COMPARISON OF ENERGY CONSUMPTION IN THE DRYING OF RED OAK BY STEAM HEATED AND DEHUMIDIFICATION KILNS

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INTRODUCTION

In recent years there has been considerable interest in improved lumber drying techniques. These innovations have been proposed to improve lumber quality (reduce degrade), shorten the drying time, and reduce energy consumption. The most significant constraint to commercial acceptance of some of these innovations has been the installation or renovation investment which must be made by the kiln operator.

Dehumidification kiln drying has only recently become accepted as a viable commercial lumber drying technique. The installation costs for a dehumidification (DH) kiln are within the range of commercial steam kilns, and the lumber quality after drying is reported to be as good or better. A significant advantage to the DH kiln is that it has less energy consumption than the steam kiln; the vent air is not exhausted, but rather dehumidified and recirculated.

Over the past decade considerable attention has been focused on energy conservation within the forest products industry. This interest has been directed towards the drying phase of the lumber manufacturing process. Comstock (1) has estimated that 70% of all energy used to manufacture lumber is used in the kiln drying of the lumber. Past studies on energy quantification in kiln drying have analyzed the way energy will be used in kiln drying. Eckelman and Baker (2) listed six areas of energy consumption in kiln drying:

1. Initial heating of the charge (and kiln structure).
2. Heat to raise the temperature of the wood and the remaining water to the temperature in the next stage of drying.
3. Heat of vaporization.
4. Heat of wetting.
5. Venting losses
6. Transmission heat loss through the kiln structure.

Of these factors, the first four are basic to the drying process and cannot easily be reduced. The venting losses and transmission losses through the kiln structure represent the most likely areas for energy savings in kiln drying.

The purpose of this study on energy consumption in kiln drying was to compare the dehumidification kiln with the conventional steam kiln and to identify the energy intensive factors in kiln drying. The kilns which were compared in this study were comparably sized experimental kilns.

EXPERIMENTAL

Two experimental dry kilns were used in this research. The conventional steam kiln is a Moore-Oregon 500 board foot experimental dry kiln which has been specially equipped for energy quantification research. A steam-flow measuring device that detects the pressure drop across an orifice is used to measure the steam flow into the kiln. A temperature transmitter is located upstream of the orifice. The temperature transmitter is located after the pressure reducer which reduces the pressure from 100 psig to 34 psig. The orifice plate is held between two orifice flanges. Extending down from each of the orifice flanges is a water leg. The water legs are connected to a flow transmitter. This flow transmitter senses the pressure drop across the orifice which has been induced by the steam flow.

The signals from the temperature and flow transmitter are fed into an integrator totalizer. The signal from the integrator totalizer is then fed into a multiplier module which drives the event counter.

Before the energy events can be used to determine the total amount of energy over a given interval, the events must be calibrated. A water barrel calorimeter consisting of a 50 gallon drum placed on a scale and wrapped with R-22 insulation was used to calibrate the steam flow apparatus. Steam flow through the orifice was diverted from the kiln into the calorimeter, and the increase in water temperature and weight was used to determine the total amount of energy put into the calorimeter. This energy total in BTUs was divided by the number of events to get the calibration factor.

The energy consumption for the steam kiln consisted of the energy from the steam flow plus the electrical energy from the fans. Energy consumption for the fans was measured with an electric meter.

The energy consumption for the dehumidification kiln was measured using electric meters to measure the energy input to the dehumidification unit, the fans, and the electric heating coils. Readings from these three meters were added together to get the total energy input for the DH kiln over a given drying interval. The dehumidification unit contains a 1 HP compressor and was built by Uraken Ltd. of Canada. The DH kiln has a 1000 board foot capacity but was loaded with the same amount of lumber as the conventional kiln.

One important difference between the two kilns compared in this study was in the insulation found within the kiln walls. The steam kiln was built with 2 inches of fiberglass insulation and aluminum skin construction. The R-factor for this wall would be about 6 at most, and is probably less because of heat bridging in the walls of the kiln due to the structural members and because of moisture which may have accumulated within the insulation over the years.

The dehumidification kiln was built much more recently. The walls were designed using a plywood sandwich construction with 2x6s used as the structural components. The design allowed for 5½ inches of polystyrene insulation with an R-factor of 25 for the walls of the DH kiln.

In preparation for drying, the lumber was weighed and stacked into the kiln and sample boards were prepared in the prescribed manner. The lumber in the steam kiln was dried according to FPL schedule T4-D2 for 4/4 red oak. There was no comparable schedule for the DH kiln, although Uraken has given some recommendations in their instruction manual. At the end of drying, the lumber was weighed again, with the difference between beginning and final weight as the pounds of water removed from the lumber

RESULTS AND DISCUSSION

The drying curves for 1S and 1DH are compared in Figure 1. Both of these drying runs used lumber from the same unit, and both were dried at about the same time (March 20 to April 8). The drying curves for both runs look very similar as the lumber is dried from a green down to about 15% moisture content. Below 15% moisture content the curves diverge; 1S was dried to an average moisture content of 5.3%, while 1DH was only dried to an average moisture content of 9.2%.

The early phase of drying for run 1DH was at a faster rate than would be expected because auxiliary heating coils were used to boost the kiln temperature to 110°[1] for part of this period. There was no way to humidify the DH kiln, therefore the average wet bulb depression (WBD) for that period was 8° (Table 1), compared to the 4° WBD recommended by the FPL schedule for 4/4 red oak (T4-D2). After some surface checking was observed on one of the sample boards, the heating coils were turned off and the kiln was operated thereafter in accordance with the recommendations of the kiln manufacturer.[2]

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[1]All temperatures listed in this paper will be in degrees Fahrenheit.

[2]Uraken recommended that the wet bulb temperature be set at 80° and the dry bulb temperature (and therefore the wet bulb depression) be adjusted so that the maximum allowable drying rate is not exceeded. For red oak the maximum allowable drying rate was 2.8% moisture content per day. Control of the dry bulb and wet bulb temperature was possible by adjusting the compressor timer and setting the heat reject.

The drying curves for runs 2S and 2DH are graphed in Figure 2. The initial drying rate of the steam kiln was significantly faster than that for the DH kiln. This was because the drying conditions within the DH kiln were milder than necessary; a WBD of only 2° was maintained (Table 3). Had the WBD for the DH kiln been equal to that for the steam kiln, their drying rates would have been comparable.

After the first 50 hours the drying rates for the two kilns were roughly parallel, down to about 15%-20% moisture content. The drying rate from 65.2% to 15.3% for the DH kiln averaged 3.6% per day (Table 3). The drying rate from 57.9% to 17.5% for the steam kiln averaged 4.0% per day (Table 4).

Below 15% moisture content the drying rate for the DH kiln slowed considerably. From 15.3% to 7.8% moisture content, the drying rate was only 1.2% per day (Table 3). The drying rate for the steam kiln did not slow nearly as much; from 17.5% to 3.8% the drying rate was 3.4% per day (Table 4). The WBD's for both kilns over their respective range of moisture contents were very similar. For the DH kiln, it ranged from 40° - 48° over the last 147 hours of drying, while for the steam kiln it was 50° over the last 87.5 hours of drying. The final dry bulb temperature (DBT) for the steam kiln was much greater than the DBT for the DH kiln (180° vs. 136°), and this difference was no doubt responsible for the difference in drying rates.

The energy consumption per pound of water removed was plotted against moisture content as shown in Figures 3 and 4. This plot is a measure of dry kiln efficiency. For both the DH and steam kilns, the greatest efficiency was early in the runs, i.e., when free water was being removed from the wood. During the early stages of drying, the difference in energy consumption for the two kilns is largely due to the differences in transmission losses through the walls and roofs of the two kilns. However, as the moisture content drops below 35%, higher dry bulb temperatures and larger wet bulb depressions (more venting) are required by the drying schedule for the steam kiln. This increases the BTUs per pound of water removed more rapidly for the steam kiln than for the DH kiln.

For both kilns the energy consumption per pound of water removed definitely increased as the wood became drier. For the steam kiln, however, the data point for below 10% MC has a much lower value than the previous one for approximately 15% MC. This observation may possibly be explained by experimental variability, but the same trend was observed for both runs 1S and 2S. It is quite probable that drying at 180° DBT and 130° wet bulb temperature (WBT) is more efficient than drying at 130° DBT and 80° WBT. While the transmission losses through the walls, floor, and roof of the kiln would be greater at 180°, the rate of diffusion, hence the rate of moisture removal, from the lumber, would also be greater. Furthermore, less venting was required at 180° because air has a much greater moisture holding capacity at 180° than 130°. Even though the incoming air must be heated to a higher dry bulb temperature, this additional energy input is more than compensated for by the added moisture holding ability of the air at 180°.

When the overall results from the DH kiln are compared to those for the steam kiln, it is clear that the DH kiln is much more efficient. Much of this, of course, was due to the greater insulation in the walls of the DH kiln.

Between approximately 35% and 15% MC the advantage of the dehumidification unit was perhaps most readily apparent. The drying schedule for the steam kiln calls for a large WBD, which was obtained by more venting. The increased WBD for the DH kiln was obtained by operating the compressor a greater percentage of the time. Since there was no venting from the DH kiln, both the sensible heat of the air and the latent heat of vaporization were retained.

The energy efficiency of the DH kiln decreased when the lumber was dried below 15% MC. This was most apparent for run 2DH in Figure 4, where the lumber was dried to about 7.0%. The highest drybulb temperature for the DH kiln was 136°, and at this temperature the drying rate below 10% was very slow. Even though there was no venting, the transmission losses accumulate over the additional hours of drying. This explains why the slope of the curve for BTU/pound of water removed (Figures 3 and 4) becomes steeper at the end of drying, especially for the last two data points.

Figures 5 and 6 are graphs of the DH kiln. In Figure 5 the initial heating of the kiln to 110° DBT caused the highest plot to occur at the beginning of the run. After the heating coils were shut off and the kiln was allowed to cool to its normal operating temperature, the energy consumption curve reached a plateau at about 3500 BTU/hour. Later in the run the timer was set so that the compressor was operating 100% of the time. When the lumber had dried below the fiber saturation point (after 287 hours) the heating coils were turned on again in an effort to speed up the drying. As the dry bulb temperature increased to 136°, the energy consumption increased to about 10,000 BTU/hour.

During run 2DH (Figure 6) the heating coils were not used at the start of the run. The plot of the energy consumption curve shows a gradual and uniform increase from 3500 BTU/hour to over 8,000 BTU/hour after 500 hours of drying. Later in the run the compressor was used a good deal more of the time. Also, after 340 hours of drying when the lumber had dried to 20% MC, the heating coils were turned on. The combination of more compressor hours along with the energy needed to operate the heating coils, was responsible for increased energy consumption later in the drying run.

The energy consumption curves for the steam kiln (Figures 7 and 8), are distinctly different from those for the DH kiln. At the start of drying, the lumber, the water within the lumber and the kiln structure must be heated to the initial dry bulb temperature.

It would be expected that the energy consumption would be greater at the very start of the drying run. Along with heating the lumber, water, and kiln, a large amount of energy is being used to dry the lumber. During this period, much of the surface of the lumber was still wet and drying proceeded very quickly until the surface dried below the fiber saturation point.

For both runs the energy consumption curve decreases from its initial high value to its minimum value, which occurs at about 35% MC. During this part of the run the drying rate has leveled off, the wood, water, and kiln structure have been heated to 110^{o}, and the kiln schedule calls for relatively small (4^{o}-8^{o}) wet bulb depressions and therefore little venting.

The energy consumption increased significantly over the last half of each run. This increase starts when the lumber is at about 35% MC, at which time the kiln schedule calls for rapid increases in wet bulb depressions and dry bulb temperatures. The larger wet bulb depressions require more venting. Higher dry bulb temperatures will mean increased transmission losses and will also mean that the replacement air during venting will need to be heated to a higher dry bulb temperature.

As would be expected, the energy consumption for the steam kiln was considerably greater than the energy consumption for the DH kiln. This is readily apparent from Figures 9 and 10 where energy consumptions are plotted as bar graphs and the two kilns can be directly compared. The factors responsible for this difference in energy consumption have already been discussed. The most important factors are the increased transmission losses from the steam kiln, and the difference between a closed, ventless drying system and one that requires venting. While the energy consumption for the DH kiln was considerably less, the tradeoff for this reduction in energy consumption was an increase in drying time. This is most apparent in Figure 10 where the lumber in the steam kiln was dried to 3.8% moisture content in 378.5 hours (Table 4), while the lumber in the DH kiln was only dried to 7.8% moisture content, but required 535.5 hours (Table 3).

There is one final comment which should be made. This study compared two comparably sized dry kilns. The purpose of the comparison was to note the differences between conventional steam and dehumidification drying, and to identify the energy intensive factors during lumber drying. It would be inappropriate to suggest that the energy consumption for a large commercial kiln would be similar to the energy consumption for these experimental kilns. Rosen (3) has pointed out that the larger surface area to volume ratio for experimental kilns will affect the comparison of experimental to commercial kilns. Transmission losses from experimental kilns will be a much larger proportion of the total energy consumption because of the increased relative surface area.

CONCLUSIONS

1. The drying rates for these experimental steam and dehumidification kilns were similar in the moisture content interval of green to 15%. Within this range the drying rate was dictated by the potential for degrade within red oak lumber. Below 15% moisture content the drying rate for the steam kiln was definitely faster than the DH kiln. The faster rate was due to the higher dry bulb temperature capability of the steam kiln.
2. The dehimidification kiln was much more energy efficient than the steam kiln. Part of this difference was due to better insulated walls and did not reflect the basic differences between steam and dehumidification drying of lumber. During the drying interval between 35% and 15% moisture content, the energy efficiency of the steam kiln was much less because of the higher dry bulb temperatures and the large wet bulb depressions (increased venting) required by the drying schedule. The energy efficiency of the DH kiln decreased significantly when the lumber was dried below 10% moisture content. The low dry bulb temperatures and correspondingly slow drying rate were responsible for the decrease in energy efficiency through increased transmission losses.
3. Energy consumption for the steam kiln was large at the beginning of the run, during heat up of the wood, the water within the wood and the kiln structure. The energy consumption dropped to about 30,000 to 35,000 BTU/hour about halfway through the run. As the wet bulb depression and dry bulb temperature were increased, the energy consumption was significantly increased during the final half of drying time. The energy consumption for the DH kiln showed a gradual and somewhat uniform increase over the course of the drying run.

Table 1

DEHUMIDIFICATION KILN - EXPERIMENTAL RUN 1DH

Dates	M.C.	Avg. M.C.	Hours	DBT	WBT	BTUs	Estimated Pounds of Water Removed	BTUs/Hour	BTUs/Pound of Water
3/20→3/22	91.5%→58.4%	75.0%	50.25	100°	92°	740,621	387.5	14,739	1,911
3/22→3/24	58.4%→49.6%	54.0%	49.50	85°	76°	167,237	103.0	3,378	1,624
3/24→3/26	49.6%→42.6%	46.1%	46.50	85°	75°	160,411	82.0	3,450	1,956
3/26→3/28	42.6%→36.4%	39.5%	49.00	84°	72°	177,476	72.6	3,622	2,445
3/28→3/30	36.4%→30.8%	33.6%	48.00	89°	74°	228,671	65.6	4,764	3,486
3/30→4/1	30.8%→25.9%	28.4%	43.50	94°	76°	228,671	57.4	5,257	3,984
4/1→4/3	25.9%→19.2%	22.6%	52.00	122°	93°	501,711	78.4	9,648	6,399
4/3→4/5	19.2%→13.6%	16.4%	49.00	134°	94°	508,537	65.6	10,378	7,752
4/5→4/8	13.6%→9.2%	11.4%	65.50	136°	92°	597,275	51.5	9,119	11,598
Totals and Averages									
3/20→4/8	91.5%→9.2%	--	453.25	--	--	3,310,610	963.5	7,304	3,436

Table 2

STEAM KILN - EXPERIMENTAL RUN 1S

Dates	M.C.	Avg. M.C.	Hours	DBT	WBT	BTUs	Estimated Pounds of Water Removed	BTUs/Hour	BTUs / Pound of Water
3/21→3/23	81.1%→60.2%	70.6%	44.25	110°	106°	2,409,353	267.0	54,449	9,024
3/23→3/25	60.2%→48.6%	54.5%	47.25	110°	106°	2,301,251	148.0	48,704	15,549
3/25→3/27	48.6%→41.4%	45.0%	49.00	110°	106°	2,062,237	91.8	42,086	22,464
3/27→3/29	41.4%→34.6%	38.0%	49.00	110°	105°	1,634,940	86.7	33,366	18,857
3/29→3/31	34.6%→28.0%	31.3%	47.00	110°	102°	1,499,843	84.2	31,912	17,813
3/31→4/2	28.0%→22.4%	25.2%	49.00	110°	96°	1,745,451	71.4	35,621	24,446
4/2→4/4	22.4%→15.0%	18.7%	49.00	130°	80°	2,638,589	94.4	53,849	27,951
4/4→4/6	15.0%→10.6%	12.8%	46.00	130°	90°	2,343,067	56.1	50,936	41,766
4/6→4/8	10.6%→5.3%	8.0%	42.50	180°	130°	2,410,269	67.6	56,712	35,655
Totals and Averages									
3/21→4/8	81.1%→5.3%	--	423.00	--	--	19,045,000	967.2	19,691	45,024

Table 3

DEHUMIDIFICATION KILN - EXPERIMENTAL RUN 2DH

Dates	M.C.	Avg. M.C.	Hours	DBT	WBT	BTUs	Estimated Pounds of Water Removed	BTUs/Hour	BTUs Pound of Water
4/9→4/11	80.7%→65.2%	73.0%	52.00	83°	81°	180,889	187.4	3,479	965
4/11→4/13	65.2%→54.1%	59.6%	55.50	86°	82°	208,193	134.2	3,751	1,551
4/13→4/15	54.1%→47.6%	50.8%	40.50	86°	81°	136,520	78.6	3,371	1,737
4/15→4/17	47.6%→38.7%	43.2%	54.00	92°	79°	255,975	107.6	4,740	2,379
4/17→4/19	38.7%→31.9%	35.3%	41.00	104°	80°	259,388	82.2	6,326	3,156
4/19→4/21	31.9%→25.3%	28.6%	50.00	112°	82°	327,648	79.8	6,553	4,106
4/21→4/23	25.3%→20.5%	22.9%	47.00	114°	82°	303,757	58.0	6,463	5,237
4/23→4/25	20.5%→15.3%	17.9%	48.50	130°	90°	408,147	62.9	8,374	6,489
4/25→4/27	15.3%→11.8%	13.6%	49.50	134°	94°	406,147	42.3	8,205	9,602
4/27→4/29	11.8%→9.3%	10.6%	49.00	134°	88°	416,386	30.2	8,498	13,788
4/29→5/1	9.3%→7.8%	8.6%	48.50	134°	86°	436,864	18.1	9,008	24,136
Totals and Averages									
4/9→5/1	80.7%→7.8%	--	535.50	--	--	3,339,914	881.3	6,237	3,790

Table 4

STEAM KILN - EXPERIMENTAL RUN 2S

Dates	M.C.	Avg. M.C.	Hours	DBT	WBT	BTUs	Estimated Pounds of Water Removed	BTUs/Hour	BTUs / Pound of Water
4/13→4/15	81.8%→57.9%	69.3%	40.50	110°	106°	1,671,215	290.2	41,265	5,759
4/15→4/17	57.9%→45.8%	51.8%	54.00	110°	106°	1,710,972	145.1	31,685	11,792
4/17→4/19	45.8%→38.1%	42.0%	41.00	110°	105°	1,301,651	93.1	31,748	13,981
4/19→4/21	38.1%→30.3%	34.2%	50.00	110°	102°	1,524,723	94.3	30,494	16,169
4/21→4/23	30.3%→24.0%	27.2%	47.00	110°	96°	1,480,798	76.2	31,506	19,433
4/23→4/25	24.0%→17.5%	20.8%	48.50	120°	90°	1,994,552	78.6	41,125	25,376
4/25→4/27	17.5%→11.5%	14.5%	49.50	140°	90°	2,771,636	72.5	55,993	38,229
4/27→4/28	11.5%→3.8%	7.6%	48.00	180°	130°	2,402,001	93.1	49,020	25,800
Totals and Averages									
4/13→4/28	81.8%→3.8%	--	378.50	--	--	14,857,548	943.1	39,254	15,754

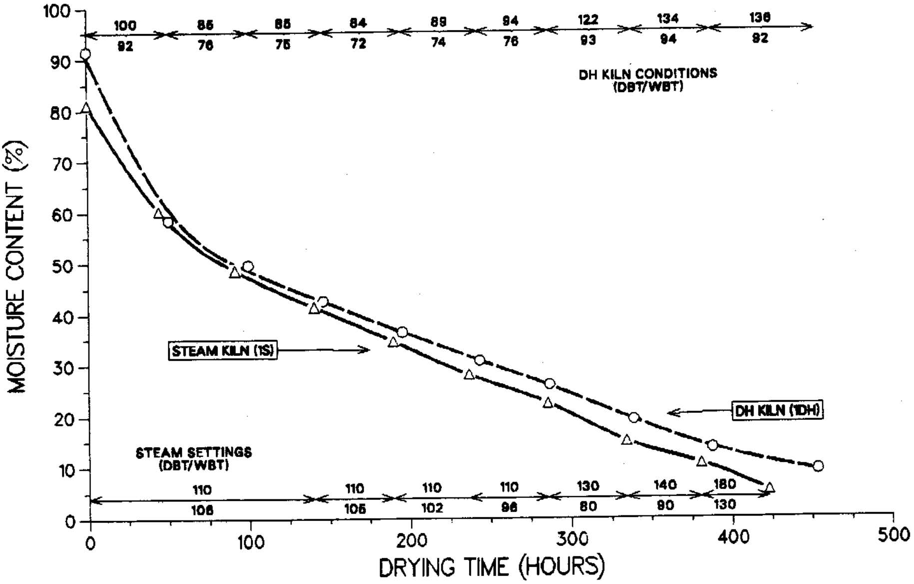

Figure 1 DRYING CURVES FOR STEAM AND DH KILNS

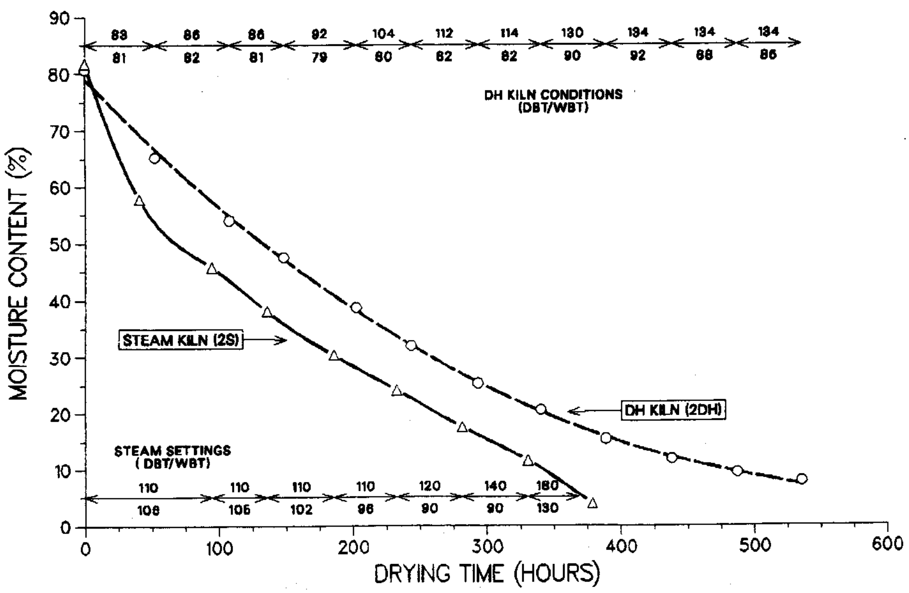

Figure 2 DRYING CURVES FOR STEAM AND DH KILNS

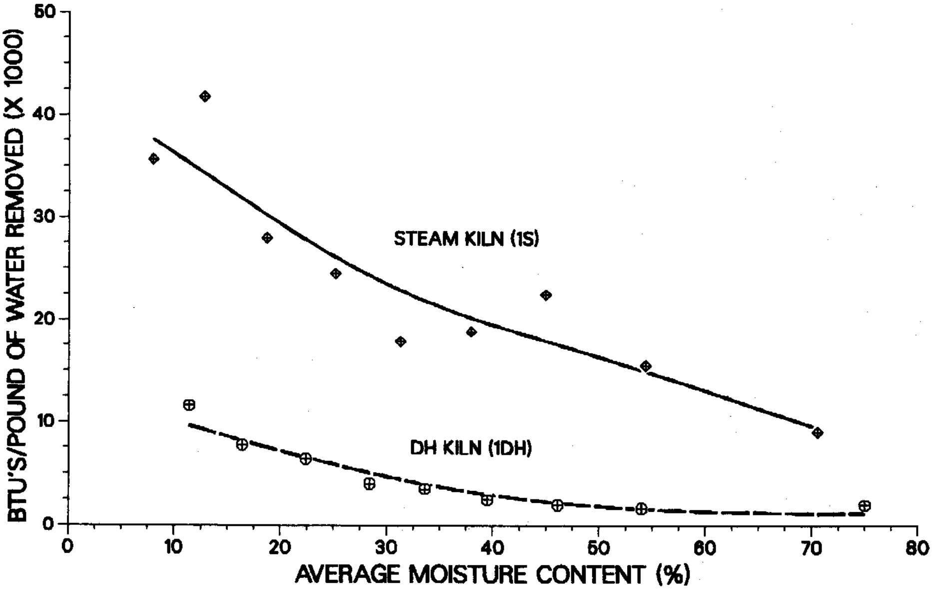

Figure 3 ENERGY CONSUMPTION PER POUND OF WATER REMOVED VERSUS AVERAGE MOISTURE CONTENT

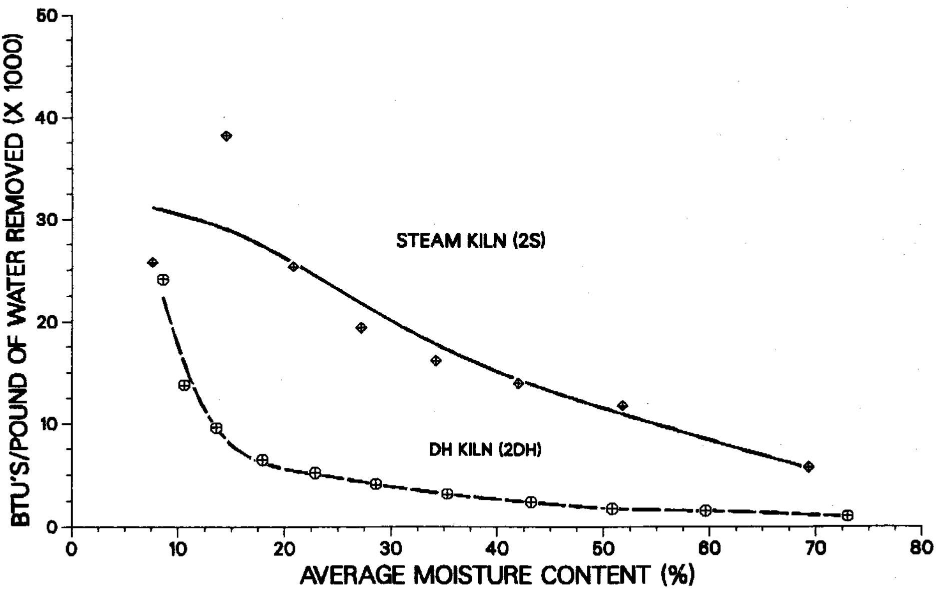

Figure 4 ENERGY CONSUMPTION PER POUND OF WATER REMOVED VERSUS AVERAGE MOISTURE CONTENT

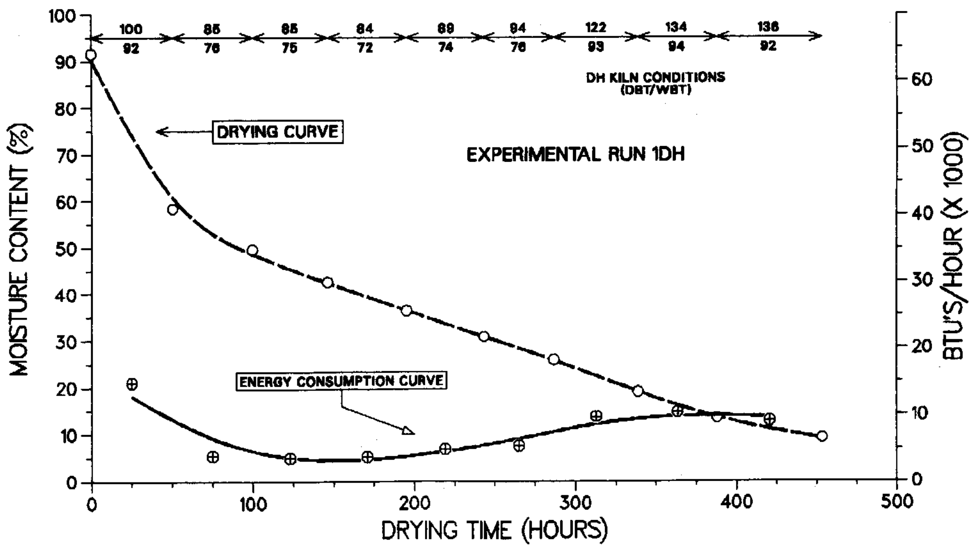

Figure 5 AVERAGE MOISTURE CONTENT AND ENERGY CONSUMPTION AS A FUNCTION OF DRYING TIME FOR THE DH KILN

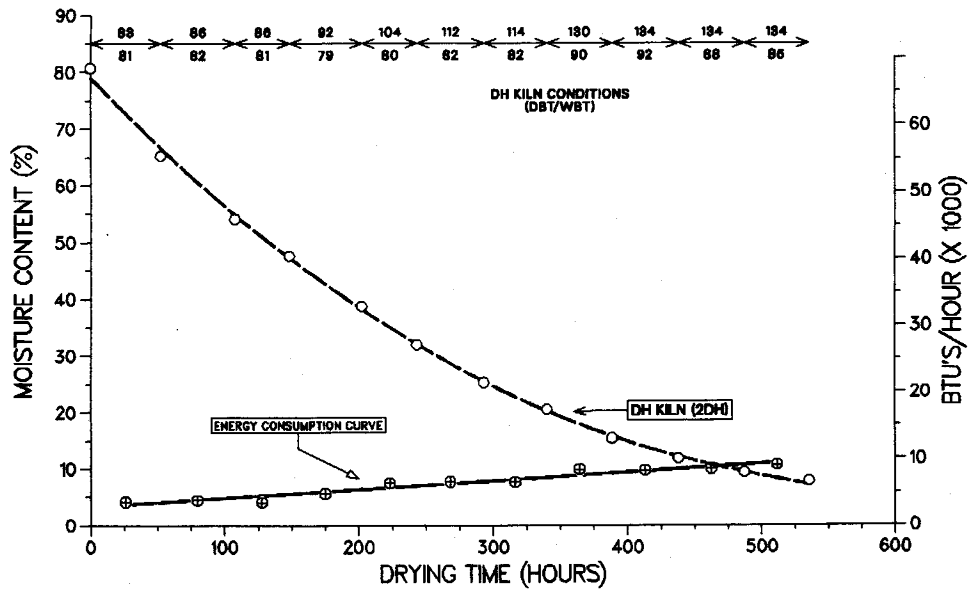

Figure 6 AVERAGE MOISTURE CONTENT AND ENERGY CONSUMPTION AS A FUNCTION OF DRYING TIME AND DH KILN CONDITIONS

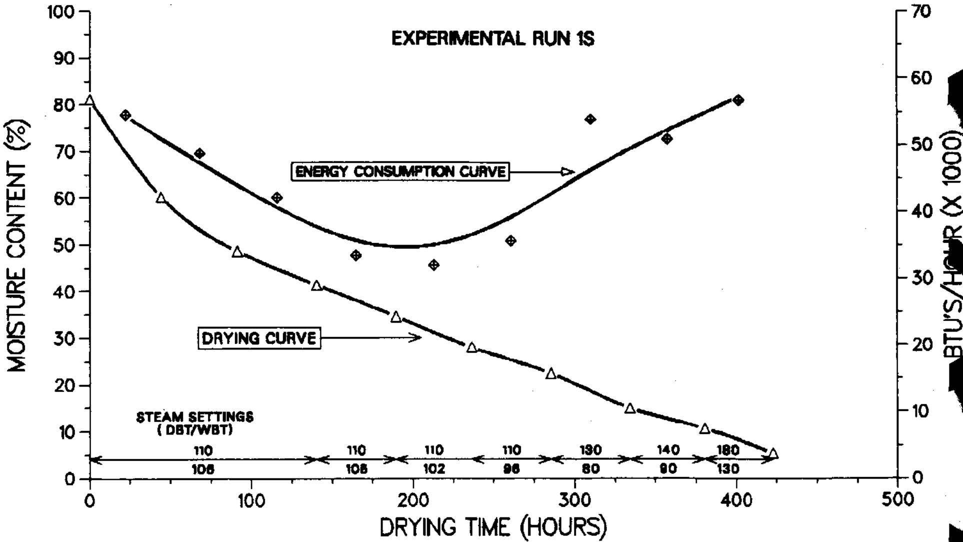

Figure 7 AVERAGE MOISTURE CONTENT AND ENERGY CONSUMPTION AS A FUNCTION OF DRYING TIME FOR THE STEAM KILN

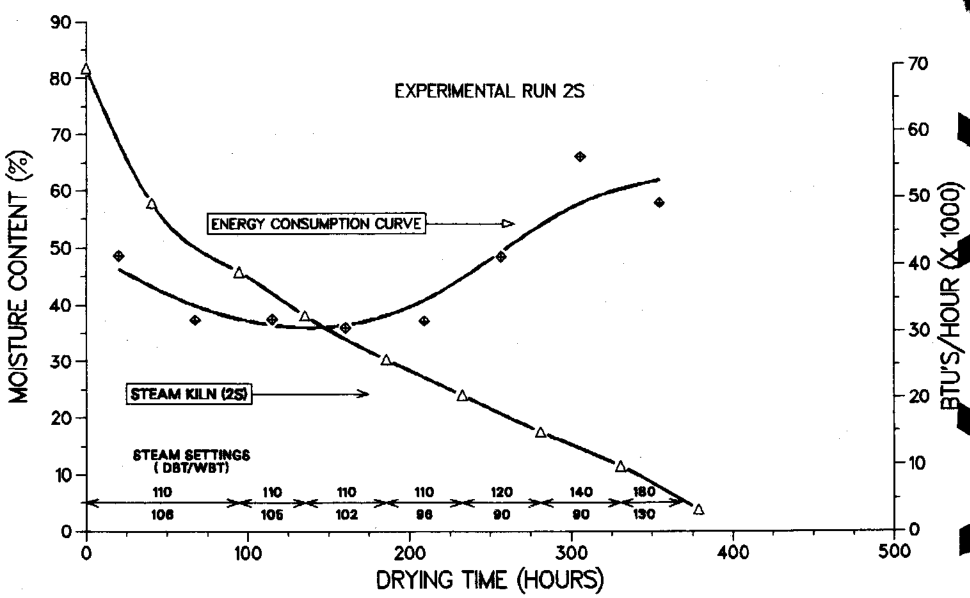

Figure 8 AVERAGE MOISTURE CONTENT AND ENERGY CONSUMPTION AS A FUNCTION OF DRYING TIME FOR THE STEAM KILN

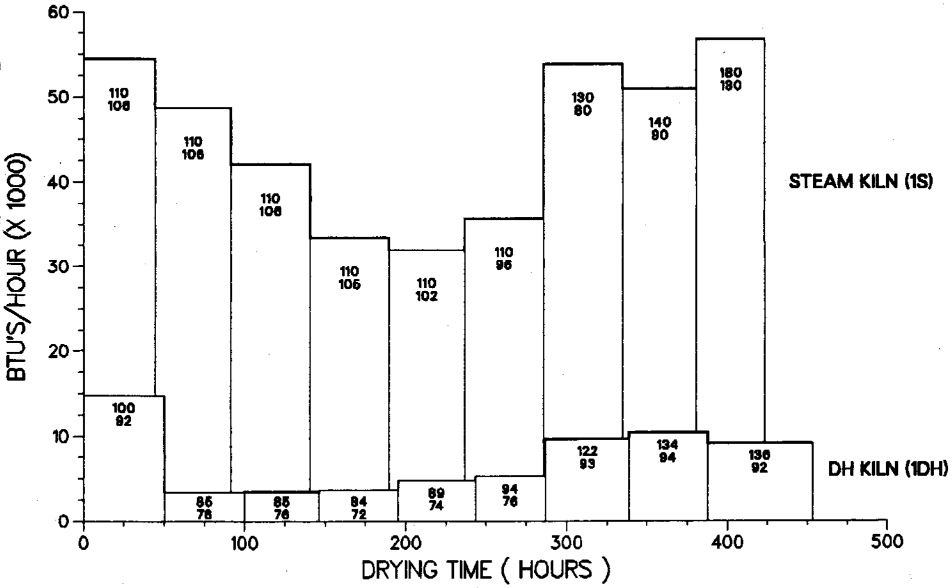

Figure 9 ENERGY CONSUMPTION PER HOUR VERSUS DRYING TIME

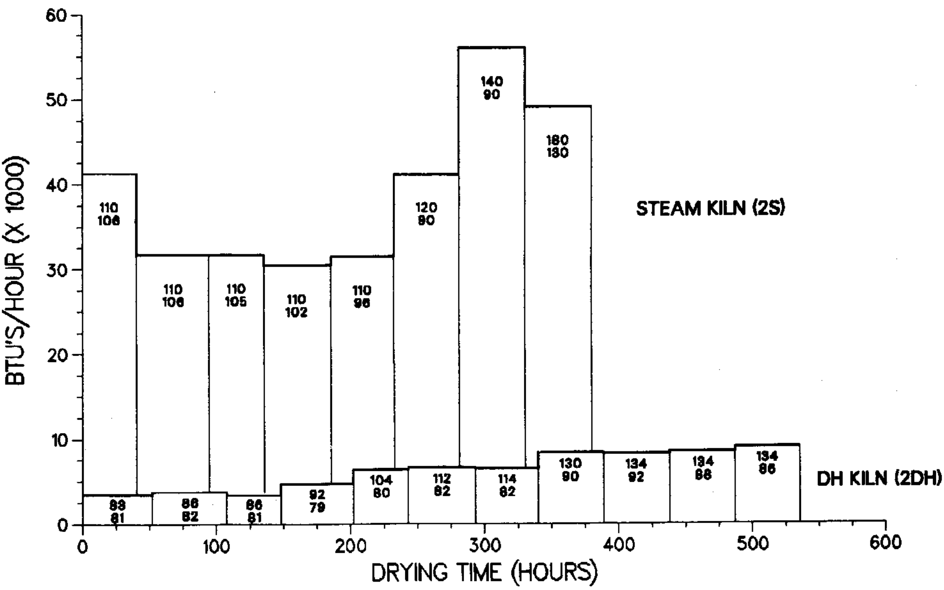

Figure 10 ENERGY CONSUMPTION PER HOUR VERSUS DRYING TIME