Modified Air Flow Rate and Temperature Hop Drying

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ABSTRACT

A method of hop drying using a varying air temperature and a varying air flow rate was tested. Compared to conventional drying, it reduced drying time by one-third and had no detectable affect on fuel use. Hop quality can be maintained at levels comparable with conventional drying if air temperature at the last part of the drying cycle is kept below 65 °C (149 °F).

INTRODUCTION

Over 24 million kg (60 million lbs) of dried hops are produced in the U.S. each year. The 1980 crop had a value of almost $150 million. All of the production is used as an ingredient of beer. Hops are harvested at about 80% moisture (wet basis) and are quickly dried to 8% moisture for safe storage. In the U.S., hops are dried in batch dryers. A typical dryer has a floor area of 10 m x 10 m (30 ft x 30 ft) and hops are loaded to a depth of 0.9 to 1.0 m (36-39 in.) Air heated to 60 ° to 70 °C (140° -158 °F) is forced upward through the hops at an entering flow rate of 0.15 - 0.20 $m^3 \cdot s^{-1}/m^2$ (30 - 40 cfm/ft²). Under these conditions, the hops will reach 8% moisture (wet basis) after 8 to 12 h of drying.

The hop drying process has been described by Bailey (1958) with the following formula:

$$T = \frac{1}{(P-p)} \left[\frac{24.7}{A^{0.95}} + \frac{20260}{A^{0.39}} \right]$$

where: T = drying time (min)
P = saturation vapor pressure of heated air, mm Hg
p = vapor pressure of heated air, mm Hg
A = air speed into hops, m/s
L = water lost per square meter of dryer floor area, kg/m^2

Bailey showed this equation predicted drying times which were in good agreement with field measurements when using air flow rates entering the hops of 0.17 - 0.20 $m^3 \cdot s^{-1}/m^2$ (34-40 cfm/ft²) and 58 ° - 66 °C (136 ° - 151 °F) air temperatures.

Zeisig (1970) showed that the drying time of a 30 cm deep bed could be predicted by:

$$T = \frac{24.8}{1.885\ (P-p) + 0.1\ (V)} \left[\frac{15(L)}{V} + \frac{910}{V^2} \right]$$

where: T = drying time, min
P = saturation vapor pressure of heated air, mm Hg
p = vapor pressure of heated air, mm Hg
L = quantity of water dried from hops, kg/m^2
V = air speed into hops, m/s

This equation predicted drying times within ± 10% of actual over a temperature range of 75 °C to 120 °C (167 °F - 248 °F) and an air flow rate range of 0.55 to 1.17 $m^3 \cdot s^{-1}/m^2$ (55-250 cfm/ft²).

Both equations predicted that drying times decreased when the partial pressure difference term was increased by increasing drying air temperature. However, Burgess (1964) indicated that hop quality was reduced by constant drying air temperatures above 40 °C (104 °F) and entering air flow rates of 0.19 $m^3 \cdot s^{-1}/m^2$ (37.5 cfm/ft²). Ziesig (1970) showed that high air temperatures did not reduce hop quality when the entering air flow rate was sufficiently high. He demonstrated that air flow rates of 0.3 - 0.4 $m^3 \cdot s^{-1}/m^2$ (60-80 cfm/ft²) allowed a 0.3 m (1 ft) depth of hops to be exposed continuously to air temperatures of 68 ° to 74 °C (155 ° to 165 °F) without reducing hop quality. These air speeds also resulted in faster drying compared with conventionally used air flow rates. However, those air flow rates can be used only at the beginning of the drying cycle when the hops are wet and heavy. At the end of the cycle, air flow rates above 0.15 $m^3 \cdot s^{-1}/m^2$ (30 cfm/ft²) will cause the hops to rise off the drying floor.

Zeisig did not investigate the effect of changing air temperature or air flow rate during the drying process. It may be possible to use high air temperatures at the beginning of drying when evaporative cooling effects are high, and when it is possible to use elevated air flow rates. Henderson and Miller (1972) proposed using high air temperatures at the beginning of drying, but made no mention of varying air flow rates. Bloxham (1980) built a dryer in 1970 that used high air temperatures and high air flow rate at the beginning of drying. He called this system "modified air flow and temperature" (MAT) drying. No tests of Henderson and Miller's proposed drying method or Bloxham's MAT drying system have been published.

Hop harvest is often lengthened by an inadequate capacity of hop dryers. An extended harvest season can result in harvesting immature hops at the beginning of the season and over mature hops at the end of the season. The project's objective was to economically increase the capacity of existing hop dryers. This would allow a

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shortened harvest season, a potential improvement in hop quality because of more timely harvest, and a reduced cost of a new dryer.

PROCEDURE

A computer-aided simulation model of deep-bed hop drying developed by Stone (1983) and was used to estimate the time-varying temperature and air flow rate conditions which would decrease drying time without hop quality. The model was based on a corn drying simulation (Bakker-Arkema et al., 1974) with modifications and thin layer equations developed by Stone. Results from the model indicated that hops in a 1.0 m (39 in.) bed could be exposed to an 82 °C (180 °F) air temperature for the first 90 min of drying with an air flow rate of 0.3 m^3-s^{-1}/m^2 (60 cfm/ft^2) without causing a quality-reducing condition called stewing. (Under stewing conditions hops develop a reddish color. The effect is believed to be caused by exposing undried hops to high temperature and humidity conditions). After this initial period, air temperature must be dropped to 65 ° -70 °C (149 ° - 158 °F) and air flow rate gradually reduced to prevent the hops from rising off the drying floor. The model indicated that MAT drying could reduce drying time by 50% and not increase fuel consumption.

MAT drying was tested in a farmer-owned hop dehydrator to determine its effects on drying time, fuel use, and hop quality compared to constant air flow rate and temperature drying. Thirteen tests were conducted in a 12 day period during the 1982 harvest season in the Yakima Valley of Washington. All tests were done with the Yakima Cluster hop variety. The kiln was a traditional batch dryer. Air heated to as high as 83 °C (180 °F) and at flow rate up to 0.3 m^3-s^{-1}/m^2 (60 cfm/ft^2) was ducted to an air plenum below a 97 m^2 (1045 ft^2) perforated floor. Hops were loaded to a depth of 1.0 m (39 in.). Drying air was vented through a cupola and not recirculated.

Air flow rate was controlled by a microcomputer-based control system, Thompson, et al. (1982). It was set to about 0.31 m^3-s^{-1}/m^2 (62 cfm/ft^2) at the beginning of drying and gradually reduced to 0.15 m^3-s^{-1}/m^2 (30 cfm/ft^2) based on the estimated moisture content of the hops. The initial hop moisture content was assumed to be equal to the measured initial moisture of the previous run. Moisture was measured using modified AOAC vacuum oven method, Stone (1982). Moisture lost to the drying air was calculated knowing the air flow into the bed of hops and the rise in humidity ratio as the air passed through the hops. Moisture lost from the bed of hops was used to periodically update the estimated hop moisture. Air flow was calculated based on the instantaneous fuel flow to the burner, temperature rise of the air as it was heated, and an empirically determined factor to account for the radiant heat loss of the burner and combustion efficiency.

Drying air temperature was also controlled by the same control system. Four tests were done with the air temperature starting at 83 °C (180 °F) and dropped in one step to 65 °C (149 °F) when the air temperature at 23 cm (9 in.) from the bottom reached 65 °C (149 °F). This control scheme was selected because it allows only the very bottom most hops to be exposed to high air temperatures and guarantees that most of the hops are dried at a conventionally used air temperature of 65 °C (149 °F). Three tests were done with an 83 °C (180 °F) starting temperature and a 70 °C (158 °F) final air temperature, to determine the maximum possible final air temperature.

Air temperatures were measured with iron-constantan thermocouples. Cumulative fuel oil use was measured with a mechanical flowmeter. Instantaneous fuel oil flow was measured with a turbine flow transducer. Fuel use for each run was adjusted to the use corresponding with a constant 21 °C (70 °F) outside air temperature, on the basis of a ratio of the drying air temperature rise if the outside air were at 21 °C (70 °F) divided by actual temperature rise. The adjustment was made every 15 min and the sum over the entire run used as the reported fuel use. Electrical energy use of the fan was not measured because it was estimated to be less than 5% of total drying energy costs. Initial and final hop moisture contents were measured. All tests were concluded on the basis of the operator's judgment of when the hops were dry.

Hop maturity and field moisture content change during the season. Each MAT test was paired with a conventional constant air flow rate and constant air temperature test using hops harvested within 24 h of the MAT dried hops. The conventional runs utilized 66 °C (150 °F) air with an entering air flow rate of 0.15 m^3-s^{-1}/m^2 (30 cfm/ft^2). The effect of MAT drying on drying time, fuel use, hop quality were analyzed using a paired t test.

Samples of the hops were collected after each drying test and used for quality evaluations. Separate samples were taken of hops at the middle, and near the bottom of the bed. Each sample consisted of sub-samples taken from each quadrant and the center of the bed of hops. Hop quality was based on an independent laboratory evaluation of chemical constituents.

The evaluation included the percentage of alpha acid and beta acid and the index of transformation. Burgess (1964) describes alpha and beta acids as complex mixtures of aromatic compounds. They are believed to be the two main categories of compounds that give hops their unique flavoring characteristics. High levels of alpha and beta acid are desirable. The index of transformation is a measure of the amount of oxidized alpha acid. Low index of transformation numbers are indicative of good quality hops.

The quality tests were performed on samples immediately after harvest and after ten months of storage at room temperature. Hops are often stored for long periods of time and drying may affect quality in the long term differently than it does in the short term quality. Data are reported as averages within a test.

RESULTS

Figs. 1 and 2 are plots of the air temperatures and air flow rates during typical 65 °C (149 °F) and 70 °C (158 °F) final temperature MAT tests. For the 65 °C (149 °F) MAT tests, the incoming air temperature was held at a maximum of 83 °C (180 °F) for the first 2 to 2.5 h and then dropped to 65 °C (149 °F) for the remainder of the test. However, the air temperature did not reach the maximum until after 30 to 45 min of operation. This was probably caused by insufficient burner capacity to provide enough heat for the high air flow rates at the

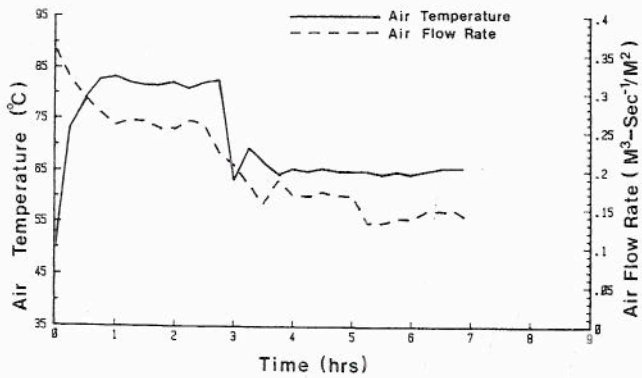

Fig. 1—Air flow rate and temperature during a 65 °C MAT hop drying test.

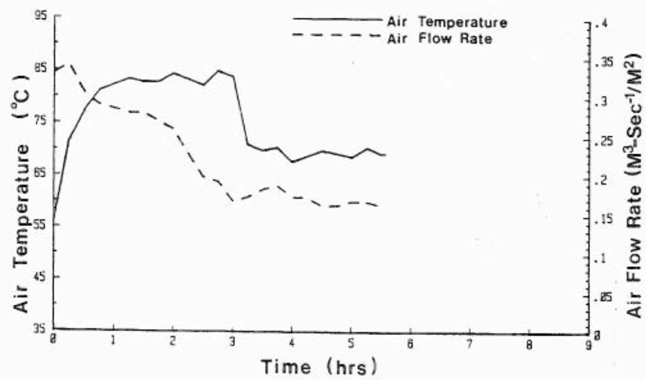

Fig. 2—Air flow rate and temperature during a 70 °C MAT hop drying test.

beginning of the drying cycle. Total drying times were about 7 h for the 65 °C (149 °F) MAT runs. Air flow rate remained at maximum levels of about 0.25-0.30 m^3-s^{-1}/m^2 (50-60 cfm/ft^2) for about the first two hours and was then gradually reduced to 0.15 m^3-s^{-1}/m^2 (30 cfm/ft^2) within the next two hours. The 70 °C (158 °F) MAT tests had similar temperature and air flow rate patterns but the time scale was slightly compressed compared to the 65 °C (149 °F) MAT runs. Fig. 3 is a plot of typical constant air temperature and constant air flow rate run. The conventional test had a constant 65 °C (149 °F) incoming air temperature and constant 0.16 m^3-s^{-1}/m^2 (32 cfm/ft^2) incoming air flow rate.

Table 1 is a summary of the drying time and fuel use results. Each MAT test is paired with a conventional test. Table 2 is a summary of the paired data analysis

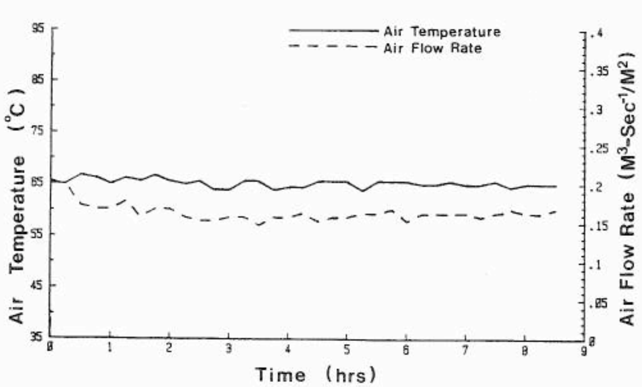

Fig. 3—Air flow rate and temperature during a conventional constant airflow rate and constant air temperature hop drying test.

TABLE 1. DRYING TIME, FUEL USE AND MOISTURE DATA FOR MAT AND CONTROL TESTS. DATA ARE LISTED IN PAIRS

Test number	Pair Desig-nation	Test type	Drying time, h	Fuel* use, L	Moisture initial	(%wb) final
1	a	65° MAT	6.05	708	76.0	9.7
2	a	control	9.70	704	76.9	12.6
3	b	65° MAT	7.00	704	77.6	9.9
2	b	control	9.70	704	76.9	12.6
4	c	65° MAT	6.87	787	79.8	6.5
5	c	control	8.80	712	77.5	— —
12	d	65° MAT	5.47	643	73.0	— —
13	d	control	8.60	712	— —	— —
6	e	70° MAT	5.57	727	— —	5.1
7	e	control	8.52	700	75.0	5.3
9	f	70° MAT	5.68	704	76.4	8.9
8	f	control	8.68	734	74.9	10.3
10	g	70° MAT	5.67	704	75.7	11.0
11	g	control	8.57	693	76.3	9.9

– no data

*adjusted to the use corresponding to a constant 21° C (70° F) outside air temperature.

with percent differences within pairs. The 65 °C (149 °F) MAT and the 70 °C (158 °F) MAT tests significantly ($P \leq 0.05$) reduced drying time by 32% and 35% respectively compared to the conventional tests. The 70 °C (158 °F) MAT tests did not significantly ($P > 0.05$) reduce drying time compared with the 65 °C (149 °F) MAT tests. The average fuel use of MAT tests was less than 1% greater than conventional drying in both series of MAT tests, however the increase was not statistically significant ($P > 0.05$).

The hop quality data are listed in Tables 3 and 4. Compared to conventional drying the 65 °C (149 °F) MAT tests did not significantly ($P > 0.05$) reduce alpha acid or beta acid levels or increase the index of transformation in samples run immediately after drying or after 10 months of storage at room temperature. Compared to conventional drying, the 70 °C (158 °F) MAT runs did not significantly ($P > 0.05$) reduce alpha acid or beta acid levels but did cause a significant ($P \leq 0.05$) increase in the index of transformation. The increase in the index of transformation averaged only 6% and 8% respectively for the hops tested immediately after drying and after 10 months of storage at room temperature. Although this level of increase in the index of transformation is statistically significant, it is small from a practical standpoint because the variability from field to field and grower to grower can easily be greater than this.

TABLE 2. SUMMARY OF PAIRED DATA FOR DRYING TIME AND FUEL USE

Pair designation	% More fuel use	% Less drying time
65° C MAT tests		
a	0.5	40
b	0.0	28
c	10.6	22
d	−9.6	36
Average	0.4	32*
70° C MAT tests		
e	3.7	35
f	−4.3	35
g	1.6	36
Average	0.3	35*

*indicates a significant difference between MAT and control tests at 95% confidence level.

TABLE 3. HOP QUALITY DATA FOR MAT AND CONTROL TESTS. DATA ARE LISTED IN PAIRS

Test number	Pair desig-nation	Test type	Alpha-acid(%) after drying*	Alpha-acid(%) after storage†	Beta-acid(%) after drying*	Beta-acid(%) after storage†	Index of transformation after drying	Index of transformation after storage
1	a	65° MAT	7.46	3.52	4.89	1.89	0.244	0.506
2	a	control	7.96	3.67	5.17	2.54	0.242	0.575
3	b	65° MAT	7.65	3.39	5.09	1.94	0.251	0.515
2	b	control	7.96	3.67	5.17	2.54	0.242	0.575
4	c	65° MAT	7.98	3.53	4.95	1.92	0.254	0.511
5	c	control	7.05	2.80	4.65	1.77	0.229	0.467
12	d	65° MAT	7.04	3.62	4.68	2.33	0.244	0.546
13	d	control	7.15	3.94	4.83	2.57	0.234	0.647
6	e	70° MAT	8.23	3.96	5.41	2.42	0.245	0.548
7	e	control	8.73	5.27	5.31	3.05	0.235	0.515
9	f	70° MAT	8.31	5.03	5.12	2.51	0.247	0.562
8	f	control	8.22	4.41	5.01	2.85	0.234	0.505
10	g	70° MAT	7.03	3.98	4.90	2.38	0.253	0.522
11	g	control	7.28	3.43	5.12	2.28	0.235	0.494

*% bone dry basis
†% as is basis

DISCUSSION

The quality data indicate that hop quality can be maintained at levels comparable to conventional drying if the 65 °C MAT system is used. The 70 °C MAT runs resulted in slightly decreased quality compared to conventional and is not recommended, especially considering that it does not reduce drying time more than 65 °C MAT. Drying time for the MAT tests was reduced by 32%-35% compared with conventional drying. The reduction drying time was undoubtedly less than it would have been if the burner could have maintained the desired temperature during the first part of the MAT runs. Proper burner sizing may allow MAT drying to achieve reductions in drying time of nearly 50% as predicted by Stone's model.

Even one-third reduction in drying time resulting from MAT drying enables a conventional batch-type hop kiln to dry 50% more commodity per day. A typical hop drying facility has four drying floors. A 4-kiln MAT dehydration facility could operate with the capacity of a conventional 6-kiln facility. The increased capacity of a dehydrator modified to use MAT drying will result in a shorter harvest period for operations that are limited by drying capacity. A shorter period will usually result in higher hop quality and increased revenue compared to a longer season.

Fuel use for MAT drying is not significantly different than that for conventional drying. The electrical energy use for MAT drying was estimated to be as much as one-third higher than conventional drying but electrical energy costs are less than 5% of fuel costs. MAT drying will have an insignificant effect on increasing total energy costs.

Implementing a MAT system will usually require installing larger burners and increasing fan capacity. MAT drying will probably also require the use of a microcomputer based or programmable controller to make the frequent adjustments in temperature and air flow rate. These modifications would probably cost about one-half as much as adding new drying kilns to achieve the same increased capacity.

There is a possibility of using even a higher airflow and air temperature than reported in this study to further reduce drying times. However, this will require developing a method of holding the hops on the drying floor. The concept of varying air flow and temperature in a fixed bed dryer may be applicable to commodities other than hops.

TABLE 4. SUMMARY OF PAIRED DATA FOR HOP QUALITY

Pair designation	% Less alpha acid after drying	% Less alpha acid after storage	% Less beta acid after drying	% Less beta acid after storage	% Greater index of transformation after drying	% Greater index of transformation after storage
65° MAT tests						
a	6	4	5	26	1	-12
b	2	8	2	24	4	10
c	-13	-26	-7	-8	11	9
d	4	8	3	9	4	-16
average	0	-2	1	13	5	-2
70° C MAT tests						
e	6	25	-6	21	4	6
f	-1	-14	-2	12	6	11
g	3	-16	4	-4	8	6
average	3	-2	-1	10	6*	8*

*indicates a significant difference between MAT and control tests at the 95% confidence level.

CONCLUSIONS

MAT drying reduced the drying time for hops by one-third compared with the conventional constant air flow rate and constant temperature method and did not significantly increase fuel use. Field tests showed no significant difference in quality, as measured by alpha acid, beta acid, and index of transformation when the temperature during the last part of drying was not allowed to rise above 65 °C (149 °F).

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