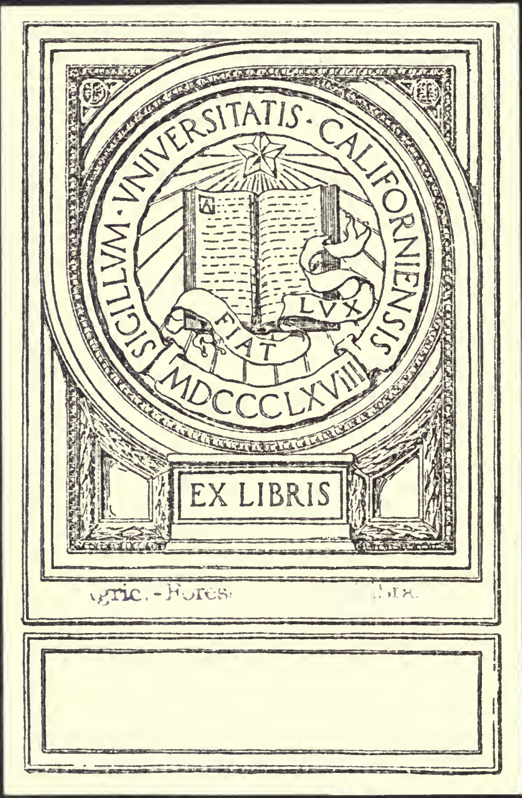
# The Theory of Drying and its Application to the New Humidity-Regulated and Recirculating Dry Kilns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# THE THEORY OF DRYING AND ITS APPLICATION TO THE NEW HUMIDITY-REGULATED AND RECIRCULATING DRY KILN.

By HARRY D. TIEMANN, *In Charge, Section of Timber Physics, Forest Products Laboratory.*

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## INTRODUCTION.

The problem of satisfactorily drying lumber without checking, honeycombing, or warping is one of very wide interest. Although an old problem, it has not yet reached an entirely satisfactory solution, especially with hardwood lumber. Even air drying, which is the slowest and what might be called the most conservative method of removing the moisture, is far from satisfactory for some species of wood. The drying of softwoods, or wood from coniferous trees, on the other hand, may be considered as having reached a fairly satisfactory solution. With few exceptions, the softwoods present no special difficulty to the lumber drier. The great trouble with the hardwoods lies in their relatively excessive and very unequal shrinkage. This is due largely to the structure of the wood. In softwoods the vertical elements are all of the same kind, regularly arranged and of approximately the same width (tangentially). The medullary rays also are very fine and regular. In hardwoods, on the other hand, the elements are very complex, varying in diameter in some species in the same section 20 to 30 times, and are often very crooked. Many woods, such as the oak, have large medullary rays, as well as very small ones, irregularly arranged. Consequently, strains are produced when the wood dries, which cause warping and checking. While air drying is undoubtedly the safest method, the process is ordinarily so slow, requiring a year or longer according to species and size, that forced "artificial" drying becomes a business necessity. Moreover, air drying is by no means always to be preferred to kiln drying from the standpoint of the quality of the product.

A correct understanding of the principles of drying is rare, and opinions in regard to the subject are very diverse. The same lack of knowledge exists in regard to dry kilns. The physical properties of the wood which complicate the drying operation and render it distinct from that of merely evaporating free water from some substance like a piece of cloth must be studied experimentally. It can not well be worked out theoretically.

The thermal process of the drying operation, however, is capable of exact theoretical analysis. It is the purpose of this article to interpret the conditions which exist in the various stages of the drying operation with respect to the heat quantities and the changes which occur in the drying medium, from a theoretical standpoint. The object of this analysis is to show the limiting conditions which may be approached, but can not be exceeded.

## ELEMENTARY PRINCIPLES OF DRYING.

Before taking up the theoretical discussion, a few remarks upon the elementary principles of drying will be of assistance.

### EVAPORATION REQUIRES HEAT.

In the first place, it should be borne in mind that it is the heat which produces evaporation and not the air nor any mysterious property assigned to a "vacuum." For every pound of water evaporated at ordinary temperatures approximately 1,000 British thermal units of heat are used up, or "become latent," as it is called. This is true whether the evaporation takes place in a vacuum or under a moderate air pressure. If this heat is not supplied from an outside source it must be supplied by the water itself (or the body being dried), the temperature of which will consequently fall until the surrounding space becomes saturated with vapor at a pressure corresponding to the temperature which the water has reached; evaporation will then cease. The pressure of the vapor in a space saturated with water vapor increases rapidly with increase of temperature. At a so-called vacuum of 28 inches, which is about the limit in commercial operations, and in reality signifies an actual pressure of 2 inches of mercury column, the space will be saturated with vapor at about 101° F. Consequently, no evaporation will take place in such a vacuum unless the water be warmer than 101° F., provided there is no air leakage. The qualification in regard to air is necessary, for the sake of exactness, for the following reason: In any given space the total actual pressure is made up of the combined pressures of all the gases present. If the total pressure ("vacuum") is 2 inches, and there is no air present, it is all produced by the water vapor (which saturates the space at 101° F.); but if some air is present and the total pressure is still maintained at 2 inches, then there must be less vapor present, since the air is producing part of the pressure and the space is no longer saturated at the given temperature. Consequently further evaporation may occur, with a corresponding lowering of the temperature of the water, until a balance is again reached. Without further explanation it is easy to see that but little water can be evaporated by a vacuum alone without addition of heat and that the prevalent idea that a vacuum can of itself produce evaporation is a fallacy. If heat be supplied to the water, however, either by conduction or radiation, evaporation will take place in direct proportion to the amount of heat supplied, so long as the pressure is kept down by the pump.

At 30 inches of mercury pressure (one atmosphere) the space becomes saturated with vapor and equilibrium is established at 212° F. If heat be now supplied to the water, however, evaporation will take place in proportion to the amount of heat supplied, so long as the pressure remains that of one atmosphere, just as in the case of the vacuum. Evaporation in this condition, where the vapor pressure at the temperature of the water is equal to the gas pressure on the water, is what is commonly called "boiling," and the saturated vapor entirely displaces the air under continuous operation. Whenever the space is not saturated with vapor, whether air is present or not, evaporation will take place, by boiling if no air be present or by diffusion under the presence of air, until an equlibrium between temperature and vapor pressure is resumed.

Relative humidity is simply the ratio of the actual vapor pressure present in a given space to the vapor pressure when the space is saturated with vapor at the given temperature. It matters not whether air be present or not. One hundred per cent humidity means that the space contains all the vapor which it can hold at the given temperature—it is saturated. Thus at 100 per cent humidity and 212° F. the space is saturated, and since the pressure of saturated vapor at this temperature is one atmosphere, no air can be present under these conditions. If, however, the total pressure at this temperature were 20 pounds (5 pounds gauge), then it would mean that there was 5 pounds air pressure present in addition to the vapor, yet the space would still be saturated at the given temperature. Again, if the temperature were 101° F., the pressure of saturated vapor would be only 1 pound, and the additional pressure of

14 pounds, if the total pressure were atmospheric, would be made up of air. In order to have no air present and the space still saturated at 101° F., the total pressure must be reduced to 1 pound by a vacuum pump. Fifty per cent relative humidity, therefore, signifies that only half the amount of vapor required to saturate the space at the given temperature is present. Thus at 212° F. temperature the vapor pressure would only be 7½ pounds (vacuum of 15 inches gauge). If the total pressure were atmospheric, then the additional 7½ pounds is simply air. "Live steam" is simply saturated water vapor at a pressure usually above atmospheric. We may just as truly have live steam at pressures less than atmospheric, at a vacuum of 28 inches for instance. Only in the latter case its temperature would be lower, viz, 101° F. Superheated steam is nothing more than water vapor at a relative humidity less than saturation, but is usually considered at pressures above atmospheric, and in the absence of air. The atmosphere at, say, 50 per cent relative humidity really contains superheated steam or vapor, the only difference being that it is at a lower pressure and temperature than we are accustomed to think of in speaking of superheated steam, and it has air mixed with it to make up the deficiency in pressure below the atmosphere.

Two things should now be clear: That evaporation is produced by heat and that the presence or absence of air does not influence the amount of evaporation. It does, however, influence the rate of evaporation, which is retarded by the presence of air. The main things influencing evaporation are, first, the quantity of heat supplied and, second, the relative humidity of the immediately surrounding space.

### IMPORTANCE OF CIRCULATION.

A piece of wood may be heated in three ways—(1) by convection of the air and vapor or other gases, (2) by conduction through some body in contact therewith, and (3) by radiation. Of these three ways, only the first is ordinarily available for use in heating a pile of lumber, since by either of the other two methods only the outside surface of the pile could be heated; hence the necessity of a large and thorough circulation of air. Drying in a vacuum would be feasible if there were some means of conveying the heat to the wood. A single stick can be readily dried in a vacuum, as it can receive heat on all sides by radiation from the walls of a steam-jacketed cylinder; but this is impracticable when it comes to any quantity of lumber, except in the case of superheated vapor alone, as will be shown later, since only the outer surface or the outside boards would receive the heat in this way and the inside ones would not dry. Even an approach to a perfect vacuum, however, is not reached in commercial apparatus. Moreover, the heat convection in a vacuum of 26 inches or less is almost as rapid as under ordinary air pressure.[1] The viscosity of the gas is a factor in the convection through small spaces, such as between the layers of lumber, and as this is almost as great at low pressures as at atmospheric pressure, it follows that the actual circulation would nevertheless be very much cut down. Thus, by drawing a vacuum the means of heating the wood is reduced. Later on it will be shown, however, that drying at low pressure in absence of air should give the highest theoretical heat efficiency, but the volume of vapor required is excessive.

### RATE OF EVAPORATION CONTROLLED BY HUMIDITY.

It is essential, therefore, to have an ample supply of heat through the convection currents of the air; but in the case of wood the rate of evaporation must be controlled, else checking will occur. This can be done by means of the relative humidity. It is clear now that when the air—or, more properly speaking, the space—is completely saturated no evaporation can take place at the given temperature. By reducing the humidity, evaporation takes place more and more rapidly.

Another bad feature of an insufficient and nonuniform supply of heat is that each piece of wood will be heated to the evaporating point on the outer surface, the inside remaining cool until considerable drying has taken place from the surface. Ordinarily in dry kilns high humidity and large circulation of air are antitheses to one another. To obtain the high humidity the circulation is either stopped altogether or greatly reduced, and to reduce the humidity a greater circulation is induced by opening the ventilators or otherwise increasing the draft. This is evidently not good practice, but as a rule is unavoidable in most kilns. The humidity should be raised to check evaporation without reducing the circulation.

## ELEMENTARY PRINCIPLES OF HYGROMETRY.

### RELATIVE HUMIDITY AND DEW POINT.

It is necessary to know something of hygrometry in order to understand the drying operations. As stated before, at any given temperature the same quantity of water vapor is required to saturate a given

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[1] Bottomly gives for radiation of a bright platinum wire to a copper envelope, at different air pressures, the temperature of the inclosure being 16° C. and the difference in temperature 408° C. expressed in the heat lost in c. g. s. units per square centimeter of inclosure (Smithsonian Table 250):

| | |
|---|---|
| At 740 mm. absolute pressure | 0.8137 |
| At 42 mm. absolute pressure | .7591 |
| At 0.44 mm. absolute pressure | .2683 |
| At 0.01 mm. absolute pressure | .0539 |

These figures evidently include radiation and convection. They show comparatively small change at pressures above 42 millimeters of mercury, which corresponds to a vacuum of about 28.4 inches.

space, whether any air is present or not; and the pressure of the vapor is the same in both cases. The total pressure (as registered by the gauge) will not be the same, however, since if air is present its pressure is added to that of the vapor. It is really the space and not the air which is saturated. For instance, at 101° F. it takes about 20 grains of vapor to saturate a cubic foot of space. If no air be present, there will be a pressure of vapor only, which will be about 1 pound, or a vacuum of 28 inches. If this is open to the atmosphere the air will rush into the space until the total pressure will be one atmosphere, or about 15 pounds. There will then be 1 pound of pressure produced by the vapor, as before, and 14 pounds of air pressure. The space will still be saturated, if the temperature is kept at 101° F. If this is now heated to 160° F. and open to the atmosphere so that the total pressure is kept constant, the ratio of the pressures of vapor and air will also remain the same; there will still be 1 pound due to vapor and 14 pounds due to the air. (The weights in the cubic foot of space of both will decrease, due to expansion by heat.) At 160° F., however, it requires 91 grains of vapor to saturate a cubic foot of space, and its pressure is nearly 5 pounds (absolute). Consequently, the relative humidity at 160° F. of this space will be one-fifth, or 20 per cent. Conversely, if this air and vapor at 20 per cent relative humidity and 160° F. temperature is cooled to 101° F., all at the same atmospheric pressure, the space will again become saturated, and any further cooling will cause precipitation or condensation. This is called the dew point; that is, 101° F. is the dew point of air with 20 per cent humidity at 160° F. In Forest Service Bulletin 104, "Principles of Drying Lumber at Atmospheric Pressure and Humidity Diagram," a humidity diagram is given for solving all problems of this nature. The concave curves on this diagram are simply curves of constant vapor pressure with change of temperature and relative humidity, and the grains of vapor per cubic foot, at saturation or the dew point, are given in numerical figures. From this it is seen that the dew point determines the relative humidity when the temperature is raised, or vice versa. If we take saturated air at known temperature and heat it up any given desired amount, the resulting relative humidity is thereby determined. This is the principle upon which the humidity regulation depends in a new kiln designed by the writer.[1] It is also evident that whenever air is cooled below its dew point condensation takes place. This is the principle of the condenser. There are a number of kilns which have made use of this principle to dry the air. Pipes are used for the condensers and cold water is circulated through the pipes. The same thing can be accomplished by a spray of cold water in place of the pipes, provided all the fine mist is subsequently removed from the air, or even by a sur-

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[1] For a description of this kiln see page 10.

face of cold water. In the new kiln a fine spray of water is used instead of a condenser. This has the additional advantage that when the water is heated above a certain temperature (the temperature of the wet bulb in a wet-and-dry bulb hygrometer) it will humidify the air. By simply changing the temperature of the spray the air may be supplied at any desired humidity.

### INSTRUMENTS FOR MEASURING HUMIDITY.

A common instrument used for measuring humidity is the wet-and-dry bulb hygrometer or "psychrometer." This consists of two thermometers mounted side by side, the bulb of one of which is covered by a silk cloth or wick which dips into a vessel of water. This should be placed in a fairly strong draft of air. The evaporation from the "wet bulb" reduces its temperature below that of the dry bulb, and the rate of this evaporation, and consequently the temperature of the wet bulb, depends upon the relative humidity in the air. By noting the two temperatures of the dry and the wet bulb thermometers the relative humidity can be determined by tables which have been carefully worked out by the Weather Bureau.[1]

In the humidity diagram in Forest Service Bulletin 104 the values are expressed in curves (the convex series of curves on the diagram), by means of which the relative humidity may be read off directly without numerical calculations. This instrument is probably the simplest reliable means for determining humidity. There are instruments which read directly from a hand on a dial, the motion of the hand being produced by the swelling of vegetable or animal tissues. These are very convenient but fragile and not to be depended upon. The most direct way of determining humidity is, of course, to determine the dew point. This may be accomplished by gradually cooling a bright surface, as polished metal, in contact with the moving air, until a mist is precipitated thereon. Special interest attaches to the wet-and-dry bulb hygrometer for the reason that the wet wood in the dry kiln is actually in the same condition as the wet bulb. It is affected in the same way. The actual temperature of the wood, while it is moist, is therefore that of the wet bulb, provided there is sufficient circulation.

### TYPES OF KILNS.

There are two distinct ways of handling lumber in kilns. One way is to place the load of lumber in a chamber where it remains in the same place throughout the operation, while the conditions of the drying medium are varied as the drying progresses. This is the compartment kiln or stationary method. The other is to run the lumber in one end of the chamber on a wheeled truck and gradually

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[1] See Psychrometer Tables by Marvin, Bulletin 235 of United States Weather Bureau.

move it along until the drying process is completed, when it is taken out at the opposite end of the kiln. An attempt is usually made in these kilns to maintain one end moist and the other end dry. This is known as the "progressive" type of kiln, and is the one most commonly used in large operations. It is the least satisfactory of the two, however, where careful drying is required, since the conditions can not be so well regulated and the temperatures and humidities are apt to change with change of wind. The compartment method can be arranged so that it will not require any more kiln space or any more handling of lumber than the progressive type. It does, however, require more intelligent operation, since the conditions in the kiln must be changed as the drying progresses. With the progressive type the conditions, once established, remain the same.

To obtain draft or circulation three methods are in use—by forced draft or a blower usually placed outside the kiln, by ventilation, and by internal circulation and condensation. A great many patents have been taken out on different methods of ventilation, but in actual operation few work exactly as intended. Frequently the air moves in the reverse direction for which the ventilators were planned. Sometimes a condenser is used in connection with the blower and the air is recirculated. It is also—and more satisfactorily—used with the gentle internal-gravity currents of air.

Many patents have been taken out for heating systems. The differences among these, however, have more to do with the mechanical construction than with the process of drying. In general, the heating is either direct or indirect. In the former steam coils are placed in the chamber with the lumber, and in the latter the air is heated by either steam coils or a furnace before it is introduced into the kiln.

Moisture is sometimes supplied by means of free steam jets in the kiln or in the entering air; but more often the moisture evaporated from the lumber is relied upon to maintain the humidity necessary. In the new humidity-regulated kiln the humidity is controlled directly. The majority of kilns make no attempt whatever to regulate this all-important factor beyond retaining an indeterminate amount at the beginning of the operation and drying the air, either by condensers or by ventilation at the end.

Other methods of drying in vacuum and in various gases have been tried from time to time.

## DRYING BY SUPERHEATED STEAM.

There is still another type of kiln which is not included in the former classification, viz, that using superheated steam. What this term really signifies is simply water vapor in the absence of air in a condition of less than saturation. Such kilns are, properly speaking, vapor kilns, and usually operate at atmospheric pressure, but may be used at greater pressures or at less pressures. As stated before, the vapor present in the air at any humidity less than saturation is really "superheated steam," only at a lower pressure than is ordinarily understood by this term, and mixed with air. The main argument in favor of this process seems to be based on the idea that steam is moist heat. This is true, however, only when the steam is near saturation. When it is superheated it is just as dry as air containing the same relative humidity. For instance, steam at atmospheric pressure and heated to 248° F. has a relative humidity of only 50 per cent and is just as dry as air containing the same humidity. If heated to 306° F., its relative humidity is reduced to 20 per cent; that is to say, the ratio of its actual vapor pressure (one atmosphere) to the pressure of saturated vapor at this temperature (five atmospheres) is 1:5, or 20 per cent. Superheated vapor in the absence of air, however, parts with its heat with great rapidity and finally becomes saturated when it has lost all of its ability to cause evaporation. In this respect it is more moist than air when it comes in contact with bodies which are at a lower temperature. When saturated steam is used to heat the lumber it can raise the temperature of the latter to its own temperature, but can not produce evaporation unless, indeed, the pressure is varied. Only by the heat supplied above the temperature of saturation can evaporation be produced. This subject will be taken up again in the theoretical analysis.

## IMPORTANCE OF PROPER PILING OF LUMBER.

The efficiency of the drying operation depends a great deal upon the way in which the lumber is piled, especially when the humidity is not regulated. From the theory of drying just discussed it is evident that the rate of evaporation in kilns where the humidity is not regulated depends entirely upon the rate of circulation, other things being equal. Consequently, those portions of the wood which receive the greatest amount of air dry the most rapidly, and vice versa. The only way, therefore, in which anything like uniform drying can take place is where lumber is so piled that each portion of it comes in contact with the same amount of air.

In the Forest Service kiln, where the degree of relative humidity is used to control the rate of drying, the amount of circulation makes little difference, provided it exceeds a certain amount. It is desirable to pile the lumber so as to offer as little frictional resistance as possible and at the same time secure uniform circulation. If circulation is excessive in any place it simply means waste of energy but no injury to the lumber.

The best method of piling is one which permits the heated air to pass through the pile in a somewhat downward direction. The natural tendency of the cooled air to descend is thus taken advantage of in assisting the circulation in the kiln. This is especially important when cold or green lumber is first introduced into the kiln. But even when the lumber has become warmed the cooling due to the evaporation increases the density of the mixture of the air and vapor. Table 3 shows analytically that the spontaneous cooling of the mixture produced by the evaporation alone increases its density. This fact is of great significance, and the method of piling lumber in the Forest Service kiln takes advantage of this principle.

## THEORY AND DESCRIPTION OF THE FOREST SERVICE KILN.

The humidities and temperatures in the piles of lumber are largely dependent upon the circulation of air within the kiln. The temperature and humidity within the kiln, taken alone, are no criterion of the conditions of drying within the pile of lumber if the circulation in any portion is deficient. It is possible to have an extremely rapid circulation of the air within the dry kiln itself and yet have stagnation within the pile, the air passing chiefly through open spaces and channels. Wherever stagnation exists or the movement of air is too sluggish the temperature will drop and humidity increase, perhaps to the point of saturation.

When in large kilns the forced circulation is in the opposite direction from that induced by the cooling of the air by the lumber there is always more or less uncertainty as to the movement of the air through the piles. Even with the boards placed edgewise, with stickers running vertically, and with the heating pipes beneath the lumber, it was found that although the air passed upward through most of the spaces it was actually descending through others, so that very unequal drying resulted. While edge piling would at first thought seem ideal for the freest circulation in an ordinary kiln with steam pipes below, it in fact produces an indeterminate condition; air columns may pass downward through some channels as well as upward through others, and probably stagnate in others. Nevertheless, edge piling is greatly superior to flat piling where the heating system is below the lumber.

From experiments and from a study of conditions in commercial kilns the idea was developed of so arranging the parts of the kiln and the pile of lumber that advantage might be taken of this cooling of the air to assist the circulation. That this can be readily accomplished without doing away with the present features of regulation of humidity by means of a spray of water is clear from figure 1, which shows a cross section of the improved humidity-regulated dry kiln.

In the form shown in the sketch a chamber or flue B runs through the center near the bottom. This flue is only about 6 or 7 feet in height and, together with the water spray F and the baffle plates D D, constitutes the humidity-control feature of the kiln. This control of humidity is effected by the temperature of the water used in the spray. This spray completely saturates the air in the flue B at whatever predetermined temperature is required. The baffle plates D D are to separate all entrained particles of water from the air, so that it is delivered to the heaters in a saturated condition at the required temperature. This temperature is, therefore, the dew point of the air when heated above, and the method of humidity control may therefore be called the dew-point method. It is a very simple matter by means of the humidity diagram,[1] or by a hydrodeik, to determine what dew-point temperature is needed for any desired humidity above the heaters.

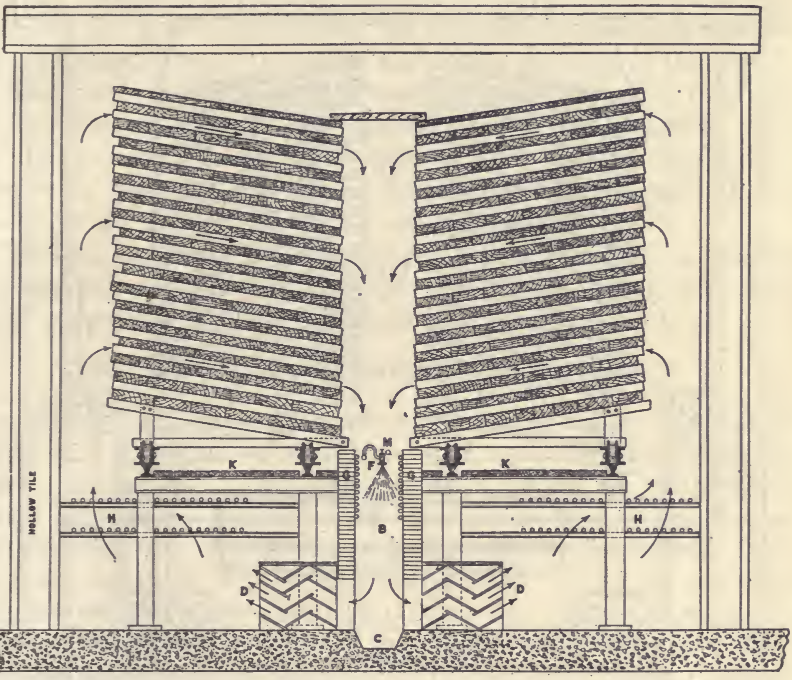

FIG. 1.—Diagrammatic section of improved dry kiln with spray chambers in center. Double-truck form.

Besides regulating the humidity the spray F also acts as an ejector and forces a circulation of air through the flue B. The heating system H is concentrated near the outer walls, so as to heat the rising column of air. The temperature within the drying chamber is controlled by means of any suitable thermostat, actuating a valve on the main steam line. The lumber is piled in such a way that the stickers slope downward toward the center.

M is an auxiliary steam spray pointing downward for use at very high temperatures. C is a gutter to catch the precipitation and

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[1] Forest Service Bulletin 104, "Principles of Drying Lumber at Atmospheric Pressure and Humidity Diagram," Superintendent of Documents, Government Printing Office, Washington, D. C. Price, 5 cents. Lumber World Review, Feb. 10. 1915.

conduct it back to the pump, the water being recirculated through the sprays. G is a pipe condenser for use toward the end of the drying operation. K is a baffle plate for diverting the heated air and at the same time shielding the under layer of boards from direct radiation of the steam pipes.

The operation of the kiln is simple. The heated air rises above the pipes H H at the sides of the piles of lumber. As it comes in contact with the piles portions of it are cooled and pass downward and inward through the layers of boards into the space between the condensers G G. Here the column of cooled air descends into the spray flue B, where its velocity is increased by the force of the water spray. It then passes out from the baffle plates to the heaters and repeats the cycle.

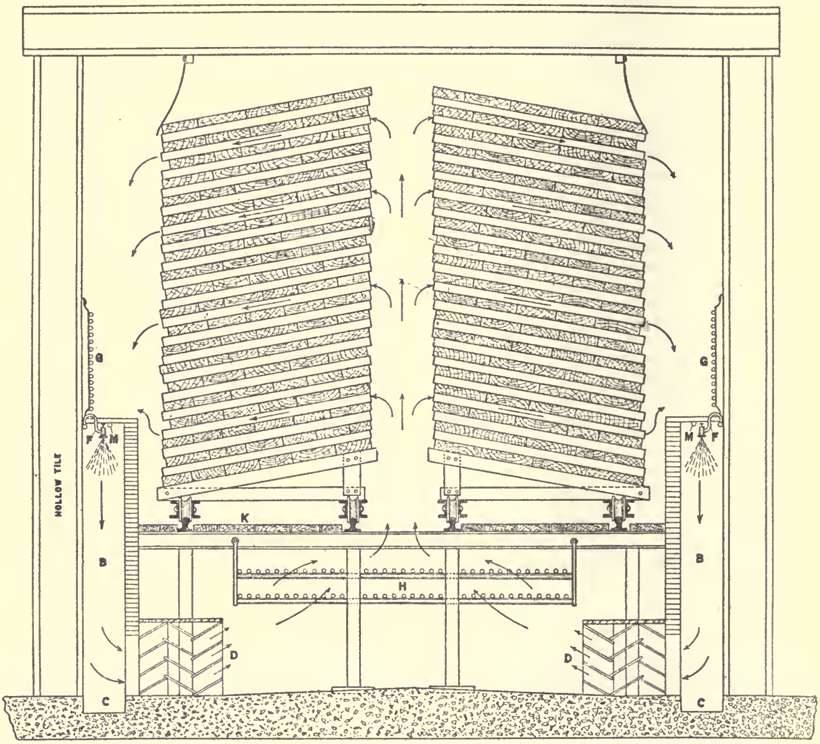

FIG. 2.—Diagrammatic section of improved dry kiln with spray chambers on sides. Double-truck form.

Various modifications of this arrangement may be made. For instance, a single-track kiln may be used. This form would be represented by simply dividing the diagram vertically into two parts by extending the wall G (on the left side) upward to represent the outer wall, and erasing the part to the left of this line. Or, again, the spray chambers may be kept on the sides as shown in figure 2. The lumber would then slope in the opposite direction with respect to the center of the kiln and the air would rise in the center and descend on the sides.

One of the greatest advantages of this natural circulation method is that the colder the lumber when placed in the kiln the greater is the movement produced, under the very conditions which call for the greatest circulation—just the opposite of the direct-circulation method. This is a feature of the greatest importance in winter, when the lumber is put into the kiln in a frozen condition. One truck load of lumber at 60 per cent moisture may easily contain over 7,000 pounds of ice.

In the matter of circulation the kiln is, in fact, self-regulatory—the colder the lumber the greater the circulation produced, with the effect increased toward the cooler and wetter portions of the pile.

Preliminary steaming may be used in connection with this kiln, but experiments indicate that ordinarily it is not desirable, since the high humidity which can be secured gives as good results, and, being at as low a temperature as desired, much better results in the case of certain difficult woods like oak, eucalyptus, etc.

This kiln has another advantage in that its operation is entirely independent of outdoor atmospheric conditions, except that barometric pressures will affect it slightly.

## THEORETICAL DISCUSSION OF EVAPORATION.

In considering the drying effect of vapor alone (superheated steam) and of air mixed with the vapor, one very significant fact must be noticed. Saturate vapor alone in cooling and in order to remain saturate must absorb heat. Its specific heat is negative, so that the only way it can heat a body is by condensation. It is, therefore, incapable of producing evaporation. When air is present with the saturate vapor, however, the air can supply some of this heat, according to the pressure of the air present, so there will be less condensation.

Still more important is the fact that when air is present with the vapor sufficient heat can be supplied to the body being dried by means of the air without greatly superheating the vapor, thus keeping a high relative humidity and at the same time supplying a sufficient amount of heat to carry on the evaporation. With vapor alone (superheated steam) a relatively high degree of superheating, which means a correspondingly low relative humidity, is required in practice in order to supply the necessary heat for evaporation, after the material has become heated through to the temperature of the saturated vapor at the pressure used. Remember that the temperature of the wet wood corresponds to that of the wet bulb in the hygrometer when air is present, but very nearly to the dew point in the presence of superheated vapor alone.

### EVAPORATION IN THE ABSENCE OF AIR.

In vapor alone, no air being present, evaporation from a surface of water takes place at the dew point, but when the water is intimately contained in other substances the temperature must be higher than the dew point. If air is present it retards the rate of evaporation from a free surface of water, so that the surface is warmer than the dew point, depending upon the degree of relative humidity in the air. While the surface of wood is wet its temperature will not rise above that of the wet bulb in the presence of air, nor above the dew point in superheated vapor alone. As it becomes drier, however, its temperature will rise, due to its affinity for retaining moisture. In the former condition there is no danger of too rapid drying, but in the latter condition, if the humidity is too low or the superheat too high, the drying from the surface may become more rapid than the rate at which the moisture is transmitted from the center, and casehardening results.

In considering the manner in which drying takes place in superheated steam, suppose the pressure is atmospheric and that a wet piece of wood has been heated in saturated steam to 212° F. No evaporation will take place until additional heat is added. Now, suppose steam superheated to 232° F. or 20° of superheat is introduced. The portion immediately in contact with the surface of the wet wood will be cooled to 212° F., and in so doing it will vaporize a certain portion of water from the surface. As the specific heat of this steam is, in round terms, one-half, and as it requires about 1,000 thermal units to vaporize one unit of water, to vaporize a single molecule of water at 212° F. will require contact of 100 of the molecules of superheated steam at 232° F. We will then have 101 molecules of steam in the saturated condition at 212° F. Evaporation must then cease unless this saturated steam is replaced by some fresh superheated steam. Evaporation from a free surface of water in the absence of air (in superheated steam) always takes place at the boiling point (which in this case is the same as the dew point). If, however, there is a deficiency of water in the wood more heat will be required to separate it and to vaporize it, and evaporation will take place at a higher temperature than the dew point. In fact, evaporation may cease altogether in the superheated steam, and a higher degree of superheating be required (which is equivalent to a lower humidity) to get the moisture out of the wood. In the case of a surface of free water the rate of evaporation depends entirely upon the amount of heat transmitted to the water, whether by increasing the circulation or by increasing the degrees of superheat. In the latter case, when the moisture is intimately contained in the wood, the rate depends largely upon the relative humidity.[1] There is a balance between what might be termed the retentive or attractive property of the wood, "hygroscopicity," and the tendency of the moisture to vaporize. It is the difference between the tension of the vapor at the higher temperature of the wood and the tension actually existing in the space surrounding the wood. This retentive property increases as the wood becomes drier and decreases as it approaches the wet condition. Experiments indicate that generally it is nearly inversely proportional to the amount of moisture remaining in the wood.

### EVAPORATION WHEN AIR IS PRESENT.

When air is present with the superheated steam or water vapor the conditions are quite different. Vaporization of a particle from the surface of the free water is retarded by the air pressure, so that the temperature of the water may be raised above the dew point.[2]

The air now, as well as the vapor, conducts heat to the water, so that the rate of evaporation at given pressures depends not alone on the quantity of heat supplied (by circulation and degree of superheating) but upon the relative amounts of vapor and air present. That is to say, the lower the relative humidity the greater is the rate of evaporation at a given temperature and pressure. The temperature of the water will correspond to that of the wet bulb, and not to that of the dew point. When the wood becomes partially dried its temperature will rise, as in the case of superheated steam, and it may be heated even above the boiling point at the given pressure without giving up all of its moisture, provided there is some vapor in the air.

### CONCLUSIONS AS TO DRYING IN VAPOR ALONE AND IN AIR AND VAPOR.

Thus it is seen that the rate of drying may be controlled by the relative humidity, provided there be sufficient circulation to supply the heat required. In the case of steam alone, the rate of drying, as just shown, depends upon the quantity of circulation as well as the degree of superheating. Hence the conclusion follows that moist air, with ample circulation, should give more uniform drying throughout than superheated steam, which varies with the rate of circulation in each portion.

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[1] In using the term relative humidity as applied to superheated steam it is understood to mean the ratio of the actual vapor pressure to that of the pressure of saturated vapor at the given temperature, as explained before.

[2] In reality what probably happens is that the layer of air in immediate contact with the water becomes saturated and has a higher vapor pressure corresponding to the temperature of the surface of the water, and the air retards the diffusion of this vapor. The temperature of the water, however, can not exceed the boiling point for the given pressure, at which point the conditions must become the same as those for superheated steam alone, since then the air will become entirely displaced by the water vapor.

But the chief difficulty with superheated steam at or above atmospheric pressure is the high temperature to which the material must be subjected, the minimum with very wet wood being 212° F., and increasing as the wood dries. Below atmospheric temperatures, costly apparatus is required for operating at a vacuum, and the heating medium is attenuated, requiring an excessive volume of vapor to be circulated if the danger is to be avoided of the wood, as it becomes dry on the surface, being heated too high. Instead of a vacuum the same result can be obtained by combining air with the vapor, in which case the air makes up the deficiency of pressure. For instance, a vacuum of 28 inches, which is about the extreme in mechanical operations, will give an absolute vapor pressure of about 1 pound and a temperature of 101° F. for saturated conditions. Precisely the same value for the vapor occurs if saturated air at 101° F. and atmospheric pressure is used instead, in which case the additional heating capacity of the air present is also available. There would then be in a cubic foot of space vapor pressure of 1 pound (nearly) per square inch and 13.7 pounds of dry air pressure. This amount of vapor would weigh 0.0029 pound and the air 1/15.2 or 0.0658 pound (15.2 being the volume in cubic feet of 1 pound of dry air at 13.7 pounds pressure and 101° F. temperature).

### HEATING CAPACITIES OF AIR AND VAPOR IN MIXTURE.

The heating capacity of the vapor in this cubic foot of space, in falling 1 degree, from 102° F. to 101° F., is $.0029 \times .42$[1]$=.00122$ B. t. u., as before, while that of the air present is $.0658 \times .237 = .0156$ B. t. u., or more than ten times that of the vapor present. The total heating capacity of 1 cubic foot of the mixture, in falling 1 degree, from 102° F. to 101° F., is then the sum of these two, viz, .01682 B. t. u. The latent heat of evaporation at 101° F. being 1044, it will require the heat given up by $1044/.01682 = 62{,}206$ cubic feet of the mixed air and vapor falling 1 degree, from 102° F. to saturation at 101° F., to evaporate 1 pound. This is very much less than that required for vapor alone, which, as will be shown farther on, is 829,433 cubic feet. In fact, the quantity in volume is less than that of dry air alone at 212° F. and one atmospheric pressure (69,000), as figured farther on. If the vapor is superheated, say, to 112° F., its pressure remaining the same as before, this is simply equivalent, so far as the vapor is concerned, to air at atmospheric pressure with a relative humidity of less than saturation. In this case the relative humidity would be the pressure of the actual vapor—0.972 pound per square inch—divided by the pressure which the vapor would have if it were saturated at 112° F., viz, $.972/1.34 = 73$ per cent humidity.

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[1] The specific heat of superheated vapor at this temperature is 0.421 as given by Thiesen.

It should now be evident that superheated vapor is the same thing as moist air with the air removed. The same effects upon the material to be dried are produced in both cases, as far as the vapor is concerned; but in the case of moist air, the effect of the air is added to that of the vapor. The same laws apply to the vapor, whether the air is present or absent. The air conveys heat, but by its presence retards the diffusion of the vapor, and consequently retards the rate of evaporation.

### RELATIVE HEATING CAPACITIES OF AIR AND VAPOR.

To compare the relative heating capacities of dry air and of superheated vapor, the following deductions are made: The specific heat of water vapor at a pressure of one atmosphere is 0.475; that is to say, 1 pound of superheated steam in falling 1° F. gives up 0.475 British thermal unit. To evaporate 1 pound of water at 212° F., therefore, will require the heat given up by 966 (latent heat at 212° F.)$\div$.475=2034 pounds of steam falling 1 degree. At 212° F. the volume per pound is 26.78 cubic feet; therefore, $2034\times26.78=54{,}470$ cubic feet of superheated steam falling 1 degree are required to evaporate 1 pound of water. The specific heat of dry air is 0.237 and the volume of 1 pound is 16.93 (0.05907 pound per cubic foot) at 212° F. and atmospheric pressure. Therefore, to evaporate 1 pound of water at 212° F. (966 B. t. u.) will require the heat given up by $966\times\frac{16.93}{.237}=69{,}000$ cubic feet of dry air falling 1 degree. Thus it is seen that the heating capacity per unit of volume of superheated steam at atmospheric pressure is but little greater than that of dry air at the same temperature and pressure, in the ratio of 69,000 to 54,470, or about 5 to 4. At temperatures above 212° F. and the same pressure of one atmosphere a greater volume is necessary to produce the same effect, since the gas and vapor expand with temperature, but the ratio of the heating capacity of superheated steam and dry air remains very nearly the same. The specific heat of vapor increases slightly at higher temperatures. Thus, figuring in a similar manner, it will be found that at five atmospheres pressure (59 pounds gauge) the heating ratio of equal volumes of steam and air is 1.42 to 1, and at 1 pound absolute pressure or a vacuum of 28 inches, it is 1.104 to 1. The volume of steam at five atmospheres pressure and 306° F. in falling 1 degree necessary to evaporate 1 pound of water at this pressure and temperature is 10,336 cubic feet, and at a vacuum of 28 inches at 101° F. it is 829,433 cubic feet.

Thus it is seen that there is but little advantage, from the point of view of the volume of gas to be moved, in the use of superheated steam over that of dry air.

In this discussion a cubic foot of space has been used as the basis of the calculations. In analyzing the heat quantities in the drying operation it will be easier to use 1 pound of dry air as a basis, with its accompanying moisture, and follow it through its various stages. Its volume will therefore not remain fixed, but will change with every change in temperature, and consequently the degree of saturation produced by a definite amount of moisture accompanying it will depend upon the volume which it occupies.

## THEORETICAL ANALYSIS OF HEAT QUANTITIES.

For this purpose the simplest way will be to follow a pound of dry air through a drying cycle as a basis for computations. While in reality the vapor does not enter the air like water in a sponge, but occupies the same space whether air is present or not, we may, for convenience, conceive of a pound of air as containing a certain amount of vapor, which, in reality, means that the space occupied by a pound of dry air under given conditions contains a certain amount of vapor.

### VAPOR AND AIR IN MIXTURE.

As already explained, the total pressure always is the sum of the individual pressures of the air alone plus the vapor alone. Thus we may speak of a pound of air as being wholly or partially saturated with vapor, meaning that it is the space occupied by the pound of air which is in this condition of vapor. If a pound of air said in this sense to contain a given weight of vapor is heated a given amount under a pressure of one atmosphere, both air and vapor will expand the same amount, so that at the new temperature both will occupy the same relative amount of space; the pound of air, however, will still contain the same weight of vapor. The amount of vapor contained in a pound of air alone, when it is saturated, can not be used as the divisor in obtaining the relative humidity when compared to the amount of vapor actually contained in the pound of air alone, because when the air is saturated the pressure of the air alone will have been reduced, corresponding to the increase in the vapor pressure (since the sum of the two make up one atmosphere), so that for a pound of air a much greater space is required, and, consequently, an equivalently greater weight of vapor to occupy this larger space. For relative humidity it is necessary to compare the weights of vapor which occupy the same amount of space when partially or wholly saturated, or, better still, to compare the vapor pressures.

### CYCLE IN DRYING OPERATION OF 1 POUND OF AIR.

In following the pound of dry air through its cycle of operation, let the air enter the heater either from outside or from the spray chamber at temperature $t_1$, and let it contain $d_1$ pounds of vapor. (See fig. 3.) After passing through the heater both the air and the vapor are raised to the temperature $t_2$. Each pound of air still contains $d_1$ pounds of moisture, since the vapor expands to the same extent as the air if no vapor is added or subtracted during the heating from $t_1$ to $t_2$. In passing through the lumber, the air and vapor become cooled to $t_3$, and an amount of moisture, w, is added from the evaporation, so that the pound of air at temperatures $t_3$ now contains $d_3=(d_1+w)$ pounds of moisture. Thence they either escape into the outer air, as in a ventilating kiln, or pass into the spray chamber, where the heat added by the heater and the extra amount of moisture w is removed from the pound of air into the spray water, and is returned at the initial temperature $t_1$ saturated to repeat the cycle. The changes in total pressure will be so slight that they may be neglected, and the whole operation considered to take place at a uniform pressure of one atmosphere. Let r equal the specific heat of air at constant pressure, and s that of superheated vapor. These will be taken as 0.237 and 0.475, respectively. Then the quantity of heat imparted to the pound of air and its accompanying $d_1$ pounds of vapor by the heater is (1), $(.237+d_1\times.475)\ (t_2-t_1)$ and the amount of heat given up in evaporating the water w is (2), $(.237+d_1\times.475)\ (t_2-t_3)$. The amount of water evaporated is $w=(d_3-d_1)$. Now the heat required to evaporate the water w in continual operation will be that required to raise it from its initial temperature to the evaporating point, plus the latent heat of vaporization at this point; also the heat necessary to raise the temperature of the wood alone the same amount. As the latter is small, it will be neglected. Suppose that the initial temperature of the outside air and of the wet wood is 32° F. Then the heat required is simply the total heat H of w pounds of vapor at the temperature $t_3$ (nearly).[1]

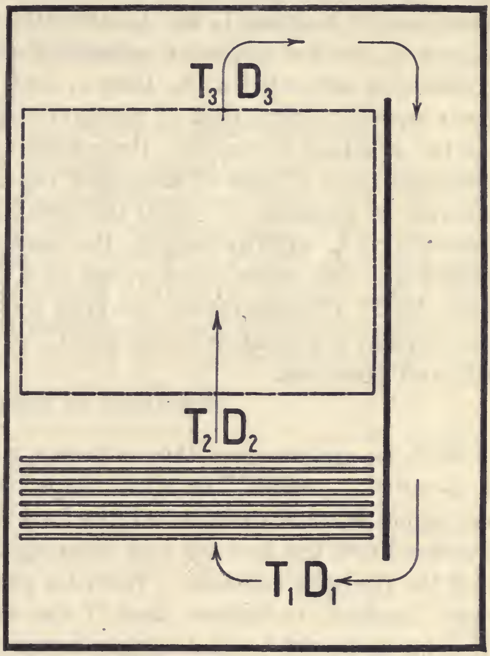

FIG. 3.—Diagrammatic plan of drying cycle.

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[1] Evaporation will actually take place at the temperature of the wet bulb if the air is not saturated, after which the vapor is superheated to $t_3$.

Hence (3), $(.237+d_1\ .475)\ (t_2-t_3)=wH=(d_3-d_1)\ H$ or $\frac{t_2-t_3}{d_3-d_1}=\frac{H}{.237+d_1 .475}$. In this equation $t_2$ is a known quantity, being dependent upon the kind and condition of the material being dried. $d_1$ is known, being the weight of moisture of the outside air per pound of dry air, or the weight required to saturate 1 pound of air in the spray kiln at the temperature $t_1$. H is known approximately (but not exactly, since its value varies with $t_3$, or more properly with the wet-bulb temperature), and may at first be assumed for some temperature between $t_2$ and $t_1$, and afterwards be correctly assigned. $t_3$ and $d_3$ are the unknown quantities required. If the air is to be considered saturated at $t_3$, then $t_3$ and $d_3$ are dependent variables, their equation being that of the curve of saturation for water vapor. As the equation is complex, their relative values can be more readily obtained from a table of saturated vapor, and successive values substituted in equation (3) until the equation is fulfilled. Having thus determined $t_3$ approximately, the correct value for H may be inserted and the more exact value of $t_3$ determined. This has been done by E. Hausbrand in "Drying by Means of Air and Steam"[1] for diffrent temperatures of $t_1$ and $t_2$, as well as for different humidities and pressures.

### EFFICIENCY OF OPERATION.

With no air present—that is to say, with water vapor alone under a so-called "vacuum," or with "superheated steam" at pressures of one atmosphere or greater—all the heat may be utilized in evaporating the moisture, the leaving and entering temperatures being the same and the pressure constant. With air present, however, and the pressure constant, it follows that if the entering air is saturated the leaving air must be at a higher temperature, in order that it may contain the additional vapor at the same pressure. Thus in raising the temperature of the air leaving the lumber a greater amount of heat is required than that utilized in evaporation.

There is another combination of conditions possible in which the temperature at exit may be the same or even less than that of the entering air or vapor. With air present this is only possible by decreasing the pressure below that of the entering saturated air. In this case the heat supplied may be even less than the theoretical amount required for vaporization, and the theoretical efficiency as reckoned by temperatures is more than 100 per cent. The advantage gained here is at the expense of the heat energy in the departing air and vapor, being somewhat analogous to the case of the condenser in a steam engine. The gain in heat is from the fact that the enter-

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[1] Translation from the German by Wright. Published by Scott Greenwood & Sons, 1901.

ing air is at a higher temperature than the leaving air. If the entering air is not saturated, a similar condition is possible, since some evaporation may take place without necessitating a higher temperature of the leaving air.

From the foregoing it might be concluded that the use of a vacuum or of superheated steam would be the most economical way in which to dry materials. In practice, however, the vacuum has certain disadvantages, as explained heretofore, the chief one being the greater volume of vapor required and the difficulty of producing a uniform circulation of vapor at high attenuation. The other drawback is the expense of the apparatus and difficulty of operation at pressures other than atmospheric. With superheated steam the temperature is too high for most woods.

### CONCRETE EXAMPLES OF RELATIONS OF HEAT QUANTITIES.

To illustrate the relations of these quantities under the various conditions, let us take a concrete example where the initial temperature of the air is 32° F. and the air is saturated both at the entrance and upon leaving. This is heated to 158° F. and then passed through the material to be dried. The volume of the gas required at the temperature of 158° F. and the theoretically least possible expenditure of heat required to evaporate 1 pound of water from an initial temperature of 59° F. at various pressures are given below in Table 1.

TABLE 1.—*Volume of gas required at a temperature of 158° F. and the theoretically least possible expenditure of heat required to evaporate 1 pound of water from an initial temperature of 59° F. at various pressures.*

| Absolute pressures. | Volume. | Total heat required. |
|---|---|---|
| | *Cubic feet.* | *B. t. u.* |
| 1½ atmospheres | 695 | 2,010 |
| 1 atmosphere=760 mm. of mercury | 876 | 1,692 |
| 500 mm. of mercury, partial vacuum | 1,247 | 1,578 |
| 250 mm. of mercury, partial vacuum | 2,121 | 1,346 |
| Using steam alone superheated from 140° to 158° F. at pressure of 148 mm. of mercury, corresponding to saturated conditions at 140° F | 16,821 | 1,125 |

The minimum theoretical expenditure of heat, as here calculated, has no direct bearing on the efficiency of any method of drying lumber, since the physical requirements of the lumber may, and generally do, demand conditions totally incompatible with the highest theoretical heat efficiency. They apply directly only to the evaporation of a free body of water, irrespective of length of time required and with no radiation losses. The calculations are useful, however, in showing the limiting values of the efficiency which it is possible to attain under the conditions which have otherwise been found most suitable for drying the lumber in question.

It is instructive to know the highest possible theoretical efficiency in evaporating a pound of water under given conditions, considering no losses by radiation or otherwise. For this purpose Table 2 has been worked out, assuming the water to start with an initial temperature of 59° F. and to evaporate at the temperature $t_3$, which is the temperature of the leaving air. The efficiency here expressed is the ratio of the total heat of water vapor at $t_3$ above 59° F. divided by the least possible expenditure of heat necessary to evaporate it under the assumed conditions of the entering and leaving air at atmospheric pressure. When the temperature $t_1$ of the entering air approaches that of the heated air $t_2$—that is, when a high humidity is used—the calculations become very uncertain, since the quantity of air called for under the assumed conditions approaches infinity, while the temperature differences between $t_1$ and $t_3$ become infinitesimal.

The minimum volume of air required to evaporate 1 pound of water is also given in Table 2.

TABLE 2.—*Maximum possible theoretical heat efficiency of evaporation under given conditions* ($t_1$, $t_2$, $h_1$, $h_3$) *at atmospheric pressure* (*760 mm.*).

| Entering air. | | After heating. | | Leaving air. | | Heat consumed to evaporate 1 pound of water from initial temperature of 59° F. | Total heat of 1 pound of vapor at $t_3$ above initial temperature of 59° F. | Minimum volume of air required. | Efficiency H÷G. |
|---|---|---|---|---|---|---|---|---|---|
| $t_1$ | $h_1$ | $t_2$ | $h_2$ | $t_3$ | $h_3$ | | | | |
| A | B | C | D | E | F | G | H | J | K |
| *° F.* | *Per ct.* | *° F.* | *Per ct.* | *° F.* | *Per ct.* | *B.t.u.* | *B.t.u.* | *Cubic ft.* | |
| 32 | 100 | 95 | 11 | 65 | 75 | 2,353 | 1,074 | 2,163 | 0.457 |
| 59 | 100 | 95 | 31 | 76 | 75 | 2,100 | 1,078 | 3,426 | .514 |
| 32 | 100 | 158 | 2 | 84 | 75 | 1,911 | 1,080 | 993 | .565 |
| 59 | 100 | 158 | 6 | 92 | 75 | 1,715 | 1,082 | 1,126 | .631 |
| 86 | 100 | 158 | 13 | 107 | 75 | 1,556 | 1,087 | 1,402 | .698 |
| 32 | 100 | 212 | 0+ | 97 | 75 | 1,758 | 1,084 | 694 | .617 |
| 59 | 100 | 212 | 2 | 103 | 75 | 1,572 | 1,086 | 731 | .690 |
| 86 | 100 | 212 | 4 | 114 | 75 | 1,422 | 1,089 | 796 | .767 |
| 32 | 100 | 95 | 11 | 84 | 25 | 6,136 | 1,080 | 5,738 | .176 |
| 32 | 100 | 158 | 2 | 110 | 25 | 2,972 | 1,088 | 1,495 | .366 |
| 86 | 100 | 158 | 13 | 141 | 25 | 4,869 | 1,098 | 4,385 | .225 |
| 32 | 100 | 212 | 0+ | 126 | 25 | 2,352 | 1,093 | 930 | .457 |
| 86 | 100 | 212 | 4 | 146 | 25 | 2,166 | 1,099 | 1,206 | .507 |
| 32 | 100 | 95 | 11 | 60 | 100 | 1,974 | 1,073 | 1,836 | .544 |
| 59 | 100 | 95 | 31 | 70 | 100 | 1,679 | 1,076 | 2,733 | .641 |
| 86 | 100 | 95 | 74 | 88 | 100 | 1,476 | 1,081 | 9,725 | .733 |
| 32 | 100 | 158 | 2 | 79 | 100 | 1,692 | 1,079 | 876 | .636 |
| 86 | 100 | 158 | 13 | 99.5 | 100 | 1,390 | 1,085 | 1,329 | .781 |
| 140 | 100 | 158 | 63 | 140.9 | 100 | 1,119 | 1,098 | 3,879 | .981 |
| 32 | 100 | 212 | 0+ | 90 | 100 | 1,582 | 1,082 | 625 | .684 |
| 86 | 100 | 212 | 4 | 106 | 100 | 1,350 | 1,087 | 721 | .804 |
| 176 | 100 | 212 | 47 | 176.5 | 100 | 1,130 | 1,108 | 2,002 | .972 |

IN WATER VAPOR ALONE.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 140 | 100 | 158 | 63 | 140 | 100 | 1,097 | 1,097 | 16,418 | 1.00 |
| 212 | 100 | 230 | 71 | 212 | 100 | 1,119 | 1,119 | 3,657 | 1.00 |
| 212 | 100 | 320 | 16 | 212 | 100 | 1,121 | 1,121 | 664 | 1.00 |

### GENERALIZATION.

A study of the theoretical heat relations, as shown by Hausbrand's tables, makes possible the following generalizations:

1. With $t_2$ constant and entering air saturated, the expenditure of heat is less, the higher the temperature, $t_1$, of the entering air.
2. With $t_1$ constant, the expenditure of heat is less, the higher the temperature, $t_2$, to which the air is heated.
3. Other things being the same, the heat expenditure increases rapidly with reduction in humidity of the emergent air.
4. Other things being the same, the heat expenditure is less, the lower the humidity of the entering air.
5. Other things being the same, the expenditure of heat increases with increase of pressure.
6. With water vapor in the absence of air, the theoretical efficiency becomes 100 per cent.

In regard to the weights and volumes of air required, the following observations are obtained, with entering air saturated:

With $t_2$ constant, both the weights and volumes of air required to evaporate 1 pound of water increases with increase of the initial temperature, $t_1$, of the entering air.

With $t_1$ constant, both weights and volumes decrease with increased temperature, $t_2$, of the heated air.

With the emergent air only partially saturated, the weights and volumes increase with decrease of relative humidity in the emergent air.

### CONCLUSIONS AS TO EFFICIENCY OF OPERATION.

From this analysis of the heat equations the following conclusions as regards the efficiency of the drying may be drawn:[1]

1. The air should be heated to the highest temperature compatible with the nature of the material to be dried.
2. The air upon leaving the apparatus should be as near saturation as practicable.
3. The temperature of the entering air should be as high as possible.

### APPLICATION OF ANALYSIS TO THE WATER SPRAY OR CONDENSING KILNS.

The above deductions apply to any form of moist-air kiln. The following have more especially to do with the Forest Service water spray humidity regulated kiln.

The amount of heat absorbed by the spray water and the condensed moisture aside from losses through the kiln walls is the

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[1] It should be noted, as stated above, that these deductions apply solely to the evaporating process alone, from a theoretical standpoint, and do not take into consideration heat losses through the kiln walls or through extraneous conditions; nor do they signify what is the condition best suited for conducting the drying operation from the standpoint of the physical effect upon the wood.

difference between the total heat in the saturated air as it leaves the lumber at $t_3$ and the total heat in the air at $t_1$. It is, in fact, the amount of heat given up by the coils, since the air is brought back to its initial state in the cycle and the water evaporated from the wood is added to the spray water. Hence the amount of heat removed in water at a temperature $t_1$ is (4), $G(t_2-t_1)\times(c+sd_1)$, when G is the weight of dry air in the mixture required to evaporate 1 pound of water. c and s are the specific heats of the air and vapor. Of this the amount $G(t_3-t_1)$ $(c+sd_1)$ represents the loss not accounted for in the latent heat of the pound of water which has been evaporated and is taken up by the spray water. The maximum possible thermal efficiency is therefore (5), $\frac{(t_2-t_3)}{(t_2-t_1)}$, if just enough air is circulating to give up all its available heat to the evaporation of the water so that it leaves the lumber in a saturated condition. From equation (2) and (3) the value of $t_3$ is determined for any given values of $t_1$ and $t_2$. These values may be most readily obtained from the tables given by Hausbrand, before referred to. $t_1$ and $t_2$ are arbitrary values determined entirely by the physical conditions of the material to be dried.

In actual operation, however, the efficiency will be much less than this maximum, since the air leaving will not be saturated, and a much larger quantity of air will need to pass through the material than the minimum indicated by the equation. If no evaporation takes place, all the heat will be used in heating and cooling the circulating medium. The total heat used per pound of air will then be $(t_2-t_1)$ $(c+sd_1)$, and this will go simply to heating the spray water.

### COMPARISON OF EFFICIENCY.

Comparing the theoretical efficiency of the condensing with that of the ventilating type of kiln, it will be seen that under identical running conditions its efficiency is much greater, because the initial temperature $t_1$ is very much higher. Let the temperature of the outside air be 32° F., so that the water has to be raised from 32° F. to the temperature of evaporation an dthen evaporated. Let the air leaving the lumber be three-fourths saturated, 75 per cent humidity. Also let $t_1=113°$ and $t_2=140°$, giving a relative humidity of 48 per cent. Then $d_1$ for 1 pound of saturated air at 113 is 0.0653 pound. Substituting those values in equation (3) it is found that $t_3=125°$ and $d_3=0.06889$. Since $w=d_3-d_1$, the number of pounds of air required to evaporate 1 pound of water is $G=\frac{1}{w}=\frac{1}{d_3-d_1}=279$, which contains $279\times0.0653=18.2$ pounds of vapor. The pressure of the saturated vapor alone at 113° is 71.4 mm. of mercury; hence that of the air alone is $760-71.4=688.6$ mm. of mercury. The volume occupied by 1 pound of dry air at 113° and a pressure of 688.6 mm. of mercury is 16 cubic feet (more exactly 15.921), which must be the same as that occupied by the 0.0654 pound of vapor present in the pound of air. As 279 pounds of air are required with its inherent 18.2 pounds of vapor, the volume of air, or combined air and vapor, is $15.921 \times 279 = 4{,}442$ cubic feet at 113°. At 125° this will occupy 4,535 cubic feet.

The total heat consumed is $279\ (0.237 + 0.0653 \times 0.475) \times (140 - 113) = 2{,}019$ B. t. u.,[1] of which the useful work has been the total latent heat of 1 pound of vapor above 32° F. evaporated at 116° F. (the wet-bulb temperature) and superheated to 125° F.=1,122 B. t. u. This should be the same as the heat given out by the air and superheated vapor in cooling from 140° F. to 125° F., $279\ (0.237 + 0.0653 \times 0.475) \times (140 - 125) = 1{,}122$. The thermal efficiency is $\frac{t_2 - t_3}{t_2 - t_1} = \frac{140-125}{140-113} = 55.6$ per cent. Also $\frac{1122}{2019} = 55.6$ per cent.

Compare this first with a ventilating kiln in which the air enters saturated at 32° F., is heated to 140° F., and leaves at 75 per cent humidity, escaping to the outer air. We then have

$t_1 = 32°$, $d_1 = .00387$ pound per pound of air
$t_2 = 140°$
$t_3 =$ calculated $= 80.2$, and $d_3$ at 75 per cent humidity $= .01692$.

The quantity of air required to evaporate 1 pound of water is:

$$G = \frac{1}{.01692 - .00387} = 76.6 \text{ pounds.}$$

This air contains $76.6 \times .00387 = 0.296$ pound of vapor. The total heat consumed is:

$$76.6\ (.237 + .00387 \times .475)\ (140 - 32) = 1{,}969 \text{ B. t. u.}$$

The thermal efficiency is $\frac{140-80}{140-32} = 55.6$ per cent, which happens to be the same as in the condensing kiln, but examination will show at once that the two cases are not analogous. In the condensing kiln the

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[1] Another way of arriving at this result is to compare the total heats; thus, in the vapor at 125° and 75 per cent saturation:

| | |
|---|---|
| Total heat in the air alone at 125°=279×0.237 (125−32) equals | 6, 149 |
| Total heat in saturate vapor at the dew point of 115° (75 per cent humidity at 125°)=279×0.06889×1117 equals | 21, 491 |
| Superheating this vapor from its dew point of 115° to 125°=279×0.06889×0.475×10 equals | 91 |
| Total at 125° | 27, 731 |
| At the initial stage, 113°: | |
| Total heat in air=279×0.237 (113−32) equals | 5, 356 |
| Total heat in saturate vapor at 113°=279×0.0653×1116.4 equals | 20, 339 |
| Total heat at 113° | 25, 695 |

The difference, 27,731−25,695=2,036 B. t. u., is the heat added to the air. This should be the same as before, namely, 2,019, the difference being in inaccuracy of the constants used.

humidity after heating to 140° F. was 48 per cent; in the other kiln it is only 3 per cent, an extremely low amount.

For a correct comparison, the condition of the air entering the lumber should be the same in both cases, namely, it is necessary to raise the humidity in the ventilating kiln from 3 per cent to 48 per cent. This can be done by allowing live steam to escape into the heated air sufficient to saturate it at 113° F., the dew point for 48 per cent humidity. Now, if 1 pound of dry air saturated at 32° F. is heated to 113° F. it will still contain its original weight of vapor, namely, 0.00387 pound; but to saturate a pound of air at 113° F. requires 0.0653 pound of vapor; consequently, the difference between this and 0.00387 or 0.06143 pound of vapor must be added for each pound of air at 113° F., in order to make the two cases comparable; they are then exactly alike, and we shall have for our kiln, to recapitulate, as before—

$t_1=113^\circ$ saturated
$t_2=140^\circ$ humidity 48 per cent
$t_3=125^\circ$ humidity 75 per cent.

Number of pounds of air required to evaporate 1 pound of water at 115° from initial temperature of $32^\circ=279$—

Total heat required$=2{,}019$ B. t. u.
Heat lost [1] $2{,}019-1{,}122=897$ B. t. u.

In the ventilating kiln, on the other hand, we shall have by comparison:

$t_1=32^\circ$ saturated.
$t_2=140^\circ$ at 3 per cent humidity.
$t_3=125^\circ$ humidity 75 per cent.
$h_2=$heat in vapor added to raise the humidity

to saturation at 113° F.; 0.0614 pound are required per pound of air. The total heat in saturate vapor at 113° above $32^\circ=1{,}117$ B. t. u. per pound; $1{,}117\times.0614=68.58$ B. t. u. required per pound of air. There are 279 pounds of dry air required as in the other case. $68.5\times279=19{,}134$ B. t. u., which must be added as vapor.

$K_2=$heat required to raise temperature of the air and vapor from 32° to $113^\circ=279\ (.237+.00387\times.475)\ (113-32^\circ)=5{,}396$ B. t. u.

Therefore, in this case the total heat which must be given to the air to evaporate 1 pound of water is—

| | *B. t. u.* |
|---|---|
| Heat given by coils to raise the air from 32° to 113° equals | 5, 396 |
| Heat given by coils to raise saturate air from 113° to 140° as before equals | 2, 019 |
| Heat supplied in vapor equals | 19, 134 |
| Total heat required | 26, 549 |
| Heat lost (provided it all escaped to the air) 26,549 minus 1,122 equals | 25, 427 |

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[1] In the spray kiln this is not in reality lost, since part is utilized in producing the circulation and all the remainder is recovered in the spray water. It is simply a transfer of heat from lumber to spray water.

Compared to the loss in the Forest Service kiln, as just shown, of only 897 B. t. u., this would be enormous. It would mean an efficiency of only $\frac{1122}{25427}=4.41$ per cent. The assumption, however, that it all escapes to the outside air is not carried out in practice in moist air kilns, but instead a large proportion of this is returned by internal circulation, and only a small amount escapes into the air. It is not possible in the latter case to calculate the theoretical efficiency, since there is no means of knowing what portion of the heat is returned in the recirculation within the kiln. The analysis is instructive, however, in showing what enormous heat losses are possible in a ventilating kiln. In no case can the theoretical efficiency of the ventilating equal that of the Forest Service kiln when operating under identical conditions within the drying chamber.

## INCREASE IN DENSITY PRODUCED BY EVAPORATION.

TABLE 3.—*Increase in density of mixture of air and vapor produced by the spontaneous cooling of the mixture from the evaporation of moisture as it passes through the lumber.*

| Entering air. | | After heating before entering lumber. | | | Leaving lumber. | | Weight of 1 c. c. of mixture in grams. | |
|---|---|---|---|---|---|---|---|---|
| $t_1$. | $h_1$. | $t_2$. | $h_2$. | Dew point. | $t_3$. | $h_3$. | Entering at $t_2h_2$. | Leaving at $t_3h_3$. |
| ° *F.* | *Per cent.* | ° *F.* | *P. ct.* | ° *F.* | ° *F.* | *Per cent.* | | |
| 32 | 100 | 158 | 1.8 | 32 | 78.8 | 100 | 0.0010264 | 0.0011658 |
| 32 | 100 | 158 | 1.8 | 32 | 110.5 | 25 | .0010264 | .0011057 |
| 86 | 100 | 158 | 13 | 86 | 99.5 | 100 | .0010126 | .0011094 |
| 86 | 100 | 158 | 13 | 86 | 140.5 | 25 | .0010126 | .0010394 |
| 140 | 100 | 158 | 64 | 140 | 140.9 | 100 | .0009525 | .0009779 |
| 140 | 100 | 158 | 64 | 140 | 151.7 | 75 | .0009525 | .0010154 |
| 86 | 100 | 212 | 14 | 86 | 105.8 | 100 | .0009310 | .0010915 |
| 86 | 100 | 212 | 14 | 86 | 146.3 | 25 | .0009310 | .0010255 |
| 176 | 100 | 212 | 47 | 176 | 176.5 | 100 | .0007820 | .0008221 |

The weights are given in grams per cubic centimeter of the mixture. The independent variables which may be assumed at choice are (1) the temperature of the entering air $t_1$; (2) the relative humidity of the entering air $h_1$; (3) the temperature to which the air is heated before it enters the lumber $t_2$; and (4) the degree of saturation of the air leaving the lumber, $h_3$. From these, $h_2$, $t_3$, and the volumes and weights of the air and vapor are determined.

### METHOD USED IN CALCULATING TABLE 3.

1. The temperature, $t_3$, of the air leaving the lumber is determined first, as for Table 1. The dew point must also be determined in order to determine the vapor pressure.

2. The following equation gives the value of the density (grams per c. c.) of the mixture of air and vapor:

$$d=\frac{B-0.378.e}{760}\times\frac{.00129305}{1+.003670\,t}.$$ [1]

B=total barometric pressure in millimeters of mercury.
e=pressure of the vapor in the mixture.
t=temperature Centigrade of the mixture.
.00129305 is the weight in grams of 1 c. c. of dry air at 0° C. pressure 760 mm. under gravity at 45° latitude and sea level. The figure .003670 is the coefficient of thermal expansion of air at 760 mm.

The first fractional expression may be explained as follows:

Let $d_1$=density of dry air at B–e mm. pressure.
$d_v$=density of vapor at e mm. pressure.

Then $d=d_1+d_v$. The air pressure alone is B–e and

$$d_1=d_0\,\frac{B-e}{760}.$$

$$d_v=.622\times d_0\times\frac{e}{760}.$$

when .622 is the density of vapor compared to air at 760 pressure.

$$\text{Whence } d=d_0\left\{\frac{B-e}{760}+\frac{.622\times e}{760}\right\}=d_0\left\{\frac{B-378e}{760}\right\}$$

Knowing the values $t_2$ and $t_3$ and the vapor pressures at these two points (pressures at the dew points) the values of $d_2$ and $d_3$ are obtained from the above equation.

It will be noted that in every case chosen in Table 3 the density increases due to the evaporation, hence the tendency of the air is to descend as it passes through the pile of lumber.

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[1] See Smithsonian Meteorological Tables, Tables 83 to 86.

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