ACCELERATED KILN DRYING BY CONTROL OF AIR TO WOOD TEMPERATURE DIFFERENTIAL

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This paper results from a study of temperature - moisture content relationships during kiln drying, and describes a novel and useful approach to kiln scheduling.

At a given position and time in a kiln three temperatures and the wood moisture content determine whether or not drying will take place, the rate of drying, whether the process takes place at constant rate or at a falling rate, and if the drying process is diffusion or accelerated. These temperatures are the dry bulb temperature of the air, the wet bulb temperature of the air and the temperature at the surface of the wood. No drying will take place if the wet bulb temperature is higher than the wood temperature. Slow diffusion drying will take place if the wood and dry bulb temperatures are substantially level. Accelerated drying requires that the dry bulb temperature be higher than the wood temperatures and that a wet bulb depression exist. If liquid water is in direct contact with the circulating air, the wood temperature and wet bulb temperature are equal. If a free water-circulating air interface does not exist the wood temperature must be higher than the wet bulb temperature.

Drying is energy absorbing. In the slow air drying process air dry bulb temperature and wood surface temperature are substantially equal, and the wet bulb temperature is lower than the wood temperature. Moisture vapor (and perhaps even some liquid water) diffuses along a moisture concentration gradient determined by internal moisture content and finally diffuses into the air and the wet bulb temperature of the air. Vaporization either within the wood or at the surface causes the wood to cool and heat energy is transferred from the air to the wood to keep the temperatures equal.

Accelerated drying results if the dry bulb temperature of the air is maintained higher than that of the wood and if the wet bulb temperature of the air is equal to or lower than the temperature of the wood. (No drying can take place if the wet bulb temperature of the air is higher than the temperature of the wood. Rather, condensation of moisture from the air on to the wood will take place until the wood temperature becomes equal to the wet bulb temperature.) Accelerated drying differs from diffusion drying in cause and effect mechanism. Whereas in diffusion drying, moisture is vaporized and travels spontaneously from the board interiors to the surfaces and thence to the atmosphere, (the cause), with heat from the air entering the wood in response to the cooling produced by the endothermic reaction, (the effect), in accelerated drying a temperature gradient is established between the air and the wood along which heat energy enters the wood (the cause) and causes vaporization and diffusion to take place (effect). A certain amount of spontaneous drying takes place during accelerated drying.

The rate at which heat energy is transferred from air to wood in accelerated drying depends upon the difference between the air and wood temperatures and the heat transfer coefficient. Thus a combination of a large temperature gradient and a high heat transfer coefficient results in a fast rate of heat transfer. For a wide range of conditions the heat transfer coefficient is substantially constant so the most significant independent variable which affects rate of heat transfer is the magnitude of air-to-wood temperature gradient.

The temperature response of the wood to continued energy addition from constant temperature air depends upon the quantity and distribution of water in the wood. If moisture content is high even that direct contact between liquid water and air exists, the wood assumes the wet bulb temperature of the air and remains at this temperature as long as the liquid-air interfaces are present. Under these conditions the air-wood temperature gradient is constant, the rate of heat energy transfer is constant, the drying rate is constant and all of the transferred energy is used for vaporization. Also, during this period the wood temperature will follow wet bulb temperature changes.

However, temperature measurements indicate that for most wood specimens being kiln dried the holding of wood temperature at wet bulb level takes place for a very short time, if at all.

If a true liquid-vapor equilibrium does not exist at the wood-air interface because of the absence of liquid water at the boundary layer, the temperature of the wood rises above the wet bulb temperature and becomes less sensitive to the lowering of the wet bulb temperature.

Increase of temperature of the wood requires energy. Therefore, a portion of the heat energy transferred from the air to the wood is used as sensible rather evaporative (or latent) heat. Also, as the wood temperature rises, the gradient between the air and the wood decreases with the result that the rate of heat transfer decreases and falling rate drying takes place. The Weyerhaeuser Research Laboratory has reported on several previous occasions that the drying process may be approximated with confidence by a first order type relation.

$$\mathrm{Ln}\,\frac{Mo}{M} = kt$$

in which Mo is initial moisture content, M is moisture content after time t and k is the specific drying rate constant with units of reciprocal time and dependent upon a number of factors including board thickness, species, density and others. It has been shown experimentally that k varies with the product of wet bulb temperature depression and

and air velocity, other factors remaining constant.

The differential form of the drying equation is

$$-\frac{dM}{dt} = kM$$

which indicates that the rate of moisture loss is linearly related to the moisture content. As the air-wood temperature gradient decreases and the wood becomes more dry the drying rate decreases exponentially.

It was reasoned that if the drying rate is due primarily to the magnitude of the air-wood temperature gradient, drying rate can be manipulated by varying the gradient. Since the wood temperature cannot be controlled by varying the wet bulb temperature and since there is no simple way of varying the wood temperature independently, the only logical means of varying the gradient is by varying the air dry bulb temperature.

If, for example, the air temperature were raised at the same rate as the wood temperature is rising, the air-wood gradient would remain constant, the rate of heat energy transfer from air to wood would remain constant and the drying rate would be substantially constant. The reduction in kiln residence time would be marked. If the air temperature were raised faster than the wood temperature rise, the gradient would increase constantly and the drying rate would accelerate as drying proceeded.

These general statements have been varified by careful air and wood temperature measurements made during kiln drying. The result has been the reduction to practice of the CRT or constantly rising temperature process which is covered by U.S. Patent 3,404,464.

There are several corallary advantages attributable to the use of the CRT process other than reduction of kiln residence time. One is that drying may be initiated at low temperature. A small air-wood gradient with its relatively low rate of drying, if maintained, will result in as much kiln residence time as an initially large gradient with its fast initial drying but falling drying rate. For example, it has been found that if wood at 70°F is started to dry at conditions of 90°F dry bulb and 65°F wet bulb a good rate of drying is quickly established. If now the dry bulb temperature is increased at the rate of 2.5°F/hr the gradient and drying rate remain substantially constant (certain items under certain kiln conditions) and a very substantial amount of drying will take place during 24 hours at which time the air temperature will have reached 150°F and the wood temperature is 130°F. Thus the critical phase of drying takes place at low temperature under conditions which do not favor chemical degradation.

The discussion thus far has dealt only with the temperature, energy transfer and drying characteristics at a point in a kiln. However, conventional kiln drying comprises the passage of air through slots over board surfaces for a substantial distance, generally 8-9 feet for single track kilns. It is necessary to enlarge upon the single point concept in order to make the CRT process operable in conventional kiln charges.

When the circulating air contacts the wood on the entering air side of the charge and transfers some energy to the wood, the air becomes cooler. If the wood throughout the charge is at the same temperature the gradient between air and wood becomes progressively smaller and the drying rate becomes lower as the air progresses across the charge. In the event the moisture content is very high and the wood assumes the wet bulb temperature the drying rates across the charge will not be uniform. However, if the free liquid-air interface does not exist, within a very short time there is established a constant air-to-wood temperature gradient and the drying rate is uniform across the load. In order to achieve this it is necessary that the wet bulb temperature be lower than the wood temperature on the leaving air side. Thus the wet bulb depression of the entering air must be equal or exceed the sum of the air-to-wood gradient and the temperature drop across the charge.

Economical drying involves not only short kiln residence but also minimum kiln-induced degrade. Degrade results from stresses due in large part to moisture gradients between the interior and the surfaces of the wood. The moisture content of the board surfaces is determined by the humidity of the air in contact with the wood. Therefore, it is desirable to maintain as high humidity conditions as possible. However, this opposes fast rate of drying as described earlier because a low entering air wet bulb depression limits the temperature drop across the charge which can take place. Four alternatives appear to be feasible. The first is to use narrow loads of lumber. Thus a significant temperature drop per foot can be achieved without a large wet bulb depression. This approach has the disadvantage of not being applicable to conventional stacking and kiln set-ups. A second approach is to use thick stickers between courses. This permits a large quantity of air to pass over the wood surfaces. A large quantity of heat energy can be transferred from air to wood with a small change in temperature resulting. Thus the entering wet bulb depression can be kept small although fast drying is being done. This has the disadvantage of reducing the holding capacity of the kiln. A third alternative is the use of high air velocities through the charge. A large mass of air contacts the wood per unit time and a large amount of heat energy can be transferred without a large change in temperature and the wet bulb depression can be kept small. There are at least two disadvantages associated with this procedure. The first is that the cost of moving air at high velocity is high. The second is that due to the "scrubbing" action of the turbulent air it is imperative that the low wet bulb depression be carefully maintained. Most kilns are incapable of maintaining small wet bulb depressions particularly at high hiln temperatures.

The fourth alternative to use low air velocity air flow to insure laminar rather than turbulent flow. Under these conditions a static layer of air is always in contact with the wood. The moisture content of this layer is higher than that of the mainstream of the circulating air and the wood surfaces remain more moist than if they were in direct contact with drier air. Although this technique has the disadvantage of reducing the heat transfer coefficient but has the economic advantage of substantially lower power cost.

Any fast change in moisture content of the wood surface region creates stress which may result in geometrical or structural degrade. Reversal of air direction, particularly when load width and temperature drop across the load are large, subjects the wood to stress. Therefore, it is recommended that air direction not be reversed while drying the lumber items which have been studied to date.

It is logical to ask whether the CRT process as described differs only in degree or in kind from conventional processes in which dry bulb temperatures are raised step-wise at intervals of several hours. It is submitted that the CRT process presents sufficient differences and advantages to merit the category of "different in kind". The process keeps the moisture moving outwardly, minimizes moisture gradient stresses, is substantially faster than conventional drying, passes through the critical stage of drying at low temperatures to minimize degrade and conserves energy.

The reduction to practice of the CRT process has been made in a laboratory kiln which will accept 1000 board feet of dimension lumber in a stack 8 feet wide and 8 feet long. At the present time extensive economic stucies are being conducted in a commercial size single track, highly instrumented kiln have a capacity of 70,000 board feet. Attention is being given to product value generated and comparisons with conventionally dried lumber are being made.