MBAA TQ doi:10.1094/TQ-47-2-0623-01

Maximizing Hop Aroma and Flavor Through Process Variables

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ABSTRACT

Craft brewers face the challenge of creating beers with high levels of bitterness and hop flavor and aroma from an extremely limited supply of aroma hops. This paper presents the findings of an experiment conducted by 35 breweries in the Rock Bottom Breweries group in which beers with identical recipes (the same gross malt and hop bill) were brewed, with the only variation in process being the time and manner of the finishing hop additions. Breweries were assigned one of four final hop procedures: 1) 1 lb of hops per bbl for 50 min of postboil kettle residence; 2) 1 lb of hops per bbl for 80 min of postboil kettle residence; 3) 0.5 lb of hops per bbl for 80 min of postboil kettle residence and 0.5 lb of hops per bbl as dry hops; or 4) 1 lb of hops per bbl as dry hops only, with no final kettle addition. In addition, the sulfate level in the brewing water of each beer was noted. The beers were then assessed by a sensory evaluation panel. We were able to show that process variables in terms of time and manner of hop addition had statistically significant effects on the perception of bitterness, hop aroma, hop flavor, citrus character, fruit character, grassy character, and malt. We also found a statistically significant negative correlation between the intensity of hop flavor and level of sulfate in the brewing water.

Keywords: dry hops, hop aroma, hop flavor, hops, sulfate

SÍNTESIS

Cerveceros artesanos enfrentan el reto de crear cervezas con una alta intensidad de amargor y sabor y aroma a lúpulo, a pesar de un suministro extremadamente limitado de lúpulos tipo aroma. Aquí presentamos los resultados de un experimento conducido en 35 cervecerías artesanas del grupo Rock Bottom Breweries con "recetas" idénticas (las mismas proporciones de malta y de lúpulo en el mosto), donde la única variación en el proceso fueron el tiempo y manera de hacer las adiciones del último lúpulado. Se les asignó a las cervecerías uno de cuatro procedimientos para la última adición: 1) 1 lb de lúpulo por bbl con 50 min de hervor final; 2) 1 lb de lúpulo por bbl con 80 min de hervor final; 3) 0,5 lb de lúpulo por bbl con 80 min de hervor final más 0,5 lb de lúpulo por bbl agregado como lúpulo seco ("dry hopping"); o 4) 1 lb de lúpulo por bbl agregado como lúpulo seco, sin ninguna adición en los últimos minutos del hervor. También se tomó nota del contenido de sulfatos en el agua cervecera en cada caso. Las cervezas fueron evaluadas por un panel de catadores. Se pudo demostrar que estos variables en la adición del último lúpulado tuvo un efecto significativo sobre la percepción de la intensidad del amargor, el aroma a lúpulo, sabor a lúpulo, carácter cítrico, carácter frutal, carácter gramíneo, y malta. También se encontró una correlación negativa entre la intensidad del sabor ("flavor") a lúpulo y el nivel de sulfatos en el agua cervecera.

Palabras claves: aroma a lúpulo, lúpulado en seco, lúpulo, sabor (flavor) a lúpulo, sulfatos

Introduction

American craft brewers often brew beers with very intense hop flavors and aromas, yet there is little agreement among small brewers about how best to attain these high levels. Furthermore, changes in brewing processes made in an attempt to increase hop aroma and flavor are often made based on anecdotal evidence or the simple belief that if some is good then more is better. Few small breweries have taken the time to methodically investigate which brewing processes truly result in greater hop aroma and flavor, and as a result, the amount of hops used, as well as the methods of use, vary widely within the craft brewing industry.

To determine which hopping processes were most effective at generating hop flavor and aroma, all 35 breweries in the Rock Bottom Breweries group brewed the same beer but varied the time and manner of the final hop addition. We had three initial hypotheses: 1) kettle hops added at the end of the boil would give more hop flavor than dry hops; 2) dry hops would give more hop aroma than kettle hops; and 3) allowing kettle hops to steep longer in the hot wort postboil would result in more hop character than if the hops were separated and the wort cooled more quickly. We also wanted to test how effective a combination of late kettle hops and dry hopping would be at developing both hop flavor and aroma.

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Based on a paper presented at the 122nd Anniversary Convention of the Master Brewers Association of the Americas, La Quinta, CA, October 2009.

Materials and Methods

Beer

An American IPA was chosen due to its popularity in the American craft brewing industry. Furthermore, the intense hop flavor and aroma of this style of beer best suited the goals of the experiment. All the breweries brewed the same recipe, and we attempted to control for as many variables as possible. The following recipe was followed by all breweries: OG 15°P, FG 2.5–3.0°P (66.6–69.3% RDF).

Malt Bill

The malt bill was 95% 2-row base malt and 5% Weyermann Munich 1. Due to the wide geographic distribution of the Rock Bottom Breweries, financial constraints prevented our breweries from using the same base malt. Therefore, four different base malts were used depending on the location of and malt supplier for each brewery.

Hop Bill

The first hop addition was at 0 min (90-min boil) and consisted of 2.8 oz of Nugget per bbl at 12.5% alpha. The second hop addition was at 60 min and consisted of 4.4 oz of Amarillo per bbl at 8.4% alpha. For the final hop addition, one of four procedures was assigned to each brewery:

1) Short: 1 lb of Amarillo per bbl at end of boil, with 50 min of postboil residence
2) Long: 1 lb of Amarillo per bbl at end of boil, with 80 min of postboil residence
3) Half: 0.5 lb of Amarillo per bbl at end of boil, with 80 min of postboil residence and 0.5 lb of Amarillo per bbl as dry hops
4) Dry: 1 lb of Amarillo per bbl as dry hops, with no kettle hops

Postboil residence time refers to the length of time from the moment the hops were added to the kettle at the end of boil to the point at which the wort was no longer in contact with the hops. For our breweries, this meant from the end of boil to the end of kettle knock out. Every brewery used the same lot number and crop year of Nugget and Amarillo hops for all hop additions.

Brewing

Every brewery brewed the beer within the same week. Mash temperature was determined at each individual brewery to achieve the target 2.5–3.0°P final gravity. Each brewery adjusted its water chemistry for proper mash and wort pH, as per its usual methods (this includes acidification of hot liquor and salt additions.) The sulfate levels of each brewery's water (taking into account salt and acid additions) were determined. Three yeast strains were used: 2 breweries used American ale yeast (Wyeast 1272), 4 breweries used California ale yeast (Wyeast 1056), and 22 breweries used Scottish ale yeast (Wyeast 1728). All beers were fermented at 20°C, and the same cooling procedures were used at every brewery. On the last day of attenuation, with less than 2°P until final gravity, dry hops (if assigned) were added as pellets through the top of the fermenter. After attenuation, all beers were left at 20°C for 2 days. Three days after attenuation the beer was cooled to 10°C, and the next day was cooled to 0–2°C. All beers, except one, were fined for clarity, and all beers were carbonated to 2.35 vol of CO_2. Once carbonated, all beers were bottled within 24 h and shipped overnight within 2 days of bottling to Colorado. All beers arrived in Colorado within 3 days of sensory analysis. (Note: we only included 28 of 35 breweries in the study—3 breweries did not participate, and 4 beers were removed from the study due to off-flavors.)

Sensory Analysis

Sensory analysis was performed at the Rock Bottom Brewery in Westminster, CO. We had four sessions (morning and afternoon on consecutive days), and in each session each taster sampled 12–14 beers. A total of 34 tasters participated over the two days, some for more than one session. The taste panels were double-blind: neither the taster nor the steward knew the identity of the beers. At the beginning of each session, all tasters scored two "calibration beers" that had been previously scored

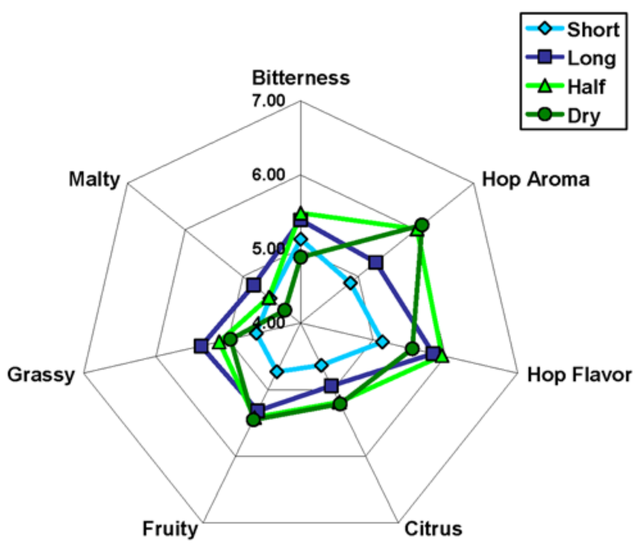

Figure 1. Mean scores for each characteristic analyzed for four hopping procedures. The graph metric is from 4 to 7.

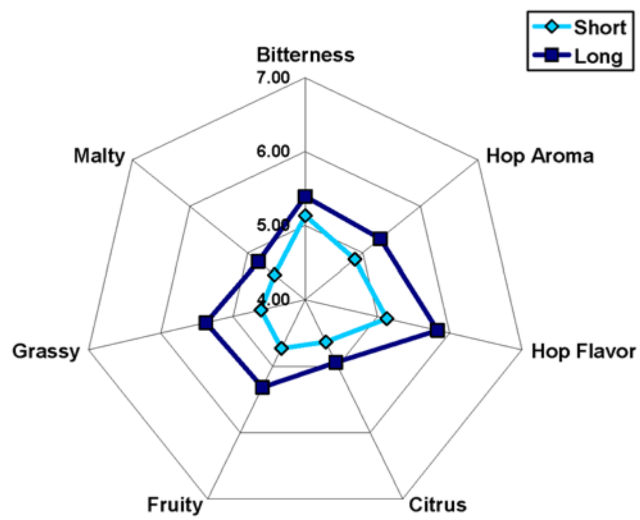

Figure 2. Comparison of results of short- and long-hopping procedures. The graph metric is from 4 to 7.

Table 1. Statistical comparison of long- and short-hopping procedures

Characteristic	Amount by which long > short (%)	Confidence level (%)
Hop aroma	9.0	95[a]
Hop flavor	13.7	99
Fruity	12.4	95
Grassy (piney)	16.4	99

[a] A priori *t* test.

by the author and one other brewer, so tasters could calibrate their scores into a standardized range. Each beer was scored on a 1–10 scale on seven different characteristics:

1) Bitterness: The level of perceived bitterness on a 0–10 scale, with 0 representing no bitterness and 10 representing 100 IBU. (Each unit on the scale represented 10 IBU.)
2) Hop Aroma: The intensity of the hop aroma of the beer, with 0 representing no hop aroma and 10 representing an overwhelmingly strong hop aroma.
3) Hop Flavor: The intensity of the hop flavor of the beer, with 0 representing no hop flavor and 10 representing an overwhelmingly strong hop flavor.
4) Malty: The intensity of the malt character of the beer, with 0 representing no perceptible malt character and 10 representing an overwhelmingly malty beer.
5) Citrus: The intensity of hop-derived citrus notes in both the flavor and aroma of the beer. These notes include grapefruit, lemon, and orange.
6) Fruity: The intensity of hop-derived fruity notes in both the flavor and aroma of the beer. These notes include mango, pineapple, apple, and pear.
7) Grassy/Vegetal: The intensity of hop-derived grassy/vegetal notes in both the flavor and aroma of the beer. These notes include grass, straw, vegetal, and pine.

Each beer was tasted by at least 10 panelists, and most were tasted by 14–17 panelists. We had a total of 444 taster–beer pairs. IBU values and pH were measured by White Labs.

Statistical Methods

Single-factor analysis of variance testing was used to analyze the differences among the four hopping procedures. Tests for statistical significance were carried out using a priori *t* tests for the specific hypotheses we wanted to test and Tukey's post-hoc test for all other results. Correlation coefficients with *t* tests for statistical significance were used elsewhere to determine the importance of relationships among results and processes.

Results and Discussion

Hop Addition Procedures

The mean scores for each characteristic for the four procedures were graphed on a spider graph (Fig. 1). The spider graph metric is from 4 to 7, not 1 to 10. This is for expository purposes only, to make the differences among the methods more clear. The graph shows obvious differences among the methods for hop aroma, hop flavor, citrus, fruity, and grassy and smaller differences for malty and bitterness.

Figure 2 compares the results for the short- and long-hopping procedures. Our initial hypothesis was that longer postboil residence of finish hops would result in more hop character in terms of both flavor and aroma. This is in contrast to a commonly voiced opinion among craft brewers that volatile hop oils are quickly driven out of hot wort, and therefore, wort cooling should happen as quickly as possible after the addition of final hops at

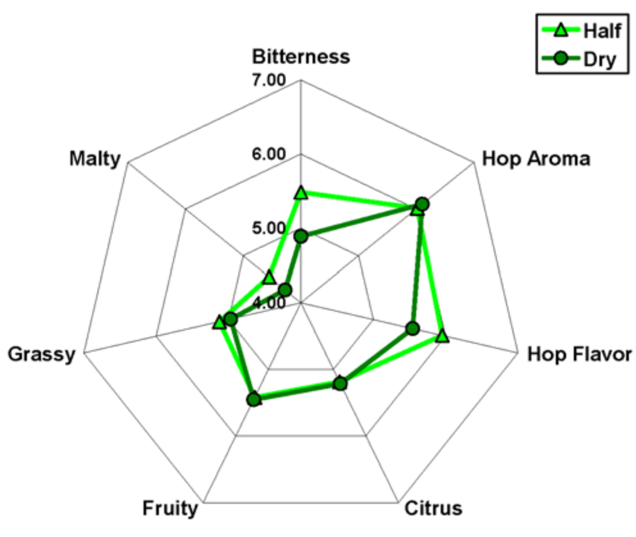

Figure 3. Comparison of results of half- and dry-hopping procedures. The graph metric is from 4 to 7.

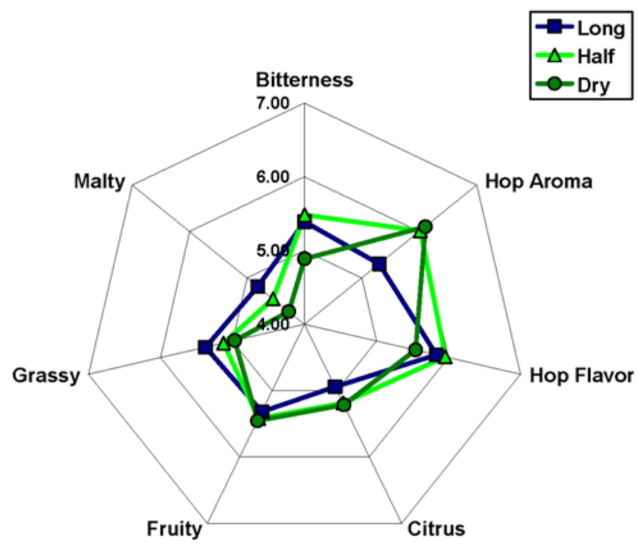

Figure 4. Comparison of results of long-, half-, and dry-hopping procedures. The graph metric is from 4 to 7.

Table 2. Statistical comparison of half- and dry-hopping procedures

Characteristic	Amount by which half > dry (%)	Confidence level (%)
Hop flavor	7.4	99
Bitterness	12.0	95

Table 3. Statistical comparison of long- and dry-hopping procedures

Characteristic	Amount by which long > dry (%)	Confidence level (%)
Hop flavor	5.2	95[a]
Bitterness	10.2	95
Malty	12.7	95

[a] A priori *t* test.

Table 4. Statistical comparison of half- and dry-hopping procedures to long-hopping procedure

Hop aroma comparison	Increase over long (%)	Confidence level (%)
Half > long	13.6	99
Dry > long	15.1	99

or near the end of boil to preserve the hop flavor and aroma in the wort. The first thing we noted is that the long-hopping procedure circumscribed the short procedure, meaning longer postboil residence seemed to give more hop flavor, aroma, and bitterness. Table 1 summarizes the statistically significant results.

Clearly, the long-hopping procedure led to greater intensity of hop flavor and aroma. In particular, the result for increased hop flavor remained statistically significant under the more rigorous Tukey's post-hoc test. Furthermore, the amount by which the hop character of the long-hopping procedure exceeded the hop character of the short-hopping procedure was noteworthy. Increases in intensity from 9.0 to 16.4% can translate into significant savings on hop costs in the brewery. (Note: grassy was also labeled as piney, since this is how most tasters interpreted this characteristic.) Citrus character was also noticeably greater for the long procedure than for the short procedure (i.e., by 6.7%), but this was only significant at a 94% confidence level, making it not quite statistically significant. The results for malty and bitterness were statistically inconclusive.

For small brewers, these results indicate that they would be better off simply adding hops at the end of boil, waiting for a set amount of time, and then whirlpooling and continuing their wort-cooling processes to better extract hop flavor and aroma from a given amount of hops. It is interesting to note that this conclusion calls into question the efficiency of hop jacks or other systems in which hot wort is merely passed through hops on the way to the wort cooler in an attempt to extract hop aroma. We did not have the ability to test such a system, and this would be an interesting area to investigate.

Figure 3 compares the results for the half- and dry-hopping procedures. Our initial hypothesis was that the dry-hopping procedure would provide more hop aroma, and the half-hopping procedure would provide more hop flavor. Interestingly, it is readily apparent from the graph that the two procedures were nearly identical for the amount of hop aroma, citrus, fruity, and grassy characteristics they provided. This would seem to indicate that there are diminishing returns for hop aroma for increased dry-hop additions. Table 2 summarizes the statistically significant results.

Clearly, our hypothesis about the half-hopping procedure providing more hop flavor than the dry-hopping procedure held up (Table 2), since the kettle addition gave 7.4% more hop flavor than dry hopping alone. As would be expected, the half-hopping procedure also gave more bitterness, since the extra kettle addition of hops with long postboil residence led to a reasonable amount of hop isomerization.

Figure 4 compares the results for the long-, half-, and dry-hopping procedures. The dry- and half-hopping procedures clearly resulted in greater hop aroma than the long-hopping procedure, confirming our first hypothesis. Our second hypothesis that the long-hopping procedure would result in greater hop flavor than the dry-hopping procedure remains questionable based on the graph. Also of interest is that the dry- and half-hopping procedures were very similar to the long-hopping procedure in terms of citrus, fruity, and grassy, and the long-hopping procedure seemed to outperform the dry-hopping procedure in terms of malty and bitterness. Tables 3 and 4 summarize the statistically significant results.

Using an a priori t test, it was clear that the greater hop flavor (5.2%) produced by the long-hopping procedure than by the dry-hopping procedure was statistically significant. The greater bitterness produced by the long-hopping procedure compared with the dry-hopping procedure was not surprising given the much greater kettle addition of hops and resulting hop isomerization. The cause of the greater maltiness produced by the long-hopping procedure compared with the dry-hopping procedure was not readily apparent but might be a result of less masking of malty flavors by aromatic compounds. Finally, the greater hop aroma derived from the use of dry hops as opposed to kettle

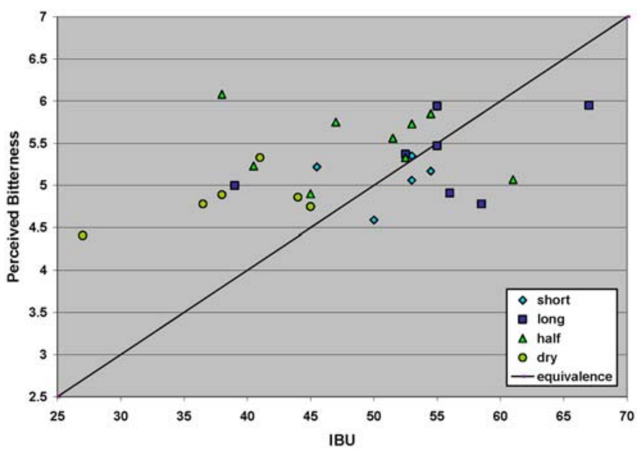

Figure 5. Correlation between international bitterness units (IBU) and perceived bitterness.

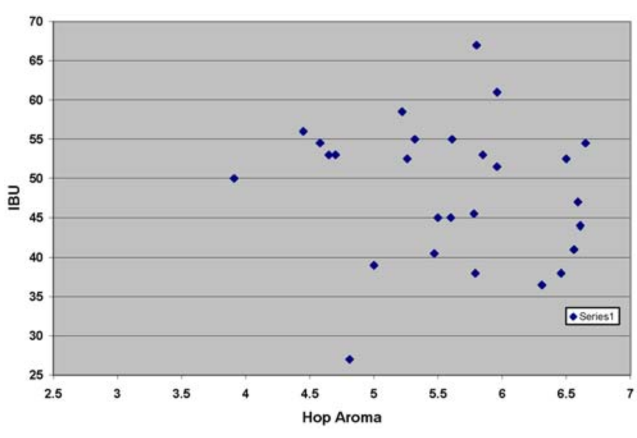

Figure 6. Correlation between international bitterness units (IBU) and hop aroma.

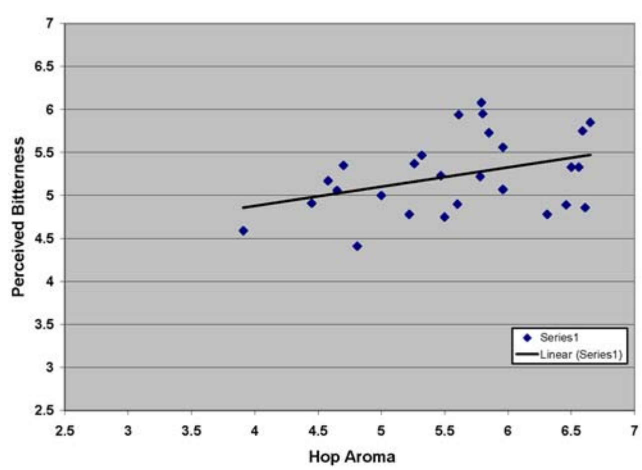

Figure 7. Correlation between perceived bitterness and hop aroma.

hops was readily apparent. What is of more interest is that the dry-hopping procedure resulted in a mere 1.5% more hop aroma than the half-hopping procedure. This seems to be a fairly clear indicator that the addition of more dry hops does not result in a corresponding increase in hop aroma.

IBU and Perceived Bitterness

Because we measured IBU values, we could correlate them statistically and graphically with our mean perceived bitterness scores for each beer. Although Figure 5 shows a positive correlation between IBU and perceived bitterness (significant at the 95% confidence level), it clearly demonstrates that this relationship is nowhere near what we would like to believe it is. Ideally, we would like to see a correlation coefficient near 1, but our data resulted in a coefficient of 0.39. There must be something else that affects the perception of bitterness than measured IBU, since the measured IBU cannot account for all of the differences observed for perceived bitterness.

Graphing the correlation between measured IBU and hop aroma showed no relationship (Fig. 6). However, when hop aroma was compared to perceived bitterness (Fig. 7), a clearly positive correlation between the two was seen (significant at the 95% confidence level). The correlation coefficient was 0.38, less than that for IBU and perceived bitterness, but nonetheless, it does point to a relationship between increased hop aroma and greater perceived bitterness. Also of note is that the datapoints were more well grouped than in the IBU and perceived bitterness graph (Fig. 5), indicating the possibility of a better predictive value when evaluating hop aroma and perceived bitterness.

Similar graphs for hop flavor compared to measured IBU and perceived bitterness show similar, but more interesting, results. Figure 8 shows no apparent relationship between measured IBU and hop flavor. However, Figure 9 shows a clear relationship between hop flavor and perceived bitterness. This relationship had a correlation coefficient of 0.51 and was statistically significant at the 99% confidence level. Clearly there was a strong positive correlation between hop flavor and perceived bitterness. In addition, all of the scores fell roughly between 4.5 and 6.5 for both characteristics, further indicating the nature of the relationship and its possible predictive value.

Sulfate Levels and Perceived Hop Flavor

We also looked at correlations with the sulfate levels of the brewing water. We found a fairly clear negative correlation between sulfate levels and perceived hop flavor (Fig. 10). The correlation coefficient was –0.44 (statistically significant at the 95% confidence level), which clearly indicates that highly hopped beer might be better made using brewing liquors with lower sulfate concentrations.

Conclusions

We have shown that process variables have statistically significant effects on the development of hop flavor and aroma in intensely hoppy beers. It is important to remember when interpreting these results that our specific conclusions are likely highly dependent on the hop variety we used (Amarillo), as well as the beer style brewed (American IPA). In general, it would be foolish to assume that longer postboil hop residence will always result in a nearly 14% increase in hop flavor. However, we do feel that we can draw some general conclusions that will lead small brewers in the right direction to most effectively utilize hops for developing hop flavor and aroma.

Longer postboil residence of kettle hop additions led to more hop flavor and aroma. We can conclude that longer postboil residence, approaching 90 min, is far better than times shorter than 60 min.

Although it was clear that dry hopping was the best way to develop hop aroma, it might not be the best way to develop hop flavor. While it was not surprising that dry hopping gave the

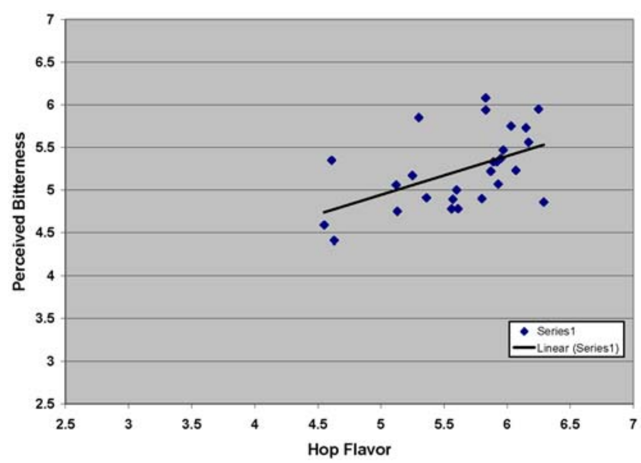

Figure 9. Correlation between perceived bitterness and hop flavor.

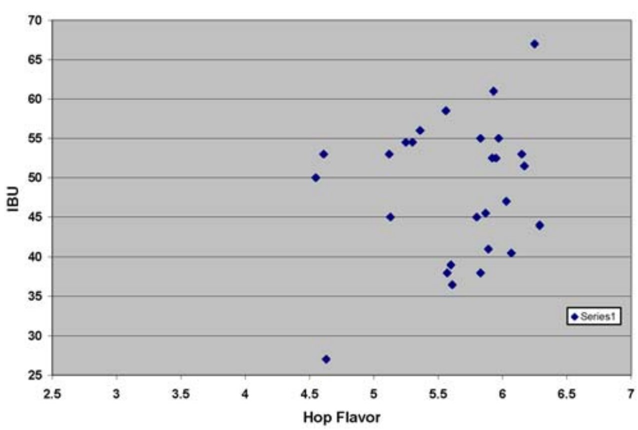

Figure 8. Correlation between international bitterness units (IBU) and hop flavor.

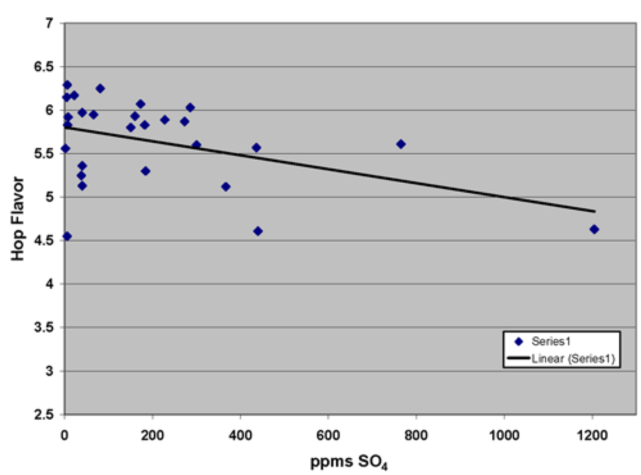

Figure 10. Correlation between hop flavor and sulfate (SO_4) level.

best results for aroma, it was surprising how much more effective long postboil hop residence was at developing hop flavor. Although we did not investigate different methods of dry hopping and their subsequent effects on hop aroma and flavor, we feel that the half-hopping procedure combining long postboil hop residence with dry hopping provided sufficient evidence to indicate that hop flavor is best developed in the kettle.

A combination of long postboil kettle hop residence and dry hopping seemed to maximize combined hop aroma and flavor. It is important to note that this result was for the same amount of hops as either kettle hopping or dry hopping and, thus, indicates there was a synergistic effect in combining the two methods. This also seems to indicate that in terms of hop aroma developed from dry hopping, there were significantly diminishing returns that occurred at rates <1 lb/bbl.

Hop aroma and flavor were closely correlated to perceived bitterness. Together, they might be a much better predictor of perceived bitterness than IBU. This result also brought into question the usefulness of using IBU as a method of measuring the hop character of very hoppy IPA-style beers.

Finally, there seemed to be a negative correlation between SO_4 levels and the intensity of hop flavor. This is an intriguing area for possible further investigation.

ACKNOWLEDGMENTS

I thank White Labs for its help in analyzing the beers in the study for IBU and pH. I also thank the following breweries and their brewers for their help with our sensory analysis panels: Boulder Beer, Bristol Brewing, CB & Potts, Gordon Biersch, Left Hand Brewing, MillerCoors, New Belgium Brewery, and Rock Bottom Breweries.