, dilution water and rinse water, is a critical determinant of the character, quality and safety of the beer produced and can have effect in three main areas, (i) microbiological composition, (ii) organic compounds, and (iii) inorganic ion and salt composition. It is important that parameters with acceptable limits are defined in brewing as this will ensure the quality and consistency of the final product as well as allowing tracking of water quality trends so the brewery can respond appropriately.

The boiling of wort in the kettle should kill most viable microorganisms, with the exception of some thermotolerant or sporulating bacteria. However, brewing liquor should still be free of any microbiological contamination as fast-growing microorganisms such as *Enterobacteriaceae* can cause detrimental changes to the wort during mashing and lautering. Dilution water must be particularly sterile and usually receives a more reliable sterilisation process than brewing liquor.

The contamination of brewing water with organic compounds such as pesticides, fungicides and phenols, can be of concern as they have the potential to inhibit yeast growth, cause health concerns, or react with other wort components to form compounds that impart undesirable flavour traits on the beer (e.g. trihalomethanes, chlorophenols).

The inorganic ion and salt composition of the brewing liquor is particularly influential on the style and character of the beer being produced and is also well documented to directly and indirectly influence enzyme activity and yeast growth and metabolism. Traditionally, different brewing regions were renowned for producing their own distinct beers because of the unique inorganic ion and salt composition of their water supply. For example, the pale ales from England's Burton-On-Trent were made using water with high inorganic ion and salt levels, while the delicate pale lagers from the Czech Republic's Pilsen were made using water low in inorganic ions and salts. The key inorganic components of brewing liquor are: calcium, magnesium, sodium, potassium, iron, zinc, copper, manganese, carbonates, bicarbonates, chloride, sulphate, nitrite, nitrate and ammonium. In order to maintain the flavour balance, dilution water should have a similar inorganic ion and salt composition to the initial brewing liquor.

Permanent water hardness as determined by the presence of chlorides or sulphates of calcium and magnesium is responsible for reducing the pH of wort throughout mashing, boiling and fermentation where the inorganic ions and salts react with a range of buffering compounds such as phosphates, organic acids, phytates and polypeptides, which are precipitated out of solution and hydrogen ions are released. Magnesium is more soluble than calcium and therefore its effect on pH is reduced. The reduction in pH is beneficial by:

- Increasing wort fermentability
- Improving extract recovery
- Increasing wort free amino nitrogen
- Increasing run-off rates, and
- Reducing the extraction of polyphenols and silica compounds

The reduction in pH has one main drawback, which is the reduced isomerization of hop α-acids. Carbonates and bicarbonates are detrimental to brewing, as they will prevent a reduction in pH by absorbing hydrogen ions. They also form scale on heating surfaces and can reduce heat transfer efficiencies.

When present at sufficient concentrations, the inorganic ions and salts of brewing liquor can affect:

- Enzyme activity during mashing
  - Zinc and iron can inhibit amylase activity during mashing
  - Calcium will stimulate both amylolytic and proteolytic enzymes
  - Calcium will help protect α-amylase from thermal degradation.

sulphury notes, which can make a positive contribution to some lagers. Apart from the hop variety and degree of ripening, the time of addition will impact significantly on the contribution of hop oil to beer aroma.

The common additions for hops are:

(i) Kettle Addition: When present throughout the kettle boil, the hop oil components are almost entirely vapourised
and removed from the beer

(ii) Late Kettle Addition: Hops added 5-20 minutes before the end of the boil. The essential oil is extracted without being entirely vapourised. The shape and material of the kettle will impact on the extraction and vapourisation of the oils. Late kettle additions usually contribute fruity, citrus characters due to the heavier esters and ketones.

(iii) Dry Hopping: Addition of aroma hop varieties (with low resin content) during maturation or cask conditioning. During dry hopping a wider range of hop oil components are extracted which impart resinous, fruity, citrus or floral notes, often with spicy characters, which can become astringent if dry hopping is overdone.

Foam Enhancement

Iso-α-acids can make a positive contribution to foam stability by either, (i) linking small polypeptides with carbohydrates or melanoidins to form foam-positive compounds, or (ii) forming hydrogen bonds with the hydrophobic groups on foam-positive proteins to produce a thicker, more stable hydrophobic layer, which can be further stabilised by cross-linking from bivalent metal ions such as Mg^{2+}. Iso-humulone is more effective in foam stability than iso-cohumulone and the reduced forms of the iso-α-acids are highly effective at enhancing foam stability, particularly tetrahydroiso- and hexahydroiso-α-acids. Some hop compounds can also be foam inhibitory, particularly lipids derived from whole hops or hop pellets.

Gushing

Certain hop components can provoke gushing in beer, which is the rapid and uncontrollable loss of carbon dioxide. Iso-humulone complexes with metal ions (such as nickel or tin), isomerised extracts and particularly dehydrated humulinic acid can all trigger gushing. Some hop compounds and derivatives are also gushing suppressants such as α-acids, cohulupone and essential oil (if present at 1ppm or more), with the most active constituent of the essential oil being caryophyllene.

Antibacterial Properties

Iso-α-acids have antibacterial properties against gram-positive bacteria, including lactic acid bacteria; however, the reduced forms of iso-α-acids have been reported to be less effective at suppressing lactic acid bacteria.

Haze

Hops contain low levels of polyphenols and proteins, which will both contribute to chill and permanent hazes by the formation of insoluble protein-polyphenol complexes. Hop resins (α- and β-acids) are closely related to polyphenols and can potentially be involved in similar complexes. The α- and β-acids are also insoluble and will precipitate upon cooling unless isomerised. All of these haze-forming compounds can be removed by cold stabilization and filtration; however, if hops are added after filtration then haze issues may arise.

Hop Selection

Selection of hops is often based on:

- α- and β-acid levels, including the relative proportions of humulone, cohumulone and adhumulone – rubbing the hops gives a rough indication of resin levels, while extractions and chemical analysis can give precise results
- Aromatic properties – usually assessed simply by smelling however headspace GC can also be used
- Brewery trials and pilot-plant trials
- Cost and availability

Details: *Processed Hop Products*

The use of whole hops in brewing is diminishing due to the advantages of using processed hop pellets and extracts. The pellitisation of hops is achieved after screening out debris and unwanted material by hammer milling followed by compression into pellet form. Type 90 pellets are manufactured from whole hops, while Type 45 pellets involve an additional enrichment process where after freezing the hops to -30°C to -40°C the lupulin and leaf fractions are mechanically seperated before hammer milling. In the manufacture of isomerised hop pellets, magnesium oxide is added prior to pelletising to produce salts of the α-acids. The pellets are then stored at 50°C with the exclusion of air to encourage isomerization to iso-α-acid salts, which takes from 7 to 14 days to complete.

The manufacture of hop extracts involves an extraction process where the hop oils and resins are dissolved into a solvent, usually either ethanol or liquid CO_2. When using ethanol, a mixture of the hops and 90% ethanol is

Single temperature infusion mashing regimes involve a single strike temperature (usually around 65°C) achieved by the equilibration of the vessel, brewing liquor and grist temperatures. The high single temperature is primarily concerned with starch degradation and is unsuitable for proteolytic or glucanolytic enzymes, therefore a higher grist to liquor ratio is often used for increased protection of the enzymes from thermal denaturation. Single temperature mashing regimes are commonly used with mash tuns designed also for wort separation. Infusion mash tuns are simple insulated vessels often with steam jackets, which are used only to preheat the vessel. The vessel has filter plates for wort separation and sparge arms to distribute hot liquor over the bed to flush residual extract from the grains during wort separation.

Temperature programmed mashing regimes require an added level control over the mash temperature and involve a number of temperature stands and ramps. The form of this temperature control varies including, (i) modern systems controlled entirely by steam coils, jackets and sometimes direct injection of treated steam, (ii) decoction systems controlled by removal of portions of the mash, which are separately heated and added back to the main mash, or (iii) double mashing where the addition of separately cooked cereal adjuncts is used to achieve a temperature ramp in the main mash. Temperature programmed mashing regimes allow temperature stands suitable for the activity of a number of enzyme groups.

Temperature programmed mashing vessels do not have filter plates and rely on the use of a lauter tun or mash filter for wort separation. Since entrained air is not important to float the mash above filter plates, temperature programmed systems often mash in against the side of the vessel or through vortex mixers to minimise aeration and subsequent oxidation of the wort. The grist to liquor ratio is often lower to protect the enzymes from product inhibition and to make transfers between vessels easier. They are typically equipped with stirrers to keep the malt suspended, prevent dry spots, ensure even distribution of the enzymes and substrates, allow a homogenous temperature and to keep the hot sides of the vessel clear to prevent burning. The vessel shape and stirrer design are optimised to ensure adequate mixing with minimal shear forces exerted on the mash, which can damage the husk, produce fine malt particles and physically extract β-glucan from the malt, which can hinder wort separation, extract recovery and cause colloidal instability of the beer.
The advantages and disadvantages of single temperature and temperature programmed mashing regimes are outlined in Table 2 below, while Figure 1 illustrates examples of the different mashing regimes in terms of temperature and pH profiles and enzyme activity.

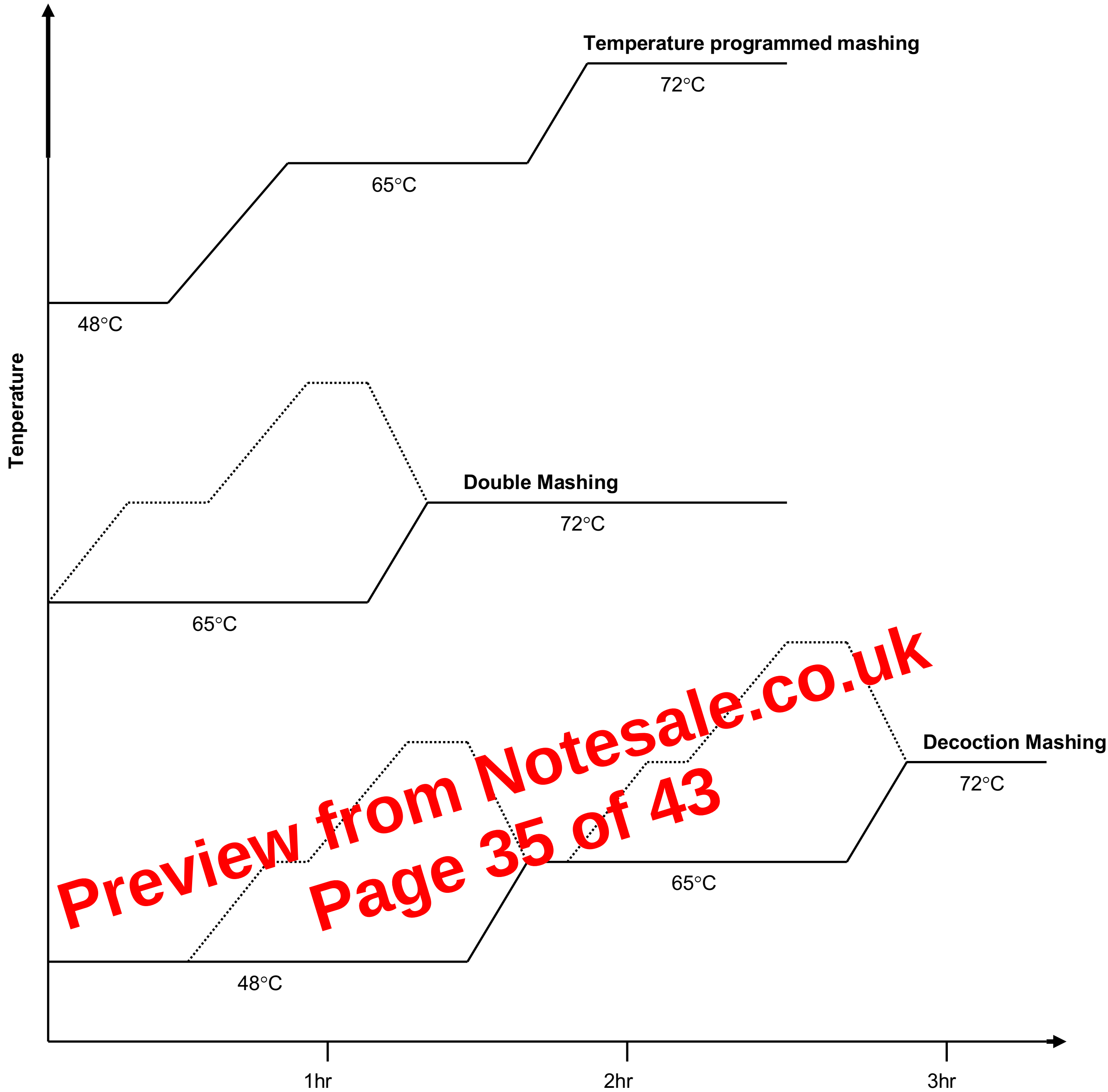

Figure 1. Examples of mash profiles using different types of mashing regimes

Details: *Design and operation of an infusion mash tun, lauter tun and mash filter for wort separation*

After mashing, the sweet wort must be separated from the spent grain, usually by means of an infusion mash tun, lauter tun or mash filter. All these systems utilise filter plates or sheets, which support the solid grain material. The grain bed acts as the filter medium in infusion mash tuns, lauter tuns and early mash filter models; however, modern mash filters use a polypropylene sheet, which is sufficient for achieving bright wort without any reliance on the grain bed. For mash tun separation and lautering, the most important component of the grain bed is the grain husk, which maintains the lightness and porosity of the bed. However, the grain husk and rest of the grain bed is susceptible to compression, which can have adverse affects on run-off rates and overall mash filtration. At the beginning of wort separation, the collected wort is recirculated until the grain bed forms and bright wort is achieved.

Sparging is common to all wort separation techniques where fresh hot liquor is used after the initial strong wort is collected, to flush remaining wort through the grain bed and to extract residual soluble components from the

Hot wort filtration techniques have also been used in breweries, from simple sieve screens to depth filtration through plate and frame, vertical leaf or candle filters using kieselguhr or perlite. Filtration of wort can be used for wort clarification with great results; however, it is unnecessarily complicated, labour intensive and incurs ongoing material and disposal costs.

Whirlpool vessels are the most common means of wort clarification in most modern breweries. The whirlpool is a simple, circular vessel where wort is introduced tangentially producing centrifugal force by creating a whirlpool effect. This centrifugal force accelerates trub particles towards the outside of the vessel where they are drawn downwards and inwards to the centre of the vessel forming a trub cone. To maximise this effect, whirlpools require a high transfer rate from the kettle and the inlets are designed to reduce velocity and subsequent shear forces whilst maintaining a high volume flow rate. Whirlpool operation is based on circulation time and is a compromise between short stands where wort clarification is incomplete or long stands where there is the risk of remaining S-methyl-methionine from the wort being broken down to dimethyl sulphide. After the optimised circulation time is reached, the clarified wort is drawn from above the trub cone through outlets on the side of the vessel at varying heights. Modern whirlpools are equipped with a hydrojet on the base of the vessel, which breaks up the trub cone after wort removal is completed and the trub is discharged from the vessel. Whirlpools are very simple with very few moving parts and therefore after optimisation they require very little maintenance or service.

Separated trub from wort clarification still contains extract and bitterness so it is common practice to recover this extract by adding it back to the mash tun or lauter tun, or separating the entrained wort using settling tanks, vibrating screens or centrifuges. Spent trub cannot be disposed of to drain due to its very high biological oxygen demand and is therefore generally added to the spent grain where it is used as cattle food.

Summary: *Wort aeration and oxygenation*

Although the fermentation of wort is a largely anaerobic process, the presence of oxygen in the initial wort is extremely important for yeast metabolism and fermentation performance. It is vital that dissolved oxygen is present at sufficient levels when yeast is first pitched into the wort as there is an absolute requirement of oxygen for the synthesis of unsaturated fatty acids and sterols. Unsaturated fatty acids and sterols are vital structural and functional components of yeast cell membranes and are needed for the formation of new cell membranes during yeast growth and maintenance.

The level of oxygen required depends on the yeast strain, pitching rate and wort gravity; however, generally falls between 7 and 18mg/L. High gravity brewing requires higher amounts of oxygen and as such the wort must be aerated with pure oxygen as opposed to sterile air. Insufficient oxygenation of wort would limit yeast growth, which would alter the fermentation of the wort potentially causing atypical flavours, haze and stuck fermentations.

Wort is typically aerated on the cold site of the wort heat exchanger due to the higher solubility of oxygen at lower temperatures and to minimize oxidative reactions, which can rapidly darken the wort and cause flavour instability. However, the aeration of the wort on the hot side of the heat exchanger would have the advantage of minimising any microbial risk. Therefore, oxygenation apparatus' are typically equipped with sterile filters and steaming capability to prevent the introduction of microbiological contamination. The air or oxygen is generally injected directly into the wort stream using a disc spreader to help dissolve the oxygen. Mass flow meters on the oxygen line and flow meters on the wort line are typically used to control the oxygenation of the wort; however, downstream oxygen meters can be used in a similar manner or for monitoring the accuracy of the oxygenation process.