Understanding Efficiency

Efficiency is a commonly discussed subject among all grain brewers. But with the abundance of definitions for it, it easily becomes a matter of comparing apples with oranges. This article tries to shed some light on the various efficiency definitions that are in place, how they are defined (sometimes differently, depending on the author) and how efficiency is affected. Everything you should know to understand a low mash, lauter or brewhouse efficiency.

Contents [hide]

Existing Definitions

In *How To Brew*, John Palmer defines the brewing efficiency as the ratio between the gravity points of the wort in the kettle and the maximum potential (laboratory extract) of the grain. The maximum potential of the grain is given in gravity points per pound and gallon. Based on that the gravity points of the kettle wort are [Palmer 2005]:

kettle gravity points = brewing efficiency * grain amount in pound * kettle volume * potential of the grains

When grains with different potential are used, the weighted average of their potential needs to be used in the above equation.

In *Designing Great Beers*, Ray Daniels defines what John Palmer calls brewing efficiency as mash efficiency [Daniels, 2000].

In *Abriss der Bierbrauerei*, German brewing author Ludwig Narziss defines *Sudhausausbeute* (German for brewhouse efficiency) as the ratio between the amount of extract in the boil kettle and the amount of grain that was used [Narziss, 2005]:

Sudhausausbeute = (kettle volume in l * kettle extract in % * kettle specific gravity) / grain mass in kg

Note that this is a different approach for defining efficiency. The reference is not the laboratory extract of the grain, but the total weight of the grain. The latter includes the weight of the husks and other insoluble material. Because of that the the*Sudhausausbeute* is also affected by the potential (or laboratory extract) of the malt used. This is also the definition that German home brewers use for efficiency. Thus care needs to be taken when reading efficiency numbers from German sources. While 75% is a very good efficiency number when based on the total grain weight (most grains laboratory extract is about 80% of their weight) it is only a modest efficiency when seen as based on the laboratory extract of the grain.

When asked how to calculate efficiency, the BYO Wizard replied with the same definition as was given in Narziss [BYO]. He calls that efficiency the brewhouse efficiency. But he also goes on and defines the efficiency that is based on the laboratory extract of the grain as brewhouse yield:

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brewhouse yield = (kettle volume in l * kettle extract in % * kettle specific gravity) / (grain mass in kg * fine grind extract in %)
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Furthermore, technical brewing articles oftentimes make mention of the Overall Brewhouse Yield (OBY). This is the same as the brewhouse yield defined by the BYO wizard. It is affected by milling, mashing and lautering, and essentially indicates how close these brewhouse processes came to the fine grind laboratory extract.

The *Handbook of Brewing* lists the total grain weight based efficiency (see *Sudhausausbeute* above) as the brewhouse yield. It furthermore mentions that the volume used in the equation is the volume of the hot wort in the kettle corrected for temperature. It only considers losses in the spent grain (unconverted starches and sugars held in the wort trapped in the grain) and not transfer losses on the way to the fermenter (e.g. wort loss in the trub) [Priest, 2006]. From this I gather that commercial brewers see the efficiency into the kettle as the brewhouse efficiency or yield.

Another popular set of efficiency definitions are the efficiency numbers given by Beersmith , a recipe design software. Three different types of efficiency are given: brewhouse efficiency, efficiency into boiler, efficiency into fermenter. The**brewhouse efficiency** indicates how much of the extractable extract made it into a wort with the measured gravity and the the target volume that has been entered for that batch. **Efficiency into boiler** is the percentage of extractable extract that made it into the boil kettle. This is based on the pre-boil volume and pre-boil gravity. Lastly the **Efficiency into fermenter** is the percentage of extractable extract that ended up in the fermenter. For that the measured gravity in the fermenter and the wort volume in the fermenter is entered. The efficiency that matters for comparison with others should be the efficiency into boiler or the brewhouse efficiency if the batch size matches the temperature corrected post boil volume. Any other efficiency measurement is not readily comparable because of losses that happened after the lautering process. One of the major additional losses is wort left behind in the kettle and its cause is fairly obvious and very much dependent of the brewers wort transfer practice and brewing process.

conversion and lauter efficiency

The brewhouse efficiency can be broken into two separate efficiencies that measure the performance of mashing and lautering separately:

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brewhouse efficiency = conversion efficiency * lauter efficiency
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Conversion efficiency measures how well the mash extracted the grist (malt and mash tun adjuncts). The benchmark is the fine grind extract that was determined in the laboratory. If all of that is extracted, the mash efficiency is 100%. Conversion efficiency is affected my mash parameters like pH, crush, diastatic power, temperature profile, mash type and mash time and should be close to 100%.

Lauter efficiency measures how well the lautering process transferred the extract, made soluble by mashing, into the boil kettle. It is affected by the design of the lauter system, type of lautering (no sparge, batch sparge or fly sparge) and sparging practice. The parameters that affect lauter efficiency for batch sparging have been discussed in Batch Sparging Analysis.

Conversion efficiency

Measuring conversion efficiency

Splitting brewhouse efficiency into conversion and lauter efficiency only helps in evaluating the brewhouse efficiency if one or both components can be measured separately. As it will be shown here, it is possible to measure conversion and lauter efficiency independent of each other. To determine the conversion efficiency it is best to calculate the theoretical maximum of the first wort extract/gravity based on the laboratory extract of the grain that was mashed and the volume of water that was added to the mash.

$$FW_{\max} = 100\% \cdot \frac{m_{grain} \cdot e_{grain}}{(V_{mash\_water} + m_{grain} \cdot e_{grain})}$$

- FW_{max} is the theoretical maximum of the extract content of the first wort in Plato (actually weight %, but that is close enough to Plato and Brix for these calculations)
- V_{mash_water} is the volume of the strike water in liter. This means the total volume of water that was added to the mash before the FW extract is determined, including water that was added after the mash but before the first run-off. But water added to compensate for decoction boil-off should not be considered.
- m_{grain} is the weight of the grist in kg
- e_{grain} is the (weighted) average of the laboratory extract of the grist. This comes from the malt analysis, but 0.8 (i.e. 80%) is a fairly accurate estimation for most malts.

An approximation of the conversion efficiency, which is most accurate when the conversion is close to 100%, is the ratio between the expected FW extract and the actual FW extract:

$$CE = 100\% \cdot \frac{FW_{measured}}{FW_{max}}$$

where

- **CE** : conversion efficiency, is the efficiency of the starch conversion in the mash in %
- FW_{max} is the expected first wort extract that was calculated using the above formula (in Plato, Brix or %)
- $FW_{measured}$ is the actual first wort extract that was measured (in Plato, Brix or %)

Peter Hopcroft pointed out that the accurate formula for the conversion efficiency is

$$CE = 100\% \cdot \frac{FW_{measured}}{FW_{max}} \cdot \frac{(100 - FW_{max})}{(100 - FW_{measured})}$$

The extract content in Plato (close enough to Brix and extract % for these cases) can be estimated form specific gravity with this formula:

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Plato = (sg - 1.000) * 1000 / 4
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The first wort extract can also be calculated from the mash thickness, which removes the actual grain weight and water volume from the equation:

$$FW_{max} = 100\% \cdot \frac{e_{grain}}{R + e_{grain}}$$

- **R** is the water to grain ratio in l/kg. If the mash thickness is known in qt/lb, multiply by 2.09 to convert to l/kg

Table 1 gives the expected first wort extract/gravity based on the mash thickness at the time that the sample is pulled. To simplify the calculations this table assumes an 80% potential extract content in the grist (which is typical for most base malts) and 100% mash efficiency. Use these numbers as a benchmark for comparing your measured first wort gravities.

mash thickness		first wort extract/gravity	
l/kg	qt/lb	Plato	SG
2.0	0.96	27.7	1.118
2.2	1.05	25.9	1.110
2.4	1.15	24.2	1.102
2.6	1.24	22.8	1.096
2.8	1.34	21.5	1.090
3.0	1.44	20.4	1.085
3.2	1.53	19.4	1.080
3.4	1.63	18.4	1.076
3.6	1.72	17.6	1.072
3.8	1.82	16.8	1.069
4.0	1.91	16.1	1.066
4.2	2.01	15.5	1.063
4.4	2.11	14.9	1.061
4.6	2.20	14.3	1.058
4.8	2.30	13.8	1.056
5.0	2.39	13.3	1.054
5.2	2.49	12.9	1.052
5.4	2.58	12.5	1.050
5.6	2.68	12.1	1.049
5.8	2.78	11.7	1.047
6.0	2.87	11.3	1.046
6.2	2.97	11.0	1.044
6.4	3.06	10.7	1.043
6.6	3.16	10.4	1.042
6.8	3.25	10.1	1.041
7.0	3.35	9.9	1.040

Table 1 - Extract content or gravity of the first wort based on the mash thickness. 100% mash efficiency, 80% fine grind extract and 4% moisture content of the malt were assumed for the grist

What affects the conversion efficiency ?

If the mash efficiency is significantly short of 100%, i.e. lower than 90%, the mash didn't perform as well as it should have. This is an indication that one or more of the mash parameters were suboptimal. To be precise, mash parameters don't have to be at their optimum for 100% conversion efficiency, they only have to be good enough. But the range in which a mash parameter is good enough depends on the other mash parameters.

The reason for that "good enough" is the fact that the amount of starch to be converted is limited. And once that starch is converted and made soluble it doesn't matter how close a mash parameter was to its optimum there isn't more available that can be converted. As a result, the conversion efficiency will plateau. This is illustrated in Figure 1

Let's assume the mash parameter in question is temperature and the mash time is 60 min. If the temperature is too low, the enzymatic activity will not be strong enough to convert all the starch in the mash within 60 min, and as a result the conversion efficiency will suffer. But if the temperature is higher, the enzymes will be active enough to convert all the starch in the mash within the given 60 min. At this point 100% conversion efficiency can be achieved. Even if the temperature is optimal and allows enzymatic activity that could convert twice the amount of starch, the conversion efficiency will not go up as it is limited by the amount of starch in the mash. At higher temperatures there comes a point where the destruction of the enzymes is quicker than the starch is being converted and as a result not all the starch will be converted. From this point on the conversion efficiency will suffer as the rest temperature is increased.

In addition to that, other mash parameters could be so far away from their optimum that even an optimal temperature will not be able to convert all the starch in 60 min. As a result of that close to 100% conversion efficiency cannot be achieved with any rest temperature.

Interestingly enough, a starch test may not be able to detect low conversion efficiency as it can only detect starch present in the mash liquid. But if the unconverted starch is still locked away in the grist (large pieces of grits or endosperm that is mostly surrounded by husk material) an iodine test on the wort cannot identify this problem. Note that a mash should never result in a positive iodine test (starch or large detxtrines present in the wort) as this can lead to diminished beer quality while a negative iodine test but poor conversion efficiency shouldn't lead to quality problems. It should just lead to a poor brewhouse efficiency.

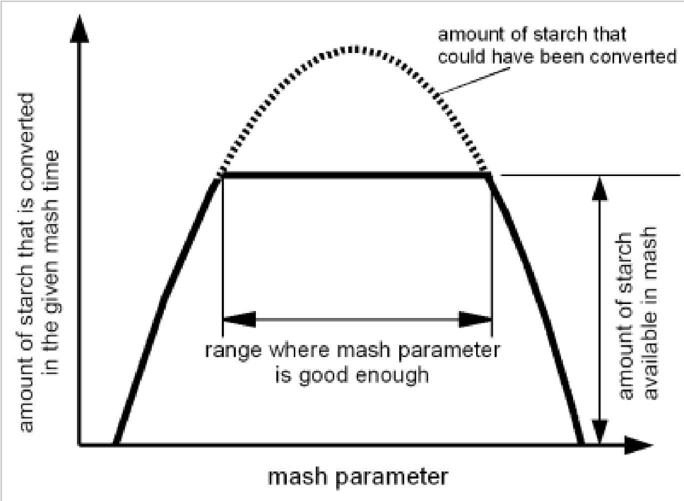

Figure 1 - A diagram that illustrates the dependency between a particular mash parameter and the amount of starch that is converted in that mash

Temperature

As shown in the Limit of attenuation experiments, the rest temperature has an affect on fermentability and conversion efficiency. Generally it can be said that lower temperatures require longer rests in order to get the mash fully converted. This is a result of the decreased activity of the enzymes. How long it takes to convert a mash at a given temperature depends on the other mash parameters. Temperatures higher than 75-80 C (167-176F) may cause too much of the alpha amylase (the main starch converting enzyme) to be denatured too quickly and thus resulting in a mash that may never convert.

Conversion below the starch gelatinization temperature (60-65 C / 140-150 F for the large starch granules which represent 85-90% of the starch and 51-92 C / 125 - 200F for the small granules that represent the rest of the starch [Briggs, 2004]) still takes place but at a slower pace since the enzymes only have access to the starch on the outside of the starch granules. Once the starch gelatinizes the enzymes have access to much more starch hence conversion occurs much quicker.

Given a constant rest time, there will be a rest temperature below which the mash is not able to fully convert in the given time and as a result efficiency will suffer. This can be compensated by a longer rest or getting other mash parameter closer to their optimum to strengthen the enzymatic power of the mash.

pH

Near their temperature optimum the amylase enzymes have a pH optimum between 5.4 and 5.7 when the pH of a cooled mash sample is measured (5.4-5.6 pH for beta amylase and 5.6-5.8 pH for alpha amylase [Narziss, 2005]). This was also confirmed in the limit of attenuation experiments. Outside this pH range the enzymes still work, but not as well and the mash doesn't convert as quickly or, if the rest time is not long enough, won't convert and the conversion efficiency will suffer. Because of this, and for beer quality, a brewer should pay attention to the mash pH and/or the residual alkalinity of the brewing water. The residual alkalility, which is a function of the water's calcium, magnesium and bicarbonate content, affects how low the acidity of the grist will be able to lower the pH. Besides a chemical reaction between the malt and the water's calcium and magnesium ions (see Understanding Mash pH)melanoidens present in the malt also have an acidic power which lowers the pH. As a result grists of darker malts require water with higher residual alkalinity than grists of lighter colored malts to create a mash pH that falls into the optimal mash pH range of 5.4-5.7 (when measured at room temperature).

Many brewers see a jump in brewhouse efficiency once they correct the mash pH. This is the result of improved conversion efficiency. On information about how to estimate and correct mash pH see Understanding Mash pH.

Time

The longer the enzymes can work, the more they can convert. Hence a longer mash time can lead to an increase in conversion efficiency. But if the mash already fully converts before the rest time is over, an increase in the rest time will not have an effect on the conversion efficiency since there is nothing left to be made soluble by the enzymes. But the attenuation of the beer may still be affected by mashing longer than it takes to reach full conversion.

This assumes that the temperature is low enough and doesn't cause excessive denaturation of the enzymes (at least for the alpha amylase). If the rest temperature causes too many enzymes to be denatured before full conversion was reached, no increase in the length of that rest will be able to fix the conversion problem. Only the addition of fresh malt or enzyme preparations can convert the mash now.

Malt Milling

How tight the malt has been crushed can have a big impact on the conversion efficiency. If the grits are to coarse and pieces of endosperm are still (partially) enclosed by the husks, the mash needs to be more intense to reach the starch inside these grits. As a result the conversion efficiency is likely to suffer. As the crush gets tighter, the size of the endosperm pieces (grits) is reduced and more of them are separated from the husks. The amount of flour also increases. There will be a point at which the largest pieces are small enough that the intensity of the chosen mashing schedule is strong enough to reach and convert all the starch. Non stirred single infusion mashes are least intense. The "intensity" is increased if a step mash is used, the mash is stirred or even boiled as it is the case for decoction and cereal mashes.

Note that the malt grain is about 1.8 mm (70 mil) thick. If it is crushed with a mill gap spacing of 1.0 - 1.5 mm (40 - 60 mil), which is the factory setting of many mills, it cannot be expected that there will be a sufficient separation between the endosperm and the husks and small enough grits that a single infusion mash is strong enough to reach all the starch. As a result many home brewers see a jump in efficiency when they start milling the grain through a tighter roller spacing or double crushing the grain.

When using a lauter tun to separate sweet wort and spent grain, there is a lower limit to the roller spacing. As the malt is crushed ever tighter the husks are shredded more and more (although that can be mitigated though Malt Conditioning) and more flour is produced. Both impede the lauter process and a stuck sparge becomes more likely. If even a mill gap spacing as low as 0.6 mm (24 mil) doesn't achieve an conversion efficiency close to 100%, attention should be paid to the other mash parameters. Most likely one or more other mash parameters are suboptimal and reduce the "strength" of the mash.

In general it is best to crush as tight as necessary for close to 100% conversion efficiency (full conversion) but not tighter as to improve the run-off speed of the lauter and avoid excessive husk shredding.

Mash Schedule

As it was already alluded to in Malt Milling the intensity of the mash also affects how well a mash converts. That "intensity" is determined by how the mash is being performed. Triple decoction mashes are regarded as the most intense mashes since the repeated boiling of the grain liberates starch that is still enclosed in cell walls (undermodified malts) or tucked away between husk pieces (poor malt crush) and makes it accessible to the enzymes. But on the other hand, decoction mashes also reduce the diastatic power of the mash by denaturing enzymes during the decoction boils. Another increase in intensity is stirring and agitating of the mash. But modern well modified malts generally don't need an mashing schedule as intensive as a decoction mash and if the other mash parameters are optimal (or good enough) a mash with these malts can convert even without decoction mashing or constant stirring.

Dough-in at temperatures below the saccharificantion rest temperatures help to preserve the diastatic power because the amylase enzymes are able to hydrate before they enter a temperature range in which they start to denature more significantly. This and the breakdown of some of the proteins that infest the starch granules and the beta glucans that are still present in undermodified parts of the endosperm can improve the conversion efficiency.

When starches like rice or corn, which have higher gelatinization temperatures, are used it is necessary to gelatinize them before they are added to the mash. Flaked grains had that already done and can be added directly to the mash. Raw rice or corn need to be cooked to accomplish that. In breweries, that use adjuncts, the vessel used for this boil is called a cereal cooker.

Mash-out

Although mashing out or not is part of the chosen mash schedule its effect on efficiency should be discussed in more detail. Some brewers report a jump in efficiency when they perform a mash out. While this can be a result of improved lautering it is most likely the result of better conversion efficiency. If the enzymes in the mash were not able to fully convert the mash during the saccharification rest, a mash out can help the conversion efficiency by "super charging" the alpha amylase which works much faster at temperatures between 70 and 75C (158F to 167F). Above 80 C it starts to denature quickly. This super charged alpha amylase now converts the starch that has not been converted during the saccharafication rest and as a result the conversion efficiency is increased. But since the beta amylase is quickly denatured during a mash-out, the extract (i.e. efficiency) gained from a mash-out is mostly unfermentable and will lower the overall attenuation of the wort. As a result a mash-out should not be seen as a tool to increase the conversion efficiency unless the decrease in fermentability is taken into account.

Some authors contribute the extraction benefits of the mash-out to its ability to provide a temperature that gelatinizes even more starch (in particular the small starch granules which have a higher gelatinization temperature)[Scandrett, 1997]. But I have not seen a significant enough increase in the conversion efficiency by performing a mash out and many brewers report the same. While it is true that elevated temperatures will make more starch accessible, the additional amount that is made accessible in well modified modern malts is only small.

Diastatic Power

Diastatic power is a measure of the enzymatic strength (in particular the amylase enzymes) of the malt. The higher that power is, the more amylase enzymes are in the mash and the more starch can be converted by these enzymes and the more forgiving the mash can be if other mash parameters are suboptimal. Diastatic power is measured in degree Linter or W-K (Windisch-Kolbach units). To determine it, gelatinized starch is incubated with a water extract made from the malt and kept at a controlled temperature. After a predetermined time, the starch breakdown is measured and it seen as an indication of the enzymatic strength of the malt [Briggs, 2004]

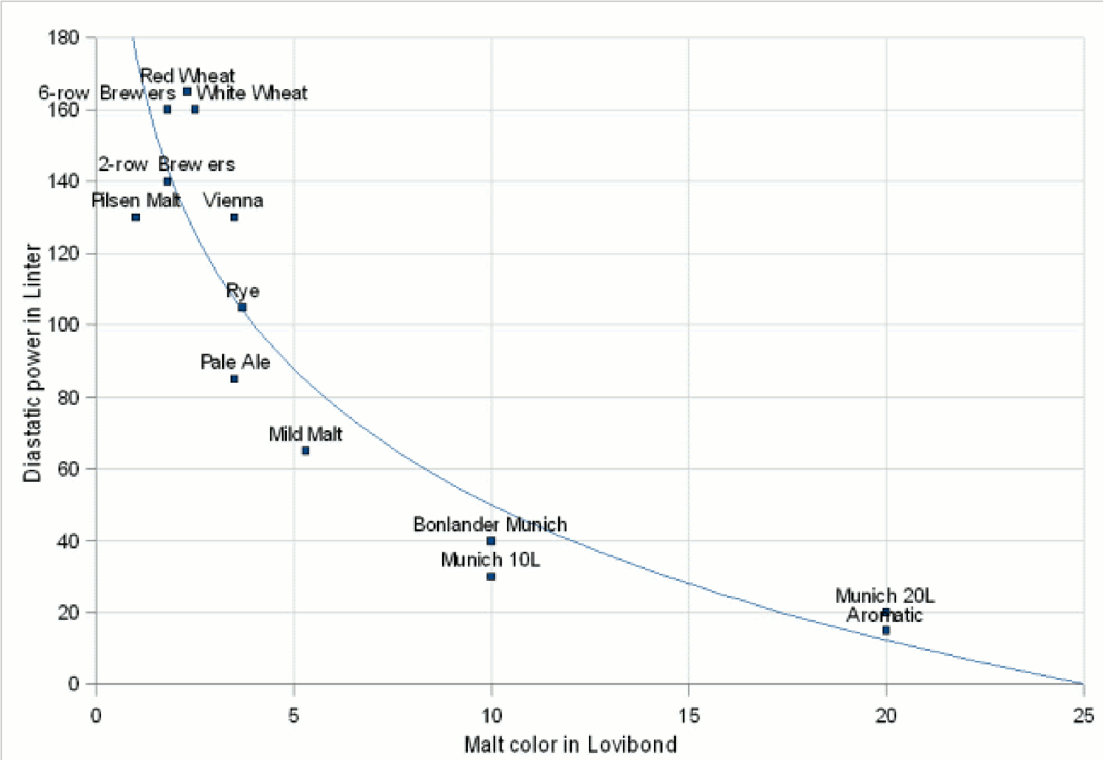

Figure 2 - Diastatic power of various malts based on the malt color. (Data source Briess Malting [Briess, 2008])

The diastatic power of malt is affected by the germination and kilning process during the malt production. While a longer germination time (higher degree of modification of the malt) increases the number of enzymes and diastatic power a higher kilning temperature (darker malts) reduces the diastatic power by denaturing a larger number of them. Figure 2 shows the dependency between malt color and the diastatic power for malts from Briess Malting. The darker the malt, the higher and/or longer the kilning process and thus the lower the diastatic power. It is interesting to note that the relationship is not linear but falls rather quickly as the malt color increases. As a result only ~20% of Pilsner malt (130 deg. Linter) need to be added to a grist of 100% dark Munich (20 deg. Linter) to double its diastatic strength while the color of the grist (now 20% Pilsner and 80% Munich) only decreases by 20%. This should be kept in mind when designing recipes: if a grist is suspected to be to weak in diastatic power, it doesn't take much lightly colored malt to correct that. In the case of Briess malts, it would be even better to use Vienna malt instead of the Pilsner malt as it is darker colored but has the same diastatic power as the Pilsner malt.

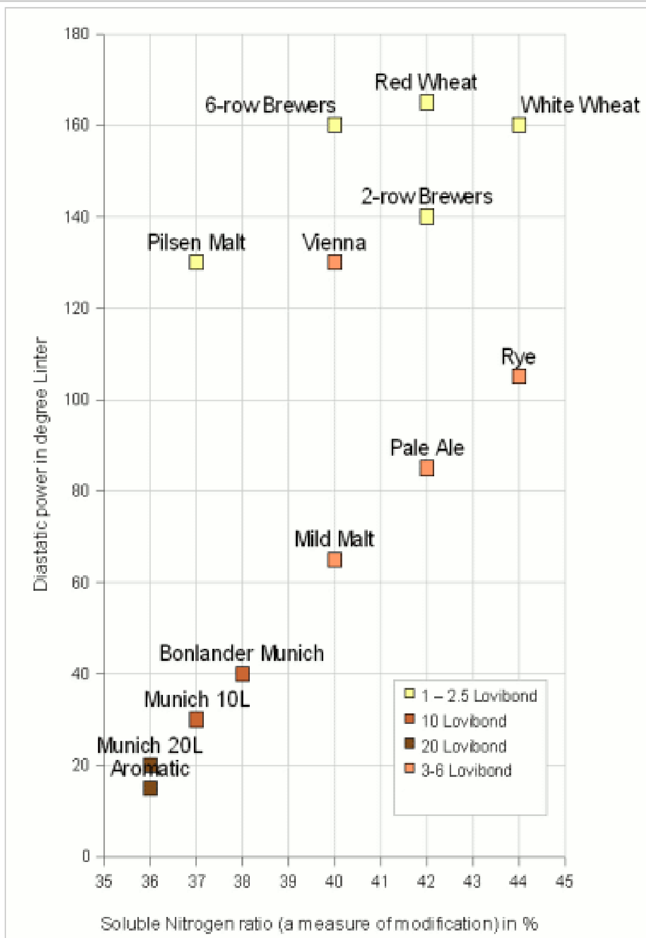

Figure 3 - Diastatic power of various malts based on their soluble nitrogen ratio which can be used as an indication of the degree of modification (Data source Briess Malting [Briess, 2008])

The reason that the Vienna malt has a higher diastatic power might be that it was produced with a longer germination time which lead to a higher modification and high soluble nitrogen ratio. The longer malt is left to germinate, the more enzymes are produced (increase in diastatic power) and the more protein (nitrogen compounds) are degraded and made soluble (increase in soluble nitrogen vs. total nitrogen i.e. soluble nitrogen ratio SNR or S/T). This relationship can be seen in Figure 3. Among malts of similar color, it is in general true that the higher the soluble nitrogen ratio, the higher the diastatic power. Some exceptions do however exist. The Briess Vienna malt for example has the same color as the Pale Ale malt and a lower SNR as the Pale Ale mat, yet its diastatic power is significantly higher.

While all this sounds complicated, most modern malts have a sufficient diastatic power to be used in a single infusion mash. But with respect to efficiency and full mash conversion, the higher a grists diastatic power is the more forgiving the mash will be with respect to conversion efficiency and other mash parameters having to be at their optimum.

Another reduction of diastatic power happens during decoction mashing. While decoction mashing makes starch more accessible to the enzymes by gelatinizing the starch present in the decoctions, it also destroys the enzymes that were present in the decoction. As a result special care should be taken when decocting mashes weak in enzymatic power (i.e. large amounts of dark base malts like Munich malt). To mitigate the reduction in enzymatic power decoctions should be rested for conversion before they are brought to a boil. This uses the power of the enzymes that are going to be destroyed soon for the starch that is present in the decoction and as a result not as much enzymatic power is needed during the saccharification rest of the main mash. If possible decoction mashes should be kept thin (3.5 to 5 l/kg / 1.75 to 2.5 qt/lb) and the decoctions itself thick (about 2 l/kg or 1 qt/lb). This keeps more of the enzymes, which are after dough-in quickly dissolved in the mash liquid, in the main mash while the decoction will contain more of the starch and other grain material. In addition to that the conversion process should be monitored with the Starch Test. If conversion is slow, a rest at 70 - 74 C (160 - 168F) can speed things up. If that is not working some (~10%) Pilsner or Pale malt may be added to add more enzymes.

Mash thickness

In order to convert the starches, water is needed. Not only for process of gelatinization or hydration of the enzymes but also for the conversion process itself. Whenever a gluclose chain is split (either to create a sugar molecule or a shorter starch chain) one molecule of water is needed. In addition to the reduced amount of free water the high sugar concentrations in thick mashes also impede the amylase enzymes [Briggs, 2004].

Traditional British style infusion mashes are with about 2-2.5 l/kg (1 - 1.15 qt/lb) very thick and German style mashes are generally much thinner (3.5-5 l/kg / 1.75-2.5 qt/lb). Historically this is rooted in the fact that the latter needed to be pumped and stirred.

In the limit of attenuation experiments it was shown that a 5 l/kg (2.4 qt/lb) mash showed much better conversion efficiency than a 2.5 l/kg (1.2 qt/lb) mash. This is also supported by anecdotal experience from home brewers who found that thin mashes generally lead to better overall efficiency.

While thick mashes help to stabilize the enzymes which makes them active for a longer time, they also inhibit their activity (substrate inhibition) and make it more difficult for the starch to gelatenize. As a result in thinner mashes the conversion processes occur faster. When it comes to conversion efficiency the main enzyme responsible, the alpha amylase, is still fairly stable at common saccharification rest temps and as a result it can take the full benefit from a thinner mash and an increase in conversion efficiency is commonly notes when the mash thickness is decreased. Beta amylase on the other hand is not as stable at these temperatures and it will be denatured more quickly in thinner mashes. But this is compensated by the faster activity of that enzyme which results in no change of the wort fermentability when the mash thickens is changed.

Dough Balls

Dough balls form when gelatinized starch encloses dry starch/malt. The gelatinized starch forms a barrier that keeps mash water from entering the dough ball. The same happens in cooking when trying to thicken a hot liquid by adding corn starch or flour. clumps are likely being created that take some whisking to be broken up. Because of that the starch or flour should be mixed with some cold water first before the mix is added to a hot liquid.

In brewing dough balls can be avoided by slowly adding malt to hot strike water and stirring well after the malt is added. Thinner mashes are also less likely to cause dough balls. No risk of dough balls exists when the dough-in happens below the starch gelatinization temperature of 60 C (140F). In contrast to the flour clumps in cooking, the enzymes of the mash will start working on the barrier of gelatinized starch and eventually break that barrier. That leads to a late release of starch which may or may not be converted in time (dependent on the enzymatic strength of the mash) which affects the conversion efficiency negatively. Because of that dough balls should be avoided through careful dough-in and thorough stirring of the mash after dough-in. Make sure you are also getting into the corners of rectangular mash tuns.

Lauter efficiency

The lautering process (i.e. separation of sweet wort and spent grain) is the other process that affects the brewhouse efficiency. Other than mashing it is a mostly physical process. In home brewing 2 strategies for lautering are employed: batch sparging (including its special case the no-sparge) and fly sparging. While batch sparging relies on the repeated dilution and run-off of the wort left in the grain by batches of sparge water to transfer the dissolved extract into the kettle, fly sparging is a continuous process in which the sparge water leaches and rinses the extract from the grain.

Estimating Lauter Efficiency (Batch Sparging)

In the lautering method referred to as batch sparging after the mash is complete the first wort is run off until the grain bed runs "dry". But the spent grain left in the lauter tun is not really dry and a volume of wort (of the same gravity as the wort that was run off) remains between the grains. Now the valve is closed and a batch of sparge water is added to the grain and stirred in. That dilutes the wort that remained in the grains and once the stirring is complete another batch of wort, which is lower in gravity this time, is run off into the boil kettle. This process is repeated until the desired pre-boil volume is reached. One to two batches of sparge water are used most often.

Because of the static nature of this problem run-off -> dilution -> run-off ... the lauter efficiency of batch sparging can easily be modeled which has been done in more detail in Batch Sparging Analysis. The efficiency of transferring dissolved extract (sugar, proteins etc.) is the ratio between run-off volume and total initial wort volume in the mash tun. Because of the presence of undissolved solids, the wort volume in the lauter tun is not equal to the mash volume and it is best to calculate the wort volume in the lauter tun as the sum of run-off volume and volume absorbed by the grain and the dead spaces of the lautertun that cannot be drained. In a properly designed lauter tun, the wort absorbed by the grain is generally much larger than the wort trapped in dead spaces. The volume absorbed by the grain is proportional to the amount of grain that was mashed.

The efficiency of one batch sparge step is:

$$Eff_{batch\_sparge\_step} = 100\% * m_{extract\_kettle} / m_{extract\_lauter\_tun}$$

$$Eff_{batch\_sparge\_step} = 100\% * e * V_{run\_off} / (e *(V_{run\_off} + V_{grain\_absorption} + V_{dead\_space}))$$

e is the extract content (i.e. gravity) of the wort. It is the same for the divisor and dividend and can be eliminated from the equation.

$$Eff_{batch\_sparge\_step} = 100\% * V_{run\_off} / (V_{run\_off} + V_{grain\_absorption} + V_{dead\_space})$$

This is also the efficiency of a no-sparge. In the subsequent discussions the dead space volume will be neglected, but if it is significant it needs to be added to the volume absorbed by the grain.

To calculate the percentage of dissolved extract (efficiency) that a subsequent batch sparge extracts from the grain the same equation can be used but the 100% need to be changes to the percentage extract that is still present in the grain:

$$Eff_{2nd\_run\_off} = (100\% - Eff_{1st\_run\_off}) * V_{run\_off} / (V_{run\_off} + V_{grain\_absorption} + V_{dead\_space})$$

As the number of run-offs increases ever weaker worts are run into the kettle and ever smaller amounts are added to the dividend. The result is a diminishing increase in efficiency.

Measuring Lauter Efficiency (Batch and Fly Sparging)

While mathematical modeling works well for batch sparging, it doesn't work so well for fly sparging due to the dynamic nature of the process. This doesn't mean that it has not been done in commercial brewing, especially by equipment manufacturers, in search for ever more efficient lauter tun designs, but there are too many parameters that affect lauter efficiency which are difficult to measure or keep constant that developing a mathematical model for fly sparging is not a practical option for the home brewer.

Instead a method of estimating the fly sparging efficiency by measuring the dissolved extract, that remains in the spent grain after the run-off is complete, exists. This method is not restricted to fly sparging, it also works for batch sparging. The idea is to dilute the wort that is in the spent grain and measure its gravity/extract. The volume of wort after the water addition can be estimated by the wort absorption rate for the grain and the amount of water that was added. Based on that volume and gravity/extract, the weight of the dissolved extract left in the spent grain can be determined and the ratio between that weight and the initial extract weight in the grain are the brew house efficiency percentage points that were lost during the lauter.

extract/gravity of mash after stirring		water added to spent grain						
		qt/lb				l/kg		
		0.5	1	1.5	2	1	2	
SG	Plato	1.05	2.11	3.16	4.21	1	2	l/kg
1.000	0.0	0	0	0	0	0	0	
1.002	0.5	2	2	3	4	2	2	
1.004	1.0	3	5	6	7	3	4	
1.006	1.5	5	7	9	11	5	7	
1.008	2.0	7	9	12	15	7	9	
1.010	2.5	8	12	15	18	8	11	
1.012	3.0	10	14	18	22	10	14	
1.014	3.5	12	16	21	26	11	16	
1.016	4.0	13	19	24	29	13	18	
1.018	4.5	15	21	27	33	15	21	
1.020	5.0	17	24	30	37	16	23	
1.022	5.5	19	26	33	41	18	25	
1.024	6.0	20	28	36	44	20	28	
1.026	6.5	22	31	40	48	22	30	
1.028	7.0	24	33	43	52	23	32	
1.030	7.5	25	36	46	56	25	35	
1.032	8.0	27	38	49	60	27	37	
1.034	8.5	29	41	52	64	28	39	
1.036	9.0	31	43	55	68	30	42	
1.038	9.5	32	45	58	71	32	44	
1.040	10.0	34	48	62	75	34	47	
1.042	10.5	36	50	65	79	35	49	
1.044	11.0	38	53	68	83	37	51	
1.046	11.5	40	55	71	87	39	54	
1.048	12.0	41	58	75	91	41	56	
1.050	12.5	43	61	78	95	42	59	

Table 2 - Table for estimating the brewhouse efficiency loss in the lauter based on the extract content/specific gravity of the mash water after adding water to the spent grain

$$m_{extract\_left\_in\_lauter} = (V_{water\_added} + V_{grain\_absorbed}) * sg * extract$$

The amount absorbed by the grain can be calculated from the total amount of water used, the amount of wort produced and the amount of extract that was extracted from the grains. The latter is important as it actually increases the volume by about 0.62 l for each kg of dissolved extract. A common absorption ratio for wort in grain is 1.56 l/kg or 0.19 gal/lb.

If an extract potential of 80% is assumed for the grain and the amount of water added is expressed as multiples of the grain weight, the following formula can be used to determine the brewhouse efficiency loss during the lauter based on the added water and gravity of the mash liquid after thorough stirring.

$$Eff_{lost\_in\_lauter} = extract * sg * (A_{grain\_absorption} + R_{water\_added}) / 0.8$$

The grain absorption rate ($A_{grain\_absorption}$) of 1.56 l/kg and the water addition rate (R_{water_added}) need to be entered as l/kg. Table 2 has been created using the above formula and Testing the Lauter Efficiency in Troubleshooting Brewhouse Efficiency shows how to calculate the lauter efficiency from the efficiency loss in the lauter tun.

What affects Lauter Efficiency in batch sparging

The parameters, that affect the batch sparging efficiency, have been discussed in detail in Batch Sparging Analysis. The following is just a brief review:

Grist Size / Starting Gravity

These two are related to each other. The higher the starting gravity of the beer, the the more grain is needed in the mash. In batch sparging, the grist size affects the efficiency by increasing the volume of wort absorbed which is in the divisor of the basic batch sparging efficiency equation:

$$Eff = 100\% * V_{run\_off} / (V_{run\_off} + V_{grain\_absorption})$$

The more grain is used the more wort will be held back by the grain ($V_{grain\_absorption}$) and the lower the efficiency will be. This is one of the reasons why big beers, which generally use more grain per given volume of water, have a lower batch sparge lauter efficiency than smaller beers.

Number of run-offs

While it is obvious that each additional sparge step (run-off) will bring more of the extract from the mash into the boil kettle and thus increase the efficiency, it should be taken into account that, in order to keep the pre boil volume the same, the size of the run-offs has to get smaller as their number is increased. That reduces the efficiency of the sparge steps and as a result a diminishing return is achieved by adding more run-offs. As a result there is a limit to the batch sparging lauter efficiency which is set by the amount of grain and the targeted pre-boil volume. Going from a no-sparge (1 run-off) to a single batch sparge (2 run-offs) gains about 8% lauter efficiency, while going from a single batch sparge to a double batch sparge (3 run-offs) gains only about 2-3%. After that the benefit in lauter efficiency quickly drops with each added sparge step while the amount of work is significantly increased (only ~1% is gained by going from 3 run-offs to 4). The quickly diminishing returns are one reason why at most 3 run-offs are done by the majority of the batch sparging brewers.

Preboil volume / boil-off

Having a larger preboil volume (which will require a larger boil-off to get to the desired post boil extract/gravity) increases the lauter efficiency by increasing the dividend in aforementioned equation. In simple terms, the more water that is available for rinsing out the extract, the higher the lauter efficiency will be. But the boil-off should only be changed within a limited range. Excessively long boil times or excessively strong boils (hourly boil-off of 15% or more) can be detrimental to the beer quality.

run-off sizes in relation to each other

In Batch Sparging Analysis the effect of unequal run-off sizes for a 2 run-off batch sparge has been demonstrated. While it was found that there is an optimum in lauter efficiency when both run-offs are equal, it was also shown that this optimum is fairly flat. Not until one run-off is less than ~30% and the other run-off is more than ~70% of the pre-boil volume is more than 1% of lauter efficiency lost. A 20/80 distribution still yields an efficiency that is only 3% less than the maximum lauter efficiency. The extreme is 0% to 100% and the efficiency for that scenario is the lauter efficiency for the no-sparge (1 run-off) case which is about 7-8% less.

Based on these findings, the run-off sizes for batch sparges should be kept about equal, but only little is lost if they are not perfectly equal.

What affects Lauter Efficiency in fly sparging

The parameters that affect the fly or continuous sparging lauter efficiency are not as easily modeled as for batch sparging. In fly sparging the lauter efficiency suffers if the grain is not rinsed evenly. The main reason for this is called "channeling" where the sparge water finds paths of least resistance (channels) which it will rinse well. The more dense areas between the channels will be sparged less or not at all. The result is a relatively high amount of extract that is held back in these areas.

Channels can form when the run-off speed is to fast. This causes a high pressure gradient between the bottom and the top of the mash which pushes the wort through the grain bed faster than it can sustain. The result is a set mash or a localized compression of the grain bed. In many cases the grain bed will pull away from the sides and open gaps through which the sparge water can flow without much contact to the extract trapped in the grains.

To avoid a set or compacted mash, grain particles should be as big as possible. But this goes against the desire of having a fine crush for increased conversion efficiency (see section Malt Milling). As a result a compromise needs to be struck between a crush that is tight enough for sufficient conversion efficiency yet coarse enough for easy lautering. While the run off speed is inversely proportional to the viscosity of the wort it is also proportional to the square of the average particle size. As a result a smaller particle size (flour, protein) is more detrimental to the flow rate as a high viscosity [Briggs, 2004]. The particle size and viscosity are both affected by performing a mash-out. While it is obvious that a higher temperature wort is less viscous it is less well known that the higher mash temps of a mash out cause more of the protein to form larger flocks which reduces the average particle size. Apparently sufficient calcium ions in the mash also aid the flocculation of proteins and improve the run-off speed [Briggs, 2004]

Special attention should be paid to the formation of the *Oberteig*, a dense layer that consists mostly of small starch granules, beta glucans, proteins and lipids. This layer can form a barrier between the grain bed and the sparge which encourages the formation of channels at its weaker points. To avoid the detrimental affect of that layer to the flow rate it should be kept from forming through raking, cutting or other forms of disturbance.

Another important parameter for fly sparging, which is of no significant importance to batch sparging, is the design of the lauter tun (or mash/lauter tun if the same vessel is used). It is important that it allows for uniform wort collection at the bottom of the grain bed without creating single or preferred drain points. This is best accomplished though a perforated plate on which the grain rests, but many brewers also have had good success with a manifold design consisting of slotted or perforated pipes. In his book *How To Brew*, John Palmer has a complete chapter dedicated to the science of lauter manifold designs [Palmer, 2006].

Like batch sparging, the amount of sparge water that is used also affects the lauter efficiency. The more water that is available for sparging, the more extract can be rinsed from the grain. But it should be kept in mind that the quality of the wort diminishes as lautering continues. The wort's extract content gets lower and lower while the buffering capacity gets weaker. The latter can cause a raise of the pH in the grain bed (especially when brewing liquor high in alkalinity is used for sparging) which leads the the excessive extraction of husk tannins (a major cause of astringent beer taste). This and the desired pre-boil volume limit how much sparging can be done and thus the efficiency of fly sparging. But if done correctly fly sparging yields a better lauter efficiency than batch sparging for the same amount of sparge water.

Related material

- NHC 2010 presentation about efficiency and how to keep it predictable

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