A Homebrewing Perspective on Mash pH I: The Grain Bill

D. Mark Riffe*

(Dated: September 6, 2013)

An overview of the effect that grist composition has on mash pH is presented. In particular, the extensive experimental work on this subject by Kai Troester (KT) is reviewed. Based on KT's results, several models to predict mash pH when using distilled water have been previously developed and incorporated into downloadable spreadsheets (EZ Water, Brun Water, and Kaiser Water) that are available to the homebrewer for calculating adjustments to their brewing water. Here we describe the models used by each of these spreadsheets. Based on our analysis of the KT data, we present an alternative model that may also be used to predict distilled-water mash pH. We then apply the four models to estimate the distilled-water mash pH of representative beers in most of the BJCP style categories; the results provide insight into how the homebrewer can treat distilled water to obtain a suitable mash liquor.

1. INTRODUCTION

Grain, Hops, Yeast, and Water. These are *the* essential ingredients in any beer. As homebrewers we typically spend most of our effort and energy devoted to the first three. And not without good reason, as the grain, hops, and yeast contribute the dominant flavors to our beloved elixer. As Charlie Papazian recommends,"If your water tastes good, just use it." OK, that's not really a direct quote, but for many of us homebrewers this is the approach to water that we adopt, at least as we are first getting into the hobby.

However, if brewing history tells us anything, it is that water is important. This can be inferred from the fact that the various classic beer styles developed in different cities, with the style correlated to the minerals in the local water supplies. The town of Pilsen and its soft water are known for the delicate pilsener; Burton on Trent with its water high in sulfate is renowned for bracing IPAs; Dublin and its bicarbonate water are famous for malty stout. If a homebrewer wants to nail a particular style, he/she may need to deal with water beyond the question, "Does it taste good?"

Case in point. Here in the intermountain west (as in much of the country), we have water that is high in the bicarbonate ion (HCO_3^-), which (in conjunction with Mg^{2+} and/or Ca^{2+}) is responsible for what is known as temporary hardness. All in all, this water is actually pretty good for producing less subtle, darker styles such as American amber ales, browns, porters, and stouts. One can actually produce lighter colored beers as long as they are fairly robust; decent IPAs can be brewed. However, delicate beers such as pilsners and Kölsch definitely suffer; their subtle maltiness does not come through when brewed with our hard intermountain water.

One of the most important ways that water affects the brewing process is through the pH of the mash. When water and grain are combined the resultant mash attains a certain level of acidity, characterized by pH. The water affects the pH through its dissolved ions, the grist through the specific grains that compose the malt bill. Ideally, the pH should be between 5.2 and 5.6.[1] If the mash is outside this range then hop extraction, protein precipitation, yeast performance, and beer clarification can all suffer [1]. Fortunately for the homebrewer, buffers contained in the malted barley usually (but not always!) bring the pH close enough to the ideal range to produce a drinkable beer.

Currently available to the homebrewer are several Excel based spreadsheets (EZ Water [2], Brun Water [3], and Kaiser Water [4]) that can be used to estimate the mash pH from knowledge of the water ions and grist composition.[2] These calculations essentially proceed in two steps. The first step, which accounts for the malt bill, calculates the pH that would result if the grains were mashed in distilled (or reverse osmosis) water. The second step then estimates the shift in pH (from the distilled water pH) that results as a consequence of the ion content of the strike water used in the mash.

It is the first step, the effect of the grist on mash pH, that is the focus of this paper.[3] Because these spreadsheets base their calculations on the experimental work of Kai Troester (KT) [7], we first review his work as it per-

*URL: http://homebrewingphysics.blogspot.com/

[1] I realize that these are fighting words. If you look at any other discussion of the subject of ideal mash pH you will likely see a slightly different range quoted. However, the range of 5.2 to 5.6 appears to be reasonably uncontroversial. By the way, this range applies to the pH of mash liquor that has cooled to near room temperature, which is standard practice for measuring pH.

[2] We also point out the existence of another spreadsheet devoted to brewing water, NUBWS (Nearly Universal Brewing Water Spreadsheet) [5]. However, due to its complexity (the user manual is 66 pages long!) it is probably of interest to only the most technically oriented homebrewers. We therefore have not included it in our survey of brewing-water spreadsheets.

[3] In a follow-up paper, *A Homebrewing Perspective on Mash pH II: Water* [6], we discuss the strike-water contribution to the mash pH.

tains to distilled-water mash pH. We then describe the approach that each spreadsheet takes in implementing KT's results for pH estimation. Based on our analysis of KTs data, we also develop a model that may be used to estimate mash pH. Lastly, we look at predicted distilled-water pH values for example beers from a number of classic beer styles [8]; these pH values provide insight into how the homebrewer can create a suitable mash liquor for successfully brewing beer in each style category.

2. KT EXPERIMENTAL RESULTS

2.1. Grist pH and malt acidity

In order to understand how the grain bill affects mash pH, KT performed a set of experiments where a single grain type is mixed with distilled water and the resulting mash pH determined [7]. Following KT, we refer to this distilled-water mash pH as the grist pH [9]. His results can be summarized as follows. First, mashes with lighter colored base malts (pilsner and 2-row, e.g.) result in the largest grist pHs, typically in the range of 5.7 to 5.8, although wheat malt produced a pH of 6.0, and Rahr 2-row had a pH of 5.6. Darker base malts (Vienna and Munich) result in slightly lower pH values, typically between 5.3 to 5.6. Mashes composed of a single type of crystal malt produce grist pHs in the range of 4.4 to 5.4, with the pH strongly correlated (inversely) to the color of the malt. Dark roasted malts (Carafa, black, e.g.) have mash pHs in a fairly narrow range, 4.6 to 4.8, independent of the specific malt color.[4,5]

A key concept developed in KTs work is malt acidity, which KT has shown to be inversely related to mash pH (as one might expect).[6] In Fig. 1 we show this relationship in a plot of grist pH vs malt acidity. We note that base, crystal, and roast malts (indicated with separate symbols) all fall along the same curve. These experiments were carried out at a mash thickness of 8 L of distilled water per 1 kg of malt. A key observation is that for malt acidity <15 mEq/kg the relationship between acidity and grist pH is very linear.[7] Beyond 15 mEq/kg the relationship deviates from linearity, with the pH data decreasing less rapidly than linear as a function of grain acidity.

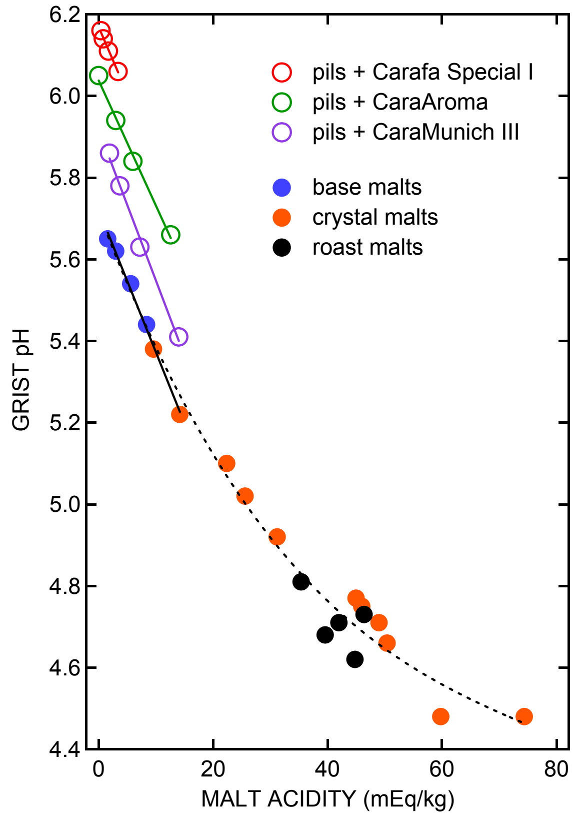

FIG. 1: KT experimental results for grist pH pH_G vs malt acidity A_m. Results for single-malt (base, crystal, and roast) mashes at 8 L/kg are shown as solid circles. Results for mixed-malt (pilsner plus specialty malt) mashes at 4 L/kg are shown as open circles. Mixed-malt data have been shifted vertically for clarity. Solid lines are linear fits to data sets (at acidity levels <15 mEq/kg). Dotted curve is a cubic fit to entire set of single-malt data; see text for details.

As part of his investigation KT also measured the grist pH for mixed-malt mashes consisting of pilsner malt plus one specialty malt (Carafa Special I, CaraAroma, or CaraMunich III). In contrast to the single-malt experiments, these experiments were carried out at a mash thickness of 4 L/kg. The results for grist pH vs (averaged) malt acidity in these three experiments are also plotted in Fig. 1. Importantly, the low-acidity slopes of all four data sets in Fig. 1 are essentially identical, indicating that changes in grist pH vs malt acidity (expressed in mEq/kg) are essentially *independent* of mash thickness.

To quantitatively assess the grist pH as as a function of acidity we have least-squares fit each data set displayed in Fig. 1 with a linear function (for acidity values <15 mEq/kg). The results of this analysis can be characterized by an averaged slope $S_{GpH} = -0.0337$ kg/mEq (-0.0741 lb/mEq). Equivalently, the inverse of this average slope (which KT defines as the malt buffer capacity B_G [9]) is 29.7 mEq/kg (13.5 mEq/lb). We have also fit

[4] The dark roast malts in the KT experiments had color ratings from 300 to 525 °L.

[5] pH values for base malts are for mash thickness of 4 L/kg, while those for crystal and roast were measured at 8 L/kg. Measurements were also made on base malts at 8 L/kg. The average shift in pH upwards from the 4 L/kg measurements is 0.13.

[6] In his experiments, the acidity of each malt is defined by the amount (in mEq) of sodium hydroxide per mass (in kg) or weight (in lb) of grain that is needed to raise the mash pH to a value of 5.7.

[7] An equivalent (Eq) is a measure of ionic content. This is discussed in more detail in [6].

the entire set of single-malt data with a polynomial. An acceptable fit requires a minimum of four terms (cubic fit), which is shown as the dotted curve through the data in Fig. 1. Denoting the grist pH as pH_G and malt acidity as A_m, this curve is described by

$$pH_G = 5.71 - 0.0367A_m + 3.89 \times 10^{-4}A_m^2 - 1.63 \times 10^{-6}A_m^3. \quad (1)$$

In this equation the units of A_m are mEq/kg. Please refer to Appendix A for remarks on symbols and units in equations throughout the paper.

2.2. Malt acidity and grain color

In order for the acidity results of KT to be of use in predicting mash pH, we need to know the acidity of each grain that goes in to the mash. Fortunately, the experimental work of KT allows us to extract approximate relationships for acidity vs malt color for each class of malt (base, crystal, and roast).

The palest (∼2°L [8]) base malts with their largest grist pHs obviously have the lowest values of acidity. The average value of grist pH of these malts is 5.76 [7].[9] In the models for calculating grist pH pale base malt is assumed to give a particular pH, and shifts from this are based on the acidities of the other malts in the grist. We can thus take by fiat the acidity of the lightest base malts to be zero. In Brun Water the base-malt pH is assumed to be 5.75, in Kaiser Water it is taken to be 5.6.[10] and in EZ Water is it assumed to be 5.7,[11]

With increasing color base-malt acidity generally increases. This is shown in Fig. 2(a), which plots acidity A_m vs malt color C_m for the darker base malts in KT's studies. Also plotted is our assumed acidity of zero for the light base malts, which have an average color C_m = 1.9°L. Although the data are somewhat scattered, they can be reasonably well approximated with a linear function, as the three approximations indicate. The solid line is a fit to the data with the constraint that the fit pass through the point representing the light base malts. This fit is given by

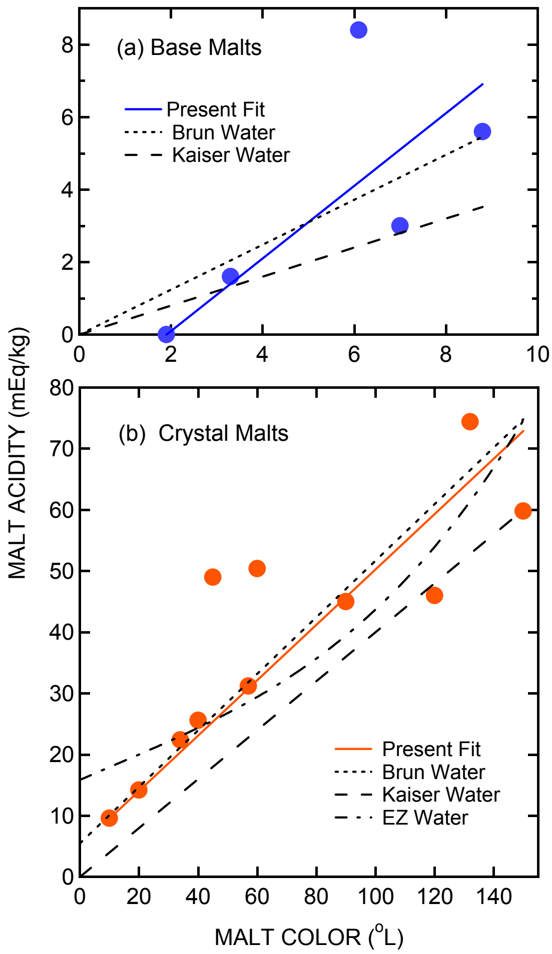

FIG. 2: KT results for malt acidity A_m as vs malt color C_m. (a) Results for darker base malts. Circles are data points (plus an average point for light base malts at 0 mEq/kg for 2°L). Solid line is fit constrained to pass through the 2°L point. Approximations used by Brun Water and Kaiser Water are indicated. (b) Results for crystal malts. Circles are data points. Solid line is fit constrained to match data at lightest values of C_m. Approximations used by EZ Water, Brun Water and Kaiser Water are indicated. See text for details.

$$A_m^{base} = -1.9 + 1.00\, C_m, \quad (2)$$

where we have added the superscript *base* to A_m to indicate that this equation applies to the acidity associated base malts. The dotted line is the approximation used by Brun Water, while the dashed line is the approximation used by KT in developing his equations for Kaiser Water [9].

Figure 2(b) plots malt acidity vs malt color for the crystal malts used in KT's studies. As with the base malts, darker colors generally result in more acidity. Here the solid line is a fit to the data with the constraint that the fit pass (nearly) through the two data points with the lightest color. This line is described by

[8] Malt color is expressed in degrees Lovibond (°L). Don't confuse this with L, the abbreviation for liters!

[9] This average pH value is for a mash thickness of 4 L/kg (1.9 qt/lb), excluding the two outliers in the study, wheat and Rahr 2-row.

[10] To be precise, the pH values of 5.75 in Brun Water and 5.6 in Kaiser Water are for a theoretical base malt that has zero color. In the Brun Water and Kaiser Water models all malts contribute a positive value of acidity.

[11] This pH of 5.7 is for generic base malt. In EZ water one can choose a particular base malt from the KT study; EZ water then uses the measured pH for that particular malt in its calculations.

$$A_m^{crystal} = 5 + 0.453\, C_m, \tag{3}$$

As shown in the figure, the approximation used by Brun Water (dotted curve) is essentially the same as our fit. The approximation KT uses for crystal malts (dashed curve) is the same as that for the darker base malts [in part (a) of Fig. 2]. As discussed below, EZ water does not directly use acidity in its calculation of grist pH; it directly relates the pH for a particular crystal malt to its color using a linear approximation. Using this relationship and the overall curve of grist pH vs acidity in Fig. 1, we have plotted the acidity vs color that EZ Water effectively uses (dot-dashed curve) in its calculations.

As can be deduced from Fig. 1, dark roast malts have an average acidity of 42 mEq/kg (19 mEq/lb). The acidity of the dark-roast malts measured by KT is not correlated with their color [7]. This value of 42 mEq/kg (19 mEq/lb) is used by Brun Water. In developing the model for Kaiser Water KT uses 40 mEq/kg (18 mEq/lb) [9]. For dark roast malts EZ water assumes a grist pH of 4.71, which (via Fig. 1) translates to ∼44 mEq/kg (20 mEq/lb).

3. MODELS OF GRIST pH

The models used by the three brewing spreadsheets for calculating grist pH, while all based on the experimental results of KT discussed above, vary appreciably from one another. In the next three subsections we describe the approaches taken by these spreadsheet in calculating pH_G.

3.1. EZ Water

The most direct approach to calculating pH is taken by the EZ Water spreadsheet [2]. Rather than utilizing malt acidity as an intermediary between malt color and pH, this spreadsheet simply uses a weighted average of grist pHs,

$$pH_G = \sum_m f_m\, pH_m. \tag{4}$$

Here f_m ($\sum_m f_m = 1$) and pH_m are the fraction and grist pH, respectively, of any particular malt m used in the mash. For (generic) base, crystal, and dark roast malts EZ Water expresses pH_m as

$$pH_m^{base} = 5.7, \tag{5}$$

$$pH_m^{crystal} = 5.22 - 0.00504\, C_m, \tag{6}$$

and

$$pH_m^{roast} = 4.71, \tag{7}$$

As mentioned above, instead of using the generic base malt pH value of 5.7, in EZ Water one has the option of using a particular base-malt pH_m^{base} value associated with any of the base malts measured in KT's experiments.

3.2. Brun Water

Grist pH is obtained in Brun Water [3] by first calculating an average acidity for the grist and then using the acidity to obtain the pH. The formula utilized by Brun Water to do this is

$$pH_G = 5.75 - \frac{0.17}{R} \sum_m f_m\, A_m, \tag{8}$$

which is very similar to an equation proposed by KT in his initial analysis [7]. Here R is the mash thickness. Obviously, the factor of $1/R$ makes the pH shift arising from malt acidity depend upon the mash thickness. However, as discussed above in conjunction with Fig. 1, KT's data indicate that the pH shift vs acidity is independent of the thickness R. In Eq. (8) the sum $\sum_m f_m A_m$ is the average acidity of the grist. To connect the pH shift produced by this term to our above analysis we note for a mash thickness of 4 L/kg that the ratio $-0.17/R$ equals -0.0425 kg/mEq. This value is somewhat larger (in magnitude) than the average slope $S_{GpH} = -0.0337$ kg/mEq we obtained from our analysis of the data in Fig. 1. In his original analysis KT proposed using 0.14 (rather than 0.17). For $R = 4$ L/kg this gives $-0.14/R = -0.035$ kg/mEq, which is essentially the same as our slope S_{GpH}.

In order to utilize Eq. (8) one must have expressions for the acidity of each malt type. For base, crystal, and roast malts Brun Water respectively uses

$$A_m^{base} = 0.62\, C_m, \tag{9}$$

$$A_m^{crystal} = 5.5 + 0.46\, C_m, \tag{10}$$

and

$$A_m^{roast} = 42. \tag{11}$$

We note that the dotted lines in parts (a) and (b) of Fig. 2 were calculated using Eqs. (9) and (10), respectively.

3.3. Kaiser Water

The approach used by the Kaiser Water spreadsheet [4] in calculating pH_G is rather more indirect than that of either EZ Water or Brun Water.[12] In Kaiser Water the user specifies the *beer* color C_B of a standard beer and the fraction f_C^{roast} of the specialty malt color that comes from roast malt. The specific equation used by Kaiser water is

$$pH_G = 5.6 - \frac{C_B}{12}[0.21(1 - f_C^{roast}) + 0.06 f_C^{roast}]. \quad (12)$$

The two terms inside the brackets are contributions to the grist pH from base/crystal malts and dark roast malts, respectively. Although not obvious, KT does use his acidity results in the development of Eq. (12). Details of this development [and the significance of the constants contained within Eq. (12)] can be found in Ref. [9].

With Kaiser Water the user must first independently calculate both f_C^{roast} and C_B. The fraction of malt color coming from roast malts is given by

$$f_C^{roast} = \frac{\sum_m f_m^{roast} C_m^{roast}}{\sum_m f_m C_m}. \quad (13)$$

Here the numerator sum is only over dark roast malts, while the denominator sum is over all malts in the grist. Beer color C_B is calculated from the color of the malts via the Morey equation

$$C_B = 1.49 \left(\frac{w_G}{V_{pb}} \sum_m f_m C_m \right)^{0.686}, \quad (14)$$

where w_G is the total weight of the grist and V_{pb} is the post boil volume of the wort. In the Kaiser Water model the values for the standard beer are taken to be 10 lbs and 5 gallons, respectively [9]. We note in passing that the quantity in parenthesis in Eq. (14) is known as the total malt color (of the wort). It has units of MCU.[13]

3.4. An Alternate Model

Based upon our above analysis of KT's data we suggest a model akin to that used by Brun Water, but without any mash-thickness dependence to the pH shift. We propose that the grist pH be estimated using

$$pH_G = 5.72 + S_{GpH} \sum_m f_m A_m, \quad (15)$$

where base, crystal, and roast malt acidities are given by Eqs. (2), (3), and (11) respectively. We remind the reader that our value for S_{GpH} is -0.0337 kg/mEq. The value of 5.72 in Eq. (15) is our estimation for the average pH for light base malts at a typical homebrewing mash thickness of 3 L/kg (1.4 quarts/lb). We obtain this from the average light-base-malt grist pH of 5.76, but then adjusted using KT's results for the mash-thickness dependence of the pH when using pilsner malt [7].

4. GRIST pH OF CLASSIC BEER STYLES

Due to the absence of Ca^{2+} ions, one should never carry out an actual mash with distilled water. However, it is very insightful to look at values of pH_G for representative beers in each of the classic beer-style categories (in the present case as defined by the BJCP [11]). To this end, and to see how the four models discussed here compare, we have calculated pH_G for a predominant majority of the recipes in the book *Brewing Classic Styles* by Zainasheff and Palmer [8]. The results of this exercise are shown in Fig. 3, which plots grist pH as a function of beer color.[14] In the figure the data are divided into two subsets of beers, those that do and those that do not use roast malt in their recipes.

As shown in Fig. 3, EZ Water, Brun Water, and our present model predict grist pH values that are typically within 0.1 of each other. On average EZ water and Brun Water respectively predict slightly higher and slightly lower values than our model. The predictions of Kaiser Water are significantly lower than the other three models. This can be traced to the zero-beer-color pH value of 5.6 in the Kaiser Water model [see Eq. (12)]. In the Kaiser Water spreadsheet the user has the ability to change this to some other value. If a value of 5.77 is used instead, then the Kaiser Water results come very close (on average) to the other three models. We also note that the Kaiser Water prediction of a linear relationship between grist pH and beer color for beers that do not use roast malt comes from the approximation that the acidity as a function of malt color is the same for base and crystal malts [see previous discussion of Figs. 1 and 2 and Eq. (12)].

So what can we learn from the data shown in Fig. 3? For the sake of this discussion let's assume that (i) we desire to build our mash water by starting with distilled (or reverse-osmosis water), (ii) our target mash pH is 5.4 (in the middle of the ideal range of 5.2 to 5.6), and

[12] The discussion here is for version 1.58 of Kaiser Water [4]. Some earlier versions (1.52, e.g.) use a substantially different model [10] to estimate grist pH.

[13] MCU = malt color unit.

[14] The results are also presented in Tables II and III, which are discussed in Appendix B

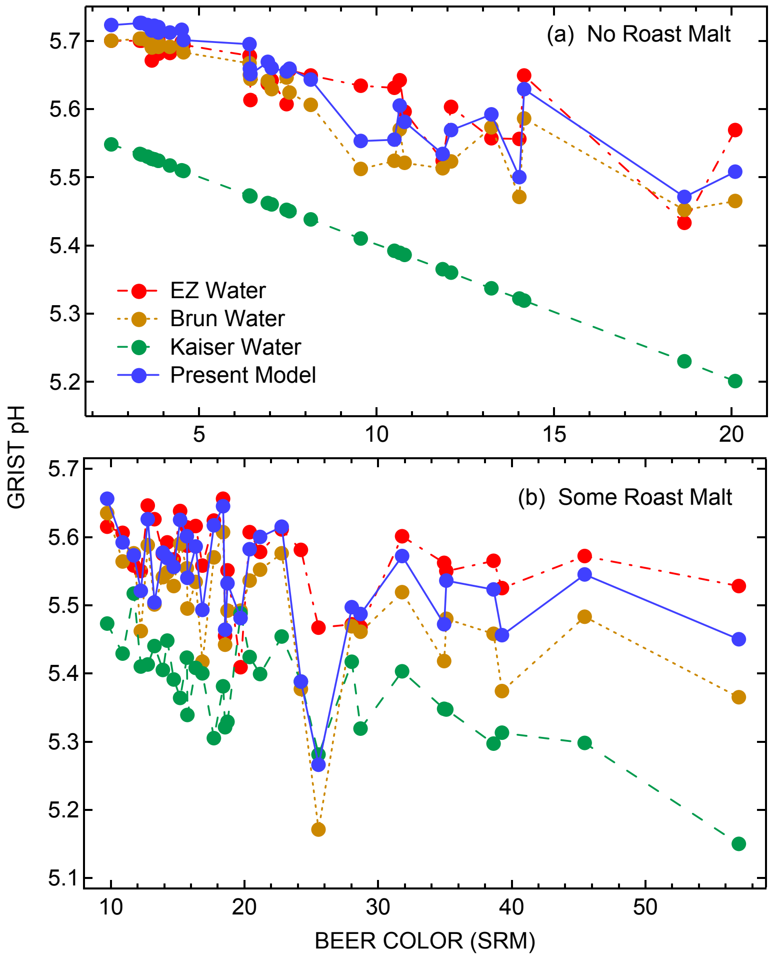

FIG. 3: Calculated grist pH pH_G vs beer color C_B of representative beers from the BJCP style categories. Line types through data points indicate models: EZ Water - dot-dashed line, Brun Water - dotted line, Kaiser Water - dashed line, present model - solid line. $R = 4$ L/kg (Brun Water). (a) pH_G values for beers that do not use dark roast malt. (b) pH_G values for beers that use some dark roast malt. The beers and calculated pH values are listed in Table II.

(iii) the EZ Water, Brun Water, and present models are more accurate than the Kaiser Water model. First, we see from Fig. 3 for nearly all beers with color ratings less than ∼20°L that the mash water will need to be acidified to some extent in order to hit this target. This can be done by adding acid to the mash water (popular choices are phosphoric or lactic acid, both available from homebrewer suppliers). However, if one starts with distilled water, one should first add some Ca to the mash. The canonical way to do this is by adding $CaSO_4$ and/or $CaCl_2$. Adding either of these will also lower the mash pH, and so for some beers a $CaSO_4/CaCl_2$ addition may be sufficient to put the mash pH on target.[15] However, for the lightest colored beers the addition of enough $CaSO_4/CaCl_2$ to sufficiently lower the pH may result in undesirable consequences with regards to the flavor of the resulting beer. In these cases an acid addition is warranted. Such an addition can come from a commercial acid solution. Alternatively, acid can be added by replacing part of the base malt with acidulated malt (which is pilsner malt infused with lactic acid). Another thing to notice from Fig. 3 is that only in rare cases (the S. English Brown beer at 25.5 SRM) will the strike water need to be made more alkaline [even after a (minimal) $CaSO_4/CaCl_2$ addition]. This is a good thing for the homebrewer, as there are generally more difficulties associated with raising the mash pH as compared to lowering it.

5. SUMMARY AND CONCLUSIONS

We have presented an overview of how the grain bill affects the pH of the mash. Specifically, we have (i) re-

[15] A minimum addition for proper mash activity (∼50 ppm Ca^{2+}) will lower the mash pH by ∼0.08.

TABLE I: Symbols and associated units used in all equations. The symbol "–" indicates the quantity is unitless.

Symbol	Meaning	Units
pH_G	grist pH	–
pH_m	single malt type grist pH	–
pH_m^{base}	base malt grist pH	–
$pH_m^{crystal}$	crystal malt grist pH	–
pH_m^{roast}	dark roast malt grist pH	–
A_m	malt acidity	mEq/kg
A_m^{base}	base malt acidity	mEq/kg
$A_m^{crystal}$	crystal malt acidity	mEq/kg
A_m^{roast}	dark roast malt acidity	mEq/kg
S_{GpH}	slope of pH_G vs A_m	kg/mEq
B_G	malt buffering capacity ($= S_{gpH}^{-1}$)	mEq/kg
C_m	malt color	°L
C_m^{roast}	roast malt color	°L
f_m	fraction of particular malt in grist	–
f_m^{roast}	fraction of particular roast malt in grist	–
R	mash thickness	L/kg
C_B	beer color	SRM
f_C^{roast}	fraction of color from roast malts	–
w_G	total weight of grist	lb
V_{pb}	post-boil wort volume	gallon

viewed the experimental work of Kai Troester [7] regarding grist pH (mash pH when using distilled water), (ii) described existing models for estimating grist pH used in three downloadable spreadsheets (EZ Water [2], Brun Water [3], Kaiser Water [4]) that are available to the homebrewer for making water adjustments, (iii) developed our own (similar) model for estimating grist pH, and (iv) used these four models to predict grist pH for representative beers from most of the BJCP style categories. As it is increasingly popular practice for homebrewers to start with distilled (or reverse-osmosis) water when building their brewing liquor, knowing the (hypothetical) mash pH that would result when using distilled water is useful when considering adjustments to the water. In our follow-up paper, we discuss these adjustments in detail [6].

Lastly, we caution the homebrewer with regards to the use of these models. As with any numerical estimations used by homebrewers (hop alpha-acid-utilization calculations come to mind), these models are only going to give the homebrewer a ball-park value for the quantity of interest; for the case at hand, we guess that the standard deviation for pH_G is in the vicinity of ± 0.1. The differences between calculated and actual pH values will largely be due to the averaged nature of the equations that describe malt acidity as a function of malt color. One should keep in mind that any particular grist may contain malts that are not particularly close to the average. As I like to say, "Be smarter than the tool you are using." This applies to a hammer as well as to a simplified predictive model of a complex chemical process.

APPENDIX A: SYMBOLS AND UNITS

In equations that contain fitted parameters, such as Eq. (1), the fitted parameters generally have units. For example, in Eq. (1) because A_m has units of mEq/kg and pH is unitless, each number multiplying a term A_m^n (n an integer) has implied units of (kg/mEq)$^{-n}$. At some level it would have been best to explicitly include the parameters' units when expressing these equations. On the other hand, leaving the units out (as we have done) makes the formatting of the equations somewhat cleaner. However, when writing these equations in this manner, one needs to be careful to use the correct units for terms such as A_m. And so rather than reminding the reader of the units associated with the symbols in each equation every time they come up, in Table I we list all symbols, their meaning, and the units that must be used for them in the equations throughout this paper.

APPENDIX B: pH_G VALUES FOR CLASSIC BEER STYLES

In Tables II and III we present our calculated values of grist pH for representative beers (from *Brewing Classic Styles* [8]) in most of the BJCP style categories. For the Kaiser Water model and our proposed model, application to the recipes is straightforward. For Brun Water one must choose the mash thickness R. We have chosen 4L/kg, the mash thickness used by KT in most of his experiments. For EZ water a couple of choices must be made: (i) for the base malt we have simply used generic base malt for all base malts (including wheat), and (ii)

TABLE II: Calculated values of pH_G for recipes with no dark roast malt. Recipes are from *Brewing Classic Styles* [8]. Beer style, BJCP category, recipe name, beer color, and four values of pH_G (one from each model: EZW = EZ Water, BW = Brun Water, KW = Kaiser Water, PM = our present model) are tabulated. $R = 4$ L/kg (Brun Water). Beer color is calculated via Eq. (14) using the total grist weight in each recipe and a post-boil wort volume of 6 gallons.

Beer style	BJCP category	Recipe name	Beer color (SRM)	EZW pH_G	BW pH_G	KW pH_G	PM pH_G
Berliner Weisse	17A	Saures Biergesicht	2.6	5.70	5.70	5.55	5.72
German Pilsner	2A	Myberger	3.3	5.70	5.70	5.53	5.73
Belgian Golden Strong Ale	2A	It's All in the Details	3.4	5.70	5.70	5.53	5.73
Weizen/Weissbier	15A	Harold-is-Weizen	3.6	5.70	5.70	5.53	5.72
Koelsch	6C	JZ Frueh	3.7	5.69	5.70	5.53	5.72
Bohemian Pilsner	2B	To George!	3.7	5.67	5.69	5.53	5.72
Witbier	16A	Wittebrew	3.7	5.69	5.70	5.53	5.72
Blonde Ale	6B	Call Me!	3.7	5.70	5.70	5.53	5.72
Munich Helles	1D	Munich Grosses Bier	3.9	5.68	5.69	5.52	5.71
American Wheat	6D	Kent's Hollow Leg	3.9	5.70	5.70	5.52	5.72
Saison	16C	Raison d'Saison	4.2	5.68	5.69	5.52	5.71
Belgian Tripel	18C	Strict Observance Tripel	4.5	5.70	5.69	5.51	5.72
Belgian Blonde Ale	18A	Lefty Blonde	4.6	5.69	5.68	5.51	5.70
Imperial IPA	14C	Hop Hammer	6.4	5.68	5.67	5.47	5.69
American Pale Ale	10A	American Pale Ale	6.4	5.68	5.65	5.47	5.66
Dortmunder Export	1E	Expat Export	6.5	5.61	5.64	5.47	5.65
American IPA	14B	Hoppiness is an IPA	6.9	5.64	5.64	5.46	5.67
American Pale Ale	10A	APA with Caramel	7.0	5.64	5.63	5.46	5.66
Maibock/Helles Bock	5A	Angel Wings	7.5	5.61	5.65	5.45	5.65
Extra Special Bitter	8C	Programmer's Elbow	7.6	5.66	5.62	5.45	5.66
Belgian Pale Ale	16B	Antwerp Afternoon	8.1	5.65	5.61	5.44	5.64
Ordinary Bitter	8A	No Short Measure	9.6	5.63	5.51	5.41	5.55
Special Bitter	8B	I'm Not Bitter, I'm Thirsty	10.5	5.63	5.52	5.39	5.55
English IPA	14A	Biere de l'Inde	10.7	5.64	5.57	5.39	5.61
Belgian Specialty Ale	16E	Val d'Or	10.8	5.60	5.52	5.39	5.58
Oktoberfest/Maerzen	3B	Munich Madness	11.9	5.52	5.51	5.36	5.53
Belgian Dubbel	18B	Black Scapular Dubbel	12.1	5.60	5.52	5.36	5.57
Eisbock	5D	Steve's Fifty	13.2	5.56	5.57	5.34	5.59
Flander's Red Ale	17B	Rouge Flamande	14.0	5.56	5.47	5.32	5.50
English Barley Wine	19B	Hard and Hardy	14.2	5.65	5.59	5.32	5.63
Doppelbock	5C	Mr. Maltinator	18.7	5.43	5.45	5.23	5.47
Belgian Strong Dark	18E	Brew like a Homebrewer	20.1	5.57	5.47	5.20	5.51

for darker base and lighter roast malts that are not in EZ Water's menu [such as Melanoidin (28°L) and Special Roast (50°L) malts] we entered these as if they were Munich malt.

[1] G. Noonan, *New Brewing Lager Beer* (Brewers Publications, 2012).
[2] *EZ Water Calculator 3.0.2* (2012), URL `http://www.ezwatercalculator.com/`.
[3] M. Brungard, *Brun Water Calculator 1.14us* (2013), URL `https://sites.google.com/site/brunwater/`.
[4] K. Troester, *Kaiser Water Calculator US units 1.58* (2012), URL `http://braukaiser.com/documents/`.
[5] A. J. deLange, *Nearly Universal Brewing Water Spreadsheet* (2009), URL `http://wetnewf.org/`.
[6] D. M. Riffe, *A Homebrewing Perspective on Mash pH II: Water* (2013), URL `http://homebrewingphysics.blogspot.com/`.
[7] K. Troester, *The Effect of Brewing Water and Grist Composition on the pH of the Wort* (2009), URL `http://braukaiser.com/documents/effect_of_water_and_grist_on_mash_pH.pdf`.
[8] J. Zainasheff and J. J. Palmer, *Brewing Classic Styles* (Brewers Publications, 2007).
[9] K. Troester, *Beer Color to Mash pH (2.0)* (2012), URL `http://braukaiser.com/wiki/index.php?title=Beer_color_to_mash_pH_(v2.0)/`.
[10] K. Troester, *Beer Color, Alkalinity and Mash pH* (2010), URL `http://braukaiser.com/wiki/index?title=Beer_color,_alkalinity_and_mash_pH`.
[11] *BJCP Style Guidelines* (2012), URL `http://www.bjcp.org/stylecenter.php/`.

TABLE III: Calculated values of pH_G for recipes that utilize some dark roast malt. See caption to Table II for details.

Beer style	BJCP category	Recipe name	Beer color (SRM)	EZW pH_G	BW pH_G	KW pH_G	PM pH_G
Biere de Garde	16D	No Culottes, No Probleme	9.7	5.61	5.64	5.47	5.66
California Common	7B	Uncommonly Lucky	10.9	5.61	5.56	5.43	5.59
Vienna Lager	3A	North of the Border Vienna	11.7	5.56	5.58	5.52	5.57
Scottish 70/-	9B	Scottish 70/-	12.3	5.55	5.46	5.41	5.52
Weizenbock	15C	Trick or Treat Bock	12.8	5.65	5.59	5.41	5.63
N. English Brown	11C	Nutcastle	13.3	5.63	5.50	5.44	5.50
Dunkelweizen	15B	Trigo Oscuro	13.9	5.58	5.54	5.40	5.58
Duesseldorf Altbier	7C	Cowboy Alt	14.2	5.59	5.55	5.45	5.57
Roggenbier	15 D	J.C.'s Roggenbier	14.7	5.57	5.53	5.39	5.56
Strong Scotch Ale	9E	McZainasheff's Wee	15.2	5.64	5.59	5.36	5.62
North German Altbier	7A	Alt.Bier.Recipe	15.7	5.61	5.55	5.42	5.60
American Amber	10B	West Coast Blaster	15.7	5.59	5.50	5.34	5.54
Irish Red Ale	9D	Ruabeoir	16.4	5.62	5.53	5.41	5.59
Mild	11A	Through a Mild Darkly	16.9	5.56	5.42	5.40	5.49
American Barley Wine	19C	Old Monster	17.7	5.62	5.57	5.31	5.62
Old Ale	19A	Old Treacle Mine	18.4	5.66	5.61	5.38	5.65
Traditional Bock	5B	Little Barnabas	18.6	5.45	5.44	5.32	5.46
Flanders Brown/Oud Bruin	17C	Flanders Brown Ale	18.7	5.55	5.49	5.33	5.53
Munich Dunkel	4B	Old Dark Bear	19.7	5.41	5.49	5.49	5.48
American Brown	10C	Dirty Water Brown	20.4	5.61	5.54	5.42	5.58
American Brown	10C	Janet's Brown Ale	21.2	5.58	5.55	5.40	5.60
Schwarzbier	4C	German Schwarzbier	22.8	5.61	5.58	5.45	5.62
Brown Porter	12A	Who's Your Taddy Porter	24.2	5.58	5.38	5.39	5.39
S. English Brown	11B	Nutty Man Brown Ale	25.5	5.47	5.17	5.28	5.27
Schwarzbier	4C	Doing it in the Dark	28.0	5.47	5.47	5.42	5.50
Baltic Porter	12C	Zek's Porter	28.7	5.47	5.46	5.32	5.49
Dry Stout	13A	Cerveza de Malto Seca	31.8	5.60	5.52	5.40	5.57
Oatmeal Stout	13C	McQuaker's Oatmeal Stout	34.9	5.56	5.42	5.35	5.47
Robust Porter	12B	Black Widow Porter	35.1	5.55	5.48	5.35	5.54
Foreign Extra Stout	13D	Extra Lying Stout	38.6	5.56	5.46	5.30	5.52
Sweet Stout	13B	Triple-X	39.3	5.52	5.37	5.31	5.46
American Stout	13E	Reprobate Stout	45.5	5.57	5.48	5.30	5.54
Russian Imperial Stout	13F	The Czar's Revenge	57.0	5.53	5.37	5.15	5.45