DURING WORLD WAR I, superheated-steam kilns were used in the Pacific Northwest and very rapid drying rates were reported. Some green 1-inch softwoods were dried to 10 percent moisture content in 24 hours; at drying temperatures as high as 230° F. in an atmosphere of steam. The relative humidity of the steam was regulated by controlling the dry-bulb temperature and maintaining a wet-bulb temperature at the boiling temperature of water (212° F.). The method is applicable to 1-inch Douglas-fir, true firs, western hemlock, ponderosa pine, southern yellow pine, basswood, and sapwood of sweet gum. So far as is known, it is not suitable for other hardwoods or for softwoods that have a tendency to collapse. While the reduction in drying time was well worthwhile, the severe drying conditions caused such rapid deterioration of materials used in kiln construction that the use of superheated-steam kilns was discontinued in the United States.

While there has been a recent revival of interest in the use of superheated-steam kilns, the principle of drying lumber by this method was recognized as early as 1867 when U. S. Patent No. 64,398, "Apparatus for Drying and Seasoning Lumber by Superheated Steam," was granted to C. F. Allen and Luther W. Campbell, Aurora, Ill. U. S. Patent No. 1,268,180 was granted to H. D. Tiemann, Madison, Wis., June 4, 1918, for a superheated-steam dry kiln in which circulation was induced by four pairs of steam-spray lines arranged in such a manner that the direction of circulation could be reversed.

Within the past several years considerable publicity has been given to three German high-temperature kilns. Early forms were constructed of steel or of masonry. In figure 1 is a transverse section of a kiln with an aluminum lining, insulated with about 5 inches of glass wool covered with a steel shell (2). Such construction is soldered so as to be vapor tight and is intended to reduce heat loss and deterioration of the metal. The modern kiln can be completely assembled at the factory and shipped as a unit ready for use as soon as steam and electrical connections are made. For foreign shipments, partial disassembly for crating is advantageous. It has been reported that 100 of these kilns have been installed in West Germany, two in Sweden, three in Canada, and several in South America. None are known in the United States. Since ordinarily they have a capacity of 2,000 to 3,000 feet of lumber, board measure, they are used primarily in small industrial plants (7).

Circulation in German high-temperature kilns is stimulated by disk fans or by centrifugal fans. The disk type is suitable when the resistance to flow is low, and the centrifugal type when the resistance is high. The disk fans are reversible. The fan axes may be parallel to or horizontally or vertically perpendicular to the long axis of the kiln (10). The motors are mounted outside the kiln.

Customarily, air-dried softwoods are loaded into a kiln in the morning, the vents and fresh-air intakes are closed, the steam-spray valve is opened unless the evaporated moisture is sufficient to maintain the desired relative humidity, the fans are started, and the heat, either steam or electric, is turned on for several hours, during which the temperature rises to 230° or 239° F. The temperature is maintained for 4 to 10 hours, and then the heat is shut off automatically (7). In some cases, the vents and fresh-air intakes are partially opened as soon as the maximum temperature is reached; but ordinarily they are not fully opened until the heat supply is shut off. The wet-bulb temperature may be maintained at 212° F., but generally is somewhat lower. The fans are in operation during the entire kiln run, which is about 24 hours. Ordinarily, these kilns are not equipped with wet- and dry-bulb record-controllers. In some cases, however, the dry-bulb temperature is thermostatically controlled (7).

Basically, water vapor is superheated when, at any pressure, its temperature exceeds that of the saturated vapor. When the wet-bulb temperature is below 212° F. at atmospheric pressure, both air and water vapor are present. When the wet-bulb temperature reaches 212° F., no air is present. Further heating of the vapor results in superheated steam at atmospheric pressure. In other words, if the wet-bulb temperature in a kiln is below 212° F., the kiln may be called a superheated-vapor kiln. On the other hand, if the wet-bulb temperature is 212° F., and if the dry-bulb temperature is above 212° F., the kiln may be called a superheated-steam kiln. If, however, the dry-bulb temperature is above 212° F., the term "high-temperature" may be applied to the kiln irrespective of whether the wet-bulb temperature is at or below 212° F.

In order to release heat for evaporation in a kiln at temperatures below the boiling point of water, the temperature of the air and vapor is lowered. The air, of course, can give up heat for evaporation as long as its temperature is higher than that of the wood to be season.
dried. The vapor, on the other hand, can, as its temperature drops, supply heat for evaporation only until the point of saturation is reached. At the standard atmospheric pressure of 14.696 pounds per square inch absolute, or zero pound gage, the temperature of saturated steam is 212° F. Wood in contact with such steam could be heated, but the water in it could not be evaporated.

Relative humidity may be defined as the ratio of the actual vapor pressure to the pressure at saturation at the given temperature. For example, at a dry-bulb temperature of 150° F. and a wet-bulb temperature of 132° F., psychrometric curves (such as those in fig. 2) commonly available to dry-kiln operators show that the dew point is 130° F. and the relative humidity is about 60 percent. In steam tables, which are commonly given in handbooks and textbooks on mechanical engineering, physics, or chemistry, the saturated-vapor pressure at 130° F. is 2.222 pounds per square inch absolute. The corresponding saturated-vapor pressure at 150° F. is 3.718 pounds per square inch absolute. The relative humidity is then 2.222/3.718 = 59.8 percent, which checks with the percentage determined from the curves as described above. When, however, a German high-temperature dry kiln is operating with a dry-bulb temperature at 230° F. and a wet-bulb temperature of 194° F., the relative humidity is less and cannot be readily calculated from steam tables. Since 230° F. and 194° F. are respectively 110° C. and 90° C., however, the corresponding relative humidity may be determined from the curves shown in figure 3, which was prepared by R. Keylwerth (8). The intersection of a horizontal line through 110° C. with the 90° wet-bulb temperature line (sloping upward from left to right) corresponds to a relative humidity of about 49 percent as shown on the horizontal axis.

Suppose now, that saturated steam at 14.696 pounds per square inch absolute is superheated from 212° F. to 230° F., while the atmospheric pressure remains unchanged. In other words, the steam is superheated 18° F. Referring again to steam tables, we find that at 212° F. the vapor pressure is 14.696 pounds per square inch absolute, and at 230° F. the vapor pressure is 20.780 pounds per square inch absolute. The relative humidity is then 14.696/20.780 = 70.7 percent.

Most kiln operators are familiar with the relationship of temperature and relative humidity to equilibrium moisture content for temperatures below the boiling point of water at atmospheric pressure. A number of investigators, notably in Germany (8) and in Australia (4), have performed experiments to determine the equilibrium moisture content of wood exposed at atmospheric pressure to superheated steam at temperatures up to 300° F. Eisenmann (2) determined corresponding values for pressures up to 31/2 atmospheres, or about 51 pounds per square inch absolute, as shown in figure 4. In this figure, the heavy horizontal and vertical lines show four combinations of temperature and relative humidity, all of which correspond to an equilibrium moisture content of 8 percent. It is interesting to note that at least up to 248° F. the determinations at atmospheric pressure (fig. 3) correspond well with estimates arrived at by the mathematical extrapolation (9) of curves (fig. 5) prepared at the U. S. Forest Products Laboratory and dated May 21, 1926.

Kiln Temperatures

Kollman (8) states that drying by superheated steam is suitable for softwoods and beech, but not for green hardwoods, such as oak, which checks and collapses readily. If they are air dried, or kiln dried at a moderate temperature to 25 percent, they can be further kiln dried at a high temperature without checking. In superheated steam at 120° C., the equilibrium moisture content of wood is 4.5 percent, and at 130° C. it is only 3 percent. Kollman regards these conditions as too severe and recommends a maximum temperature of 115° C. In this case, the equilibrium moisture content is about 5.5 percent. He, as well as Egner (1), considers a range of 110° to 115° C. as being most expedient. At 100° C., the equilibrium moisture content is 7 percent.

In figure 6 is shown an example of conditions in a superheated-vapor kiln during the drying of 1-inch spruce from a moisture content of 30 to 8 percent in 6 hours. The initial temperature of the wood was 68° F. During the first 11/2 hours the relative humidity rose to 85 percent. The wet-bulb temperature during most of the next 4-hour period was slightly below 100° C. (212° F.). As the dry-bulb temperature rose to 118° C. (244° F.), the relative humidity dropped to 52 percent and then fluctuated between 48 and 53 percent while the dry-bulb temperature remained constant at 118° C. Practically all the drying occurred during 411/2 hours.

Drying Gradient

Keylwerth (6) developed a concept that the ratio of the moisture content (below the fiber-saturation point) of the lumber at a given instant to the equilibrium moisture content should be a constant. He set up the condition that the equilibrium moisture content should be chosen so that the lumber during the entire drying process would always require the same time to reach that equilibrium. Mathematically, he expressed the concept thus:

\[ \frac{u_m}{u_{eq}} = \text{constant} \]

where \( u_m \) is the instantaneous moisture content and \( u_{eq} \) the corresponding equilibrium moisture content. To this ratio he applied the term "drying gradient"
and worked out the following values, which are applicable below the fiber-saturation point.

1. For mild drying conditions and high-quality stock, or for stock thicker than 1.2 inches: hardwood, about 1.5; and softwood, about 2.0.

2. For more severe drying conditions and low-quality stock, or for stock less than 1.2 inches in thickness: hardwood, 2.0 to 3.0; softwood, 3.0 to 4.0.

Above the fiber-saturation point the equilibrium moisture content is maintained constant at 14 to 18 percent, depending on the particular item being dried.

**Rates of Circulation**

Various investigators advocate rates of circulation of 2 to 10 meters per second (394 to 1,970 feet per minute); 2 to 3 meters per second (394 to 590 feet per minute) are most commonly mentioned. Among the factors affecting the rates are, presumably, differences in species, in initial moisture content, in the presence of open doors, in relative humidity, and in length of air travel. Sturany (11) refers to "amount of air exchanged," rather than to linear rate. He states that in a certain superheated-steam kiln, the amount of "air" is exchanged 2,100 times, while for standard kilns the corresponding figures range from 200 to 800. The usual rates of circulation in American ventilated kilns range from 250 to 350 feet per minute. Because high temperatures result in high rates of drying, it is to be expected that the rates of circulation mentioned for foreign kilns would be higher than those in American kilns in order to carry the moisture away from the lumber as rapidly as it comes to the surface.

**Energy Required for Drying**

Keylwerth (5) indicates that, with a superheated-vapor kiln, the usual range of energy required is 1.2 to 1.5 kilowatt-hours per kilogram (2.2 pounds) of water evaporated, and that the corresponding range is 2 to 4 kilowatt-hours with low-temperature drying. He attributes the lower energy requirement to the lower heat loss, lower heat capacity of the construction materials, and the shorter drying time in the case of the superheated-vapor kiln.

Eisenmann (3) cites an example of the drying of 1-inch spruce from a moisture content of 30 to 6 percent after it was heated for 4.5 hours in a superheated-vapor kiln. In this connection the following data were tabulated for an electrically heated kiln:

- Oven-dry weight of wood: 350 kilograms per cubic meter (21.9 pounds per cubic foot)
- Reduction of 24 percent in moisture content: 84 kilograms (185 pounds)
- Heat required to evaporate 1 kilogram of water at 20° C.: 620 kilocalories (2,460 British thermal units)
- 84 kilograms of water require: 52,080 kilocalories (207,000 British thermal units)
- 1 kilowatt-hour is equivalent to: 860 kilocalories (3,415 British thermal units)
- 74 kilowatt-hours required per cubic meter of wood is equivalent to: 63,640 kilocalories (232,650 British thermal units)

**Distribution of Moisture**

Some investigators have indicated considerable difficulty in attaining a reasonable degree of uniformity in moisture content values among kiln-dried boards. Eisenmann (2), however, reports the following when a stack of 26 other values was 6.5 to 10.4 percent, with an average of 8.5 percent.

**Effects of High-Temperature Drying on Wood Properties**

Keylwerth (5) found that samples of red beech dried in superheated steam at 115° C. (239° F.), as compared with those dried at 65° C. (149° F.), had an equilibrium moisture content value about 2 percent lower at 12 percent moisture content also, they had somewhat higher modulus of rupture, maximum crushing strength, and modulus of elasticity. In impact bending and in tension perpendicular to the
grain, however, the samples dried at 115° C. had somewhat lower values. The radial and tangential shrinkages were reduced 24 and 20 percent, respectively. Graf and Egner (2) reported that pine dried at 115° C. shrank and swelled only 70 percent as much as air-dry pine.

Available information concerning the effect of high-temperature drying on case-hardening is not very detailed. General reports indicate, however, that case-hardening resulting from this method of drying is not of commercial importance in Germany.

Kollman (8) determined "relative whiteness" of pine boards photo-spectrographically over a considerable range of wave lengths, after drying them in a steam-air mixture at temperatures of 60° to 140° C. (140° to 284° F.). His conclusions were as follows:

1. The action of temperature during the first 5 to 10 hours has the greatest influence on whiteness.
2. The discoloration is slight up to 70° C. (158° F.), moderate between 70° C. and 140° C., and heavy above 140° C. (284° F.).
3. In the moisture content range of 0 to 15 percent, the effect of moisture content is negligible; between 15 and 40 percent, the effect is perceptible; and above 40 percent the effect is marked.

Data obtained by the Forest Products Laboratory have indicated, for example, that in ordinary kiln drying of 6/4 ponderosa pine sapwood it was possible to minimize brown stain by applying a low-temperature, low-humidity schedule: for example, one with initial conditions of 120° F. and 55 percent relative humidity and with final conditions of 160° F. and 24 percent. The commonly accepted theory is that chemical brown stain usually results from chemical reactions that occur in water-soluble extractives as they are concentrated and deposited during drying. It is quite possible that, at the very high temperatures cited by Kollman, the movement of moisture in the vapor phase, rather than in the liquid phase, predominated. If this be the case, it would be expected that the concentration of extractives and consequently the discoloration would be less. Furthermore, the much shorter drying time at high temperatures may be an important factor. There is also some evidence that the discoloration that does occur at high temperatures can be readily surfaced off, whereas in ordinary kiln operation the entire cross section of a board may be heavily discolored.

Conclusions

In recent years marked advances have been made in the construction of high-temperature kilns in Germany. The kilns are well insulated and vapor-tight, so that heat losses and deterioration of the construction materials are minimized. Moreover, the operating temperatures of up to 115° C. (239° F.) permit very rapid drying of lumber. In some instances drying time has been reduced 80 percent. While most of the kilns of this type can be operated with a wet-bulb temperature at or below 212° F., they are ordinarily operated at a wet-bulb temperature below 212° F. One advantage of such operation is a reduction or elimination of chemical discoloration.

Another advantage, as compared with that resulting from drying in a standard ventilated kiln, is a reduction in hygroscopicity. Increases in some strength properties and losses in others are reported. By and large, however, German investigators do not consider the changes in strength properties important.

It would be desirable to begin an investigation of the effects of high-temperature drying on hardwoods and softwoods growing in the United States.

Literature Cited