The Effects of Temperature on Major Beer Compounds During Barrel Maturation

Molly Browning
Barrel Program Manager, Brooklyn Brewery

ABSTRACT

Recent years have seen the rise of breweries undertaking beer maturation in different types of oak barrels. Different types of barrels will give different flavors and aromas to the respective beers aged in the barrels; however, the mechanism of maturation is still relatively unknown. In this research project, a strong (O.G. 1.078), dark (237.5 EBC) beer was brewed and aged in two separate first-use Woodford Reserve bourbon barrels for 6 months. One barrel was placed in a cold room (average temperature 9.4°C); the other was placed in an uncontrolled ambient room (average temperature 14.6°C). Monthly tests were carried out for higher alcohols, esters, vicinal diketones, acetic acid, and aldehydes, for each environment. Additionally, taste panels were also conducted at the beginning and end of maturation. These tests were selected in order to gain a comprehensive understanding of how different maturation temperatures affect the development of major beer compounds. A correlation between low temperature maturation and a decrease in oxidation reactions was perceived. Low temperature maturation in addition to a low pH and a high alcohol content may have also contributed microbiological protection. In general, warm temperature maturation led to an increased reaction rate for many of the compounds studied.

Keywords: barrels, beer maturation, wood-aged beer

SÍNTESIS

En los últimos años se ha visto un aumento de cervecerías que realizan la maduración de la cerveza en diferentes tipos de barricas de roble. El mecanismo de la maduración aún no es bien conocido, pero los diferentes tipos le dan un sabor y aroma diferente a las cervezas. En este proyecto de investigación se elaboró una cerveza fuerte (E.O. de 1,078) y oscura (237,5 EBC) fue elaborada y madurada en dos barriles de Woodford Reserve bourbon no usados antes, durante seis meses. Un barril fue colocado en un cuarto frío (temp. prom. de 9,4°C) mientras que el otro estuvo en un cuarto a temperatura ambiente no controlada (temp. prom. de 14,6°C). Se analizó cada cerveza a cada mes por su contenido de alcohol molecular, esteres, diquetonas vecinales, ácido acético y aldehídos. También se efectuaron pruebas sensoriales al comienzo y al final de la maduración. Estas pruebas se realizaron con la intención de llegar a entender como diferentes temperaturas de maduración afectan el desarrollo de estos compuestos principales de la cerveza. Se detectó una correlación entre la temperatura baja de maduración y una reacción de oxidación disminuida. La temperatura baja de la maduración, además del pH bajo y un alto contenido de alcohol, puede haber contribuido a su protección microbiológica. Por lo general se puede decir que la temperatura más alta de maduración condujo a una reacción más fuerte para muchos de los compuestos estudiados.

Palabras claves: barriles, cerveza madurada en madera, maduración de cerveza

Introduction

The maturation of alcoholic beverages in oak barrels is a long practiced tradition that began out of the availability and ease of using wood to mature, store, and serve these beverages. While barrel maturation may have transitioned to maturation in stainless steel as technology dictated, maturation in oak barrels still continues today, most popularly in both the Scotch whisky and bourbon industries. However, there is a very sharp and definite rise in beer maturation in barrels, noticeably in the North American craft brewing sector.

One area in which beer maturation in oak is being advanced is through identifying and studying flavor-active monophenols that derive from oak. It has been observed that heavily toasted American oak chips in a model medium decrease the levels of vanillin, syringaldehyde, acetovanillone, and acetosyringone with oxygen addition (16). What is more, it was discovered that all the monophenols studied were more easily extracted at low pH values, higher EtOH content, and higher temperatures (20°C) (16).

This project encountered difficulty in properly testing for monophenols in beer, which is why it relied heavily on gas chromatography (GC) analysis of the more abundant volatile compounds in beer. However, sensory analysis was used in order to ascertain some of the flavor attributes of many monophenols.

Oak acts as an active medium in which maturation occurs; as such, the structure of the oak merits discussion. This project used an American oak (Quercus alba) barrel with a medium-heavy char layer. As a species, American oak wood is noted for the following properties:

- Lower levels of polyphenols
- Higher amounts of whisky lactone than European oak (β- methyl-γ-octalactone)
- Higher amounts of ellagic acid and vanillin (2,10).
The process of charring cracks and breaks down the wood to the sub-surface levels, where further flavor and aromatic thermal degradation products are produced up to a depth of 6 mm (5). In whisky maturation, the broken char layer permits the spirit to more easily extract these thermal degradation products. Additionally, the char layer is considered an “active” layer, able to remove a spirit’s immature character, and specifically, assist in the oxidation and adsorption of dimethyl sulfide and other sulfur compounds from the spirit (5).

The thermal degradation of lignin that occurs during the charring process produces monophenol compounds that include: vanillin, syringaldehyde, coniferaldehyde, and sinapaldehyde (5). Charring will increase these lignin degradation products and allow for greater extraction by the spirit. In examining different types of wood, it was found that *Q. alba* has the highest concentration of vanillin compared to other European species of oak (1). Phenolic aldehydes and phenyl ketones are also produced during the thermal degradation of lignin (11). These compounds produce smoky, spicy, and phenolic notes in oak-aged wines (11).

During heat treatment, hemicellulose will degrade before the more abundant cellulose to produce furfural. Furfural is thought to have little sensory qualities; however, its formation is believed to accompany many other compounds that produce sweet, caramel aromas (5). In this study, furfural is examined as a staling aldehyde. This is comparable to many whisky studies, where furfural is pointed to as a possible aging marker (8).

Oak also contains numerous hydrolysable tannins, or polyphenols, in particular: gallotannins and ellagitannins, and non-hydrolysable polyphenols, or proanthocyanidins (9). American oak contains a lower amount of these compounds than other oak varieties. Moreover, it is believed that the level of polyphenols, specifically the complex ellagittannins, will usually be reduced during heat treatment (5). In whisky maturation, it is thought that these non-volatile, non-aromatic compounds work to change the mouthfeel and taste of the whisky (5). Additionally, there is some debate in the literature as to whether these compounds contribute any antioxidant capabilities during whisky maturation.

This paper seeks to map how temperature affects major compounds during beer maturation in an oak barrel. While barrel maturation can encompass many different types of barrels, beer styles, and practices, this paper will examine a strong (O.G. 1.078), dark (237.5 EBC) beer aged for 6 months in bourbon barrels. In doing this, it will purposely ignore sour or wild beers that are aged in oak barrels with or without the addition of wild yeast and/or bacteria.

The beer was brewed and fermented at BlackBar Brewery outside of Cambridge, England, and matured for 6 months in Woodford Reserve barrels. In order to examine the temperature effects on barrel maturation, one barrel was placed in a temperature-controlled cold room, while the other was placed in the ambient temperature room within the brewing facility. Daily temperature checks and monthly samples were taken for the following tests: gravity, color, aroma, and taste of the beer, then rate a range of taste/aroma compounds from 0 to 3 (where 0 is not detected and 3 is overwhelming). The range of compounds rated were: pungent, smoky, malty, floral, fruity, solventy, oily, nutty, woody, vanilla, sweet, buttery, spicy, musty, rancid, catty, sour, and acetic (vinegar).

The second taste panel was held using the 6 month old barrel-matured beer. Ten tasters were asked to perform the same analysis, with the addition of astringent to flavors given in the previous taste panel. A control sample (non-barrel aged) was given to act as a basis for evaluation, but was not evaluated by the tasters. The tasters only evaluated the sixth month matured ambient room and cold room beer. They then asked to state which environment they preferred.

Both taste panels were conducted in the pilot brewery of the International Centre for Brewing and Distilling at Heriot-Watt University. Each sample was poured in a clear glass so as to allow the tasters to evaluate the color.

**Results and Discussion**

The average monthly temperatures for each environment are given in Table 1 with the corresponding monthly parameters for each beer are given in Tables 2 and 3. As evident from Tables 2 and 3, the ambient room barrel’s gravity declines more

<table>
<thead>
<tr>
<th>Month</th>
<th>Cold room barrel (°C)</th>
<th>Ambient room barrel (°C)</th>
<th>Temperature difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February (Month 1)</td>
<td>6.7</td>
<td>8.0</td>
<td>1.3</td>
</tr>
<tr>
<td>March (Month 2)</td>
<td>7.1</td>
<td>8.8</td>
<td>1.7</td>
</tr>
<tr>
<td>April (Month 3)</td>
<td>9.3</td>
<td>13.8</td>
<td>4.5</td>
</tr>
<tr>
<td>May (Month 4)</td>
<td>9.6</td>
<td>15</td>
<td>5.4</td>
</tr>
<tr>
<td>June (Month 5)</td>
<td>11.3</td>
<td>18.7</td>
<td>7.4</td>
</tr>
<tr>
<td>July (Month 6)</td>
<td>12.2</td>
<td>23.8</td>
<td>11.6</td>
</tr>
</tbody>
</table>
sharply than the cold room barrel. The pH declines more sharply in the cold room barrel; however, on average, there was little difference between environments.

**Esters**

The majority of esters decreased during maturation, with the ambient room barrel experiencing a greater rate of decline than the cold room barrel (Table 4). This decline in esters is most likely caused by hydrolysis; however, some adsorption by the charred wood, which occurs in whisky maturation, should not be ruled out.

As evident by Table 5, both ethyl lactate and ethyl acetate increased during maturation in both environments, with the ambient room barrel showing a greater rate of increase than the cold room barrel.

It is believed that barrel maturation favors the esterification process that forms ethyl lactate and indeed, the rise in ethyl lactate levels evident here is only slightly higher than found in non-barrel aged beers (6,17). On the other hand, the rise in ethyl acetate levels may be partially attributed to extraction from the wood as well as oxidation of ethanol into acetic acid. The later of these two mechanisms is responsible for the appearance of ethyl acetate in whisky maturation (10). Additionally, ethyl acetate has been noted as one of the more volatile compounds in the headspace above bourbon whiskies (12).

**Acetic Acid**

Acetic acid levels show a high degree of sensitivity to temperature, rising dramatically from 8°C in both the ambient room barrel (month 1) and the cold room barrel (month 2) (Fig. 1). This increase in acetic acid could be the result of two factors. During maturation, acetic acid can arise from the oxidation of ethanol and, in oak maturation, can be extracted from the wood (10). Oak is also a source of organic acids, in particular acetic acid, which originates “from the acetyl groups present in the wood xylans” (4,5).

**Table 2. Ambient room barrel parameters during maturation**

<table>
<thead>
<tr>
<th>Ester</th>
<th>Month 1</th>
<th>Month 3</th>
<th>Month 4</th>
<th>Month 5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>1.0162</td>
<td>1.0157</td>
<td>1.0154</td>
<td>1.015</td>
<td>1.0156</td>
</tr>
<tr>
<td>pH</td>
<td>4.13</td>
<td>4.19</td>
<td>4.12</td>
<td>4</td>
<td>4.1</td>
</tr>
<tr>
<td>Color (EBC)</td>
<td>325</td>
<td>275</td>
<td>287.5</td>
<td>287.5</td>
<td>293.75</td>
</tr>
</tbody>
</table>

**Table 3. Cold room barrel parameters during maturation**

<table>
<thead>
<tr>
<th>Ester</th>
<th>Month 1</th>
<th>Month 3</th>
<th>Month 4</th>
<th>Month 5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>1.0165</td>
<td>1.0165</td>
<td>1.0164</td>
<td>1.0163</td>
<td>1.0164</td>
</tr>
<tr>
<td>pH</td>
<td>4.12</td>
<td>4.06</td>
<td>4.1</td>
<td>3.97</td>
<td>4.1</td>
</tr>
<tr>
<td>Color (EBC)</td>
<td>262.5</td>
<td>275</td>
<td>262.5</td>
<td>262.5</td>
<td>265.63</td>
</tr>
</tbody>
</table>

**Table 4. Esters that declined during maturation**

<table>
<thead>
<tr>
<th>Ester (ppm)</th>
<th>Month 1</th>
<th>Month 3</th>
<th>Month 4</th>
<th>Month 5</th>
<th>Rate of decline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iso-amyl acetate (control 1.806)</td>
<td>Ambient room</td>
<td>1.265</td>
<td>1.0815</td>
<td>1.0155</td>
<td>0.844</td>
</tr>
<tr>
<td>Cold room</td>
<td>1.4685</td>
<td>1.25</td>
<td>1.152</td>
<td>0.9323</td>
<td>48.4%</td>
</tr>
<tr>
<td>Iso-butyl acetate (control 0.281)</td>
<td>Ambient room</td>
<td>0.27</td>
<td>0.216</td>
<td>0.208</td>
<td>0.192</td>
</tr>
<tr>
<td>Cold room</td>
<td>0.24</td>
<td>0.225</td>
<td>0.220</td>
<td>0.21</td>
<td>25.3%</td>
</tr>
<tr>
<td>Ethyl hexanoate (control 0.367)</td>
<td>Ambient room</td>
<td>0.305</td>
<td>0.283</td>
<td>0.231</td>
<td>0.213</td>
</tr>
<tr>
<td>Cold room</td>
<td>0.359</td>
<td>0.321</td>
<td>0.299</td>
<td>0.263</td>
<td>28.3%</td>
</tr>
<tr>
<td>Ethyl butyrate (control 0.401)</td>
<td>Ambient room</td>
<td>0.324</td>
<td>0.315</td>
<td>0.313</td>
<td>0.275</td>
</tr>
<tr>
<td>Cold room</td>
<td>0.34</td>
<td>0.323</td>
<td>0.319</td>
<td>0.285</td>
<td>29.0%</td>
</tr>
<tr>
<td>Ethyl octanoate (control 0.77)</td>
<td>Ambient room</td>
<td>0.539</td>
<td>0.505</td>
<td>0.470</td>
<td>0.409</td>
</tr>
<tr>
<td>Cold room</td>
<td>0.702</td>
<td>0.6395</td>
<td>0.594</td>
<td>0.544</td>
<td>29.3%</td>
</tr>
</tbody>
</table>

**Table 5. Esters that increased during maturation**

<table>
<thead>
<tr>
<th>Ester (ppm)</th>
<th>Month 1</th>
<th>Month 3</th>
<th>Month 4</th>
<th>Month 5</th>
<th>Rate of increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl lactate (control 1.79)</td>
<td>Ambient room</td>
<td>3.831</td>
<td>4.460</td>
<td>4.401</td>
<td>4.857</td>
</tr>
<tr>
<td>Cold room</td>
<td>3.158</td>
<td>3.66</td>
<td>3.955</td>
<td>4.0825</td>
<td>128.1%</td>
</tr>
<tr>
<td>Ethyl acetate (control 50.48)</td>
<td>Ambient room</td>
<td>60.48</td>
<td>85.19</td>
<td>85.89</td>
<td>87.2</td>
</tr>
<tr>
<td>Cold room</td>
<td>57.42</td>
<td>63.96</td>
<td>66.50</td>
<td>72.29</td>
<td>43.2%</td>
</tr>
</tbody>
</table>

Fig. 1. Acetic acid levels during maturation.

Fig. 2. Propanol and iso-butanol levels during maturation.
Higher Alcohols

As seen from Figures 2 and 3, both propanol and iso-butanol decrease during maturation, while 2-methylbutanol and 3-methylbutanol increase.

As evident in Figure 2, propanol levels do not significantly differ in either environment until the temperature reaches above 10°C; furthermore, iso-butanol is relatively resistant to temperature changes until 20°C. In Figure 3, 3-methylbutanol in the ambient room barrel only starts to significantly differ from the cold room barrel in month 3, or around 10°C. 2-methylbutanol is relatively resistant to changes in temperature during maturation.

The slight decrease seen in propanol and iso-butanol is most likely due to low-molecular weight melanoidin-facilitated oxidation (3). Oxygen, high storage temperatures, and a low pH are factors that contribute to an increased rate of oxidation of higher alcohols by melanoidins; however, these factors appear to be limited at best during barrel maturation as reflected in the small decrease in propanol and iso-butanol. This resistance to oxidation is most likely due to the low porosity of *Q. alba*, the high alcohol content of the beer, the presence of iso-α-acids and polyphenols, and, to an extent, low storage temperatures (3).

The increase in 2-methylbutanol and 3-methylbutanol may be attributed to extraction of the barrel’s previous contents, of which 3-methylbutanol shows more sensitivity to maturation temperatures.

Vicinal Diketones

As seen by Figure 4, 2,3-butanedione, in comparison to 2,3-pentanedione, has a greater sensitivity to temperature, rising steadily from around 10°C (month 3). This increase in 2,3-butanedione could be the result of Maillard reactions, which have been observed to occur under storage conditions in dark beers with a high alcohol content (17). Notably, 2,3-butanedione levels in both environments are considerably higher than other non-barrel aged beers of similar characteristics (17). This might be a result of increased oxygen diffusion during barrel maturation, which may facilitate Maillard reactions.

Aldehydes

All aldehydes examined in this study increased in both environments throughout the maturation period. Table 6 lists the aldehydes studied here, with figures for acetaldehyde and furfural.

It is clear from Table 6 that there is a significantly greater rate of increase in these aldehydes in the ambient room barrel than in the cold room barrel. The increase in aldehydes can be partially indicative of the degree of aging that has occurred during the maturation period. Another cause for the increase could be extraction of the barrel’s previous contents. This is particularly in reference to 2-methylpropanal, 2-methylbutanal, 3-methylbutanal, and acetaldehyde, which were found to be some of the major constituents in the headspace above bourbon (12).

Notably, most of the aldehydes studied here (3-methylbutanal, 2-methylbutanal, hexanal, and furfural) had lower levels than non-barrel aged beers (13,17). Similarly, 2-methylpropanal only reached levels found in these other studies around 10°C, in month 4 (ambient room) and month 5 (cold room) (13). The lower levels of aldehydes could be attributed to antioxidation in the form of melanoidins from the malt and extraction of polyphenols from the barrel. Additionally, charring a barrel “forms a layer of active carbon that may remove undesirable flavor congeners” (10). Charring also produces Mail-

---

**Table 6. Aldehyde levels during maturation**

<table>
<thead>
<tr>
<th>Aldehyde (ppb)</th>
<th>Month 1</th>
<th>Month 3</th>
<th>Month 4</th>
<th>Month 5</th>
<th>Rate of increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-methylpropanal (control 6.8)</td>
<td>Ambient room</td>
<td>15.23</td>
<td>33.20</td>
<td>41.60</td>
<td>50.26</td>
</tr>
<tr>
<td>2-methylbutanal (control 2.70)</td>
<td>Cold room</td>
<td>7.81</td>
<td>19.17</td>
<td>23.29</td>
<td>28.88</td>
</tr>
<tr>
<td>3-methylbutanal (control 11.35)</td>
<td>Ambient room</td>
<td>3.03</td>
<td>4.56</td>
<td>5.22</td>
<td>6.42</td>
</tr>
<tr>
<td>Pentanal (control 0.485)</td>
<td>Cold room</td>
<td>2.82</td>
<td>3.27</td>
<td>3.68</td>
<td>4.04</td>
</tr>
<tr>
<td>Hexanal (control 1.25)</td>
<td>Ambient room</td>
<td>14.22</td>
<td>21.40</td>
<td>24.52</td>
<td>27.9</td>
</tr>
<tr>
<td>3-methylbutanal (control 0.485)</td>
<td>Cold room</td>
<td>12.07</td>
<td>14.17</td>
<td>15.49</td>
<td>16.40</td>
</tr>
<tr>
<td>2-methylbutanal (control 2.70)</td>
<td>Cold room</td>
<td>0.82</td>
<td>1.59</td>
<td>1.76</td>
<td>1.94</td>
</tr>
<tr>
<td>Pentanal (control 0.485)</td>
<td>Cold room</td>
<td>0.545</td>
<td>0.694</td>
<td>0.884</td>
<td>0.98</td>
</tr>
<tr>
<td>Hexanal (control 1.25)</td>
<td>Cold room</td>
<td>2.12</td>
<td>3.30</td>
<td>4.41</td>
<td>5.42</td>
</tr>
</tbody>
</table>

---

**Fig. 3. 2-methylbutanol and 3-methylbutanol levels during maturation.**

**Fig. 4. Vicinal diketone levels during maturation.**
lard reaction products, which may contribute a degree of anti-
oxidant capability or flavor stability, similar to their function
in dark beers.

Both furfural and acetaldehyde are two aldehydes worthy of
special attention due to their importance in beer and wood
maturation. Furfural is a Maillard reaction product that is evi-
dence of the “heat load placed on the mash, wort, and beer,
and for flavor staling in general,” but also occurs during charring
from the pentose in the hemicellulose in wood (3,8).

As Figure 5 depicts, furfural levels rise about twice as much
in the ambient room barrel than in the cold room barrel; what
is more, in the latter environment, there is only a steady rise
toward the end of maturation when the temperature reaches
approximately 10°C. This is most likely due to the higher tem-
peratures, accelerating both Maillard reactions and extraction
of furfural present in the barrel. Perhaps a result of the antioxi-
dants present, furfural levels in both environments are lower
by about 100 ppb in the ambient room barrel and 250 ppb in
the cold room barrel than non-barrel aged beer levels matured
for a similar amount of time (17).

Acetaldehyde is the only aldehyde that declined during the
first month of maturation (Fig. 6). A possible reason for this
decline could be attributed to the action of residual yeast
mopping up any acetaldehyde. A more likely reason is initial
evaporation of acetaldehyde from the barrel (7). However,
from month 1, levels in both environments increased steadily.
Similar to furfural, acetaldehyde only begins to significantly
increase when the temperature approaches and moves beyond
10°C in both environments. One likely reason for this subse-
quent increase in acetaldehyde is that, as the environment
reached close to 10°C in month 3, ethanol became more sus-
ceptible to oxidation.

**Sensory and Taste Panel**

A panel of 15 tasters evaluated the control (non-barrel aged)
beer in February 2012. Initially, the tasters were asked to de-
scribe the color, aroma, and taste of the beer (Table 7). They
were then asked to rate different descriptors from 0 (nonexist-
ent) to 3 (overwhelming). These results are shown in Figure 7.

Most tasters rated the control beer as nutty, pungent, with
some equivalence between spicy, sweet, fruity, and malty (Fig.
7). When asked to describe the beer, most people responded
that it was dark brown in color with a coffee, chocolate-like
aroma and a coffee, slightly bitter taste (Table 7).

After 6 months of aging, tasters were then asked to evaluate
both the ambient room beer and the cold room beer. They were
given the identical taste panel sheet as the control beer, except
for the addition of astringent to the new taste panel evaluation.
Ten tasters evaluated beers from both environments with the
control beer given as a reference (but not evaluated).

In contrast to the control sample, taste panelists detected an
oloroso sherry like color, vanilla aroma, and woody, oxidized,
and alcoholic taste in the ambient room barrel sample (Table
8). This oxidized character could be partially attributed to the
high amount of 2,3-butanedione present, which can give an
“aged” flavor to beer (13). Tasters also identified the ambient
room barrel with a higher degree of vanilla, sweet, astringent,
and buttery character compared to that of the cold room barrel
(Figs. 8 and 9). These characters are probably derived from
vanillin, 3-methylbutanol, and 2,3-butanedione, respectively.

---

**Table 7. Control sample taste panel descriptors**

<table>
<thead>
<tr>
<th>Color</th>
<th>Aroma</th>
<th>Taste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark brown</td>
<td>Coffee, chocolate fruity</td>
<td>Coffee, slightly bitter,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>astringent, sweet</td>
</tr>
</tbody>
</table>

**Table 8. Ambient room barrel beer taste panel descriptors**

<table>
<thead>
<tr>
<th>Color</th>
<th>Aroma</th>
<th>Taste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark brown,</td>
<td>Chocolate, woody,</td>
<td>Chocolate, spicy, woody,</td>
</tr>
<tr>
<td>oloroso sherry</td>
<td>vanilla, fudge, coffee</td>
<td>oxidized, alcohol, fruity,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>roasty, bitter, liquorice</td>
</tr>
</tbody>
</table>
Notably, while tasters described both beers as having a woody flavor, more tasters rated the cold room barrel with a greater woody character than the ambient room barrel (Figs. 8 and 9). This is slightly peculiar as, in Sterckx et al.'s work on monopernels and wood-aged beer, the compounds most associated with a wood-like character were present in greater quantities at warmer temperatures (16). Perhaps the difference between beers aged on oak chips compared to beers aged in barrels could account for this.

Tasters also found a greater nutty, floral character in the cold room barrel than in the ambient room barrel. However, in terms of vanilla, while the average for each environment is nearly identical, more tasters could not perceive this character in the cold room (Fig. 9). Also, interestingly, tasters perceived the same level of smoky character in both environments (Figs. 8 and 9).

In terms of preference, six out of the 10 tasters said they preferred the ambient room barrel to the cold room barrel. This suggests that the sweet/malty/vanilla/buttery character of the ambient room is more desirable than the woody/nutty/malty character of the cold room. Global quality, or roundness, was not asked; however, this might have given a more complete picture in terms of sensory/taste quality.

Conclusion

The results of this study suggest that 10°C is a crucial temperature at which there is a noticeable increase rate of reactions for many compounds. While ethyl acetate, acetic acid, 2,3-butanedione, and furfural levels exhibited a great degree of sensitivity to temperature, increasing from around 8°C during barrel maturation, most other aldehydes, higher alcohols, and esters showed clear changes around 10°C. The oxidation of higher alcohols begins around 10°C, but becomes more apparent around 20°C. Moreover, at 10°C, the oxidation of ethanol into acetaldehyde begins to occur. However, this might not be the sole mechanism for the increase in acetaldehyde, as extraction of the previous spirit contents could feasibly contribute to the increase experienced over the maturation period.

From this study, it is evident that esters, aldehydes, acetic acid, and 2,3-pentane-dione are more susceptible to change during barrel maturation than other compounds. The barrel as a maturation vessel facilitates oxygen diffusion, which may have a direct effect on the levels of 2,3-butanedione. Oxygen diffusion may also occur at an increased level in warmer maturation environments than cooler ones.

As previously stated, there is a slower rate of reaction for all the compounds studied in the cold barrel room (average temperature over maturation period 9.5°C) than in the ambient barrel room (average temperature over maturation period 14.7°C). This is especially true of all the staling aldehydes studied, where the rate of reaction occurred two to three times slower in the cold room than in the ambient room. This slower rate of reaction experienced in the cold room as well as what taste panelists described as “oxidized” character in the ambient room sample suggests that cold temperature maturation lends itself to a greater antioxidant capability.

In terms of flavor, while tasters identified the cold room barrel with a greater perceived “woody” character, most tasters preferred the ambient room barrel beer. This might be a reflection of the degree of aromatic and flavor compounds extracted from the barrel. As Sterckx et al. has previously explored, flavor-active monophenols are extracted at a lower pH, higher alcohol content, and at a higher maturation temperature (16). Surprisingly, though aldehydes increased in both environments, in general, there was not the degree of staling in either barrel compared to those seen in non-barrel aged beer. This may be due to the antioxidant capabilities of polyphenols, the reductones and melanoidins in the dark malt, and possibly the presence of the char layer. Additionally, the small amount of yeast present, which has been proven to “decelerate the appearance of aged flavor,” may have contributed some antioxidant capabilities (14). Undoubtedly, as illustrated here, low temperatures are crucial to stall the effects of aging.

Hopefully, this study has demonstrated and presented a useful outline for the maturation of beer in oak barrels. Crucially, it has been observed that maturation temperatures between 8 and 10°C are necessary for beer and flavor stability. Additionally, the presence of certain dark malts appears to help barrel aging, especially during long-term maturation. Surprisingly, Lactobacillus, Pediococcus, and acetic acid bacteria were not found in these barrels, a result that could be attributed to the low pH, relatively high IBU content, and high alcohol content.

Obviously, more studies on barrel-aged beer are needed to fill in the missing pieces of this complex puzzle. Exploration into barrel-aged beer and antioxidant capacity would be worthwhile. Additionally, more studies on the effects of monophe-
nols and barrel-aged beer are necessary. The abundance of barrel varieties and spirit combinations makes the study of barrel-aged beer almost limitless.

ACKNOWLEDGMENTS

The author gratefully acknowledges the help of Dr. Anne Hill for her supervision, patience, and guidance over this past year of work. A sincere thank you also to Jim MacKinnay for his valuable GC testing; Ashvatinayak Parad for running and helpful guidance with the PCR; Vicky Goodfellow with lab work assistance; and Graham McKernan for allowing me use of the brewery for testing and taste panel. Thank you also to Chris Burke for his help with microbiology lab work.

The author appreciatively thanks Andrew Ety, Assistant Brewmaster of the Brooklyn Brewery, Brooklyn, New York; Zeke Bogan, Specialty Brewing Operation at Bell’s Brewery, Galesburg, MI; and Joe Walts, Head Brewer of Narrows Brewing Company, Tacoma, WA; with their help in discussing barrel techniques.

A special thank you to John Haggerty, Brewmaster/Partner of Warped Wing Brewing Company, Dayton, OH, with his instrumtental guidance and questions over the course of this project and throughout the years I have known him. A large debt of gratitude and thanks is owed to Joseph Kennedy, Owner and Brewer of BlackBar Brewery, Cambridge, England, who lent me use of his brewery and collaborated with me on the brewing and maturation of these beers.

REFERENCES


