EFFECTS OF BOUNDARY LAYER ON DRYING POROUS MATERIAL*

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During the past decade, little significant progress has been made in developing new, efficient methods of seasoning lumber and veneer. Refinements in technique have resulted in better drying schedules and improved quality control, but increased production has been achieved primarily through the addition of more kiln space and veneer dryer sections.

Today the forest products industry recognizes that important improvements in seasoning wood must be preceded by basic and engineering research. Increased attention must be focused on learning fundamentals of physical phenomena and properties of wood. Until we understand the underlying factors influeincing wood drying, such as permeability, diffusion, and heat transfer, efforts to develop new techniques for drying can meet with only partial success.

In keeping with its fine tradition of forest products research, the U.S. Forest Products Laboratory, Madison, Wisconsin, recently has made grants to several colleges and universities to encourage basic research on wood. One of these grants provided funds for a study at Oregon State University entitled, "The Effects of Boundary Layer in Air Flow on Free and Hygroscopic Water Evaporation. " The research is attempting to determine the effects of air flow on the rate at which wood dries.

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CONSIDERATIONS BASIC TO DRYING

To understand how boundary layer affects evaporation, a review of fundamental concepts involved in drying any porous material is necessary. The objective of drying is to evaporate water from a wet surface into a surrounding stream of air, but to accomplish this objective, a quantity of heat must be transferred to the water and the material. The amount of heat required is equal to the latent heat of evaporation, plus the heat necessary to bring the water to the temperature of the air or to the boiling point of water. Consequently, two transfer phenomena are involved: first, transfer of heat from the air to the surface; and second, mass transfer of water vapor into the air (6).

Drying of porous materials is characterized by three distinct stages, as illustrated in Figure 1. During the warm-up period (A-B), the drying rate increases to a constant level. With paper, this period may be short, but in seasoning lumber, warm-up requires a substantial period of time. After the evaporation rate reaches equilibrium, drying continues at a constant rate as long as diffusion of moisture to the surface of the material exceeds the rate of evaporation into the air stream. Because the period during which rate of drying is constant (B-C, Figure 1) can be likened to evaporation from a water surface, the equipment used for drying is the limiting factor.

The period of decline (C-E) in rate of drying begins when moisture can no longer diffuse to the surface at a rate sufficient to keep the surface wet. Not only does nature of the material influence rate of drying, but it also influences the particular moisture content (C) at which the rate of drying begins to decrease. The moisture content at which drying ceases is, of course, determined by drying conditions. In many instances, drying is continued to an equilibrium moisture content rather than to zero moisture content (1).

Because transfer of heat to the surface and the interior of a material is essential to drying, and because it is proportional to the quantity of water evaporated, a study of heat transfer can provide much information concerning drying systems.

Over a period of time, differences in temperature are reduced by flow of heat from regions of high temperature to regions of low temperature. In solids, flow of heat occurs on a molecular level, and is termed conduction. A second mode of heat transfer, known as convection, occurs in liquids and gases on a macroscopic level. Here, heat is carried from one point to another by the flowing medium. A third means of heat transfer is radiation, in which thermal energy is transmitted in the form of electromagnetic waves. In drying processes all three modes may contribute to heat transfer; however, for one discussion of boundary layer, convection will be the predominate form considered.

If a plane wall of solid material separates two fluids flowing at different temperatures, as in Figure 2, a given quantity of heat will flow through an area of wall in a unit of time. Because the surfaces of the wall (A and B) are at temperatures above and below the temperatures of the cold and hot liquids (C and D), a resistance to flow of heat exists between the fluid and the solid surface. If we consider only the hot fluid and the solid surface, the rate of heat flow (Q) is proportional to the product of the temperature difference between the two $(t_1 - t_2)$ and the surface area (A). The proportionality constant (h) is termed the film heat-transfer coefficient.

$$Q = hA(t_1 - t_2)$$

If expressed in a different manner,

 $(t_1 - t_2) = \frac{(1)(Q)}{h} \frac{A}{A}$

the equation can be compared with Ohm's law for electric currents,

1.

2.

^{*} Numbers in parentheses refer to references cited.



Figure 1.

Typical drying-rate curve for porous materials in which rate of drying increases during the warming period (A to B), levels off to a constant rate while the surface is covered by a film of moisture (B to C), then slows as moisture content decreases (C to D).



HEAT TRANSFER

Figure 2. A solid wall dividing hot and cold fluids (liquids or gases) shows drop in temperature across two boundary layers and across the wall because of their resistance to flow of heat.



Figure 3. Development of laminar and turbulent boundary layers along a flat plate immersed in a uniform stream of air.



MULTIPLE JETS



E = R I

where E is the voltage, R is the resistance, and I is the electric current. Here we see that the temperature difference $(t_1 - t_2)$ acts as a potential or driving force, with heat flow (Q) resulting from this force. The thermal resistance to flow of heat is expressed as 1/h, and by reducing this factor, a greater quantity of heat can be transferred with an equal difference in temperature. Because the thermal resistance is equal to the reciprocal of the heat-transfer coefficient, a large coefficient is desirable in drying materials. Rearranging the formula again, the heat-transfer coefficient (h) can be computed by knowing the rate of heat flow (Q), the area (A), and the temperature difference, $(t_1 - t_2)$ (see reference 3).

$$h = \frac{Q}{A(t_1 - t_2)}$$

4.

BOUNDARY-LAYER THEORY

What is boundary layer, and how does it affect heat transfer and drying rates? Boundary layer is a film of air adjacent to the surface, in which the air velocity is less than the free-stream velocity. At the surface of the material, air velocity is virtually zero, and increases to the free-stream velocity as the distance from the solid is increased. The film acts essentially as an insulating layer between the surface of the material and the free air stream, retarding water evaporation and heat transfer.

There are basically two types of boundary layer, laminar and turbulent. When a uniform stream of air passes over a flat plate, thickness of the boundary layer at the leading edge (A in Figure 3) is zero, but as the air moves along the surface, a film builds up. Within this region, the boundary layer is laminar, and little mixing of the air occurs. At a critical distance from the leading edge (B in Figure 3), a transition from laminar to turbulent flow takes place. Although the thickness of the turbulent boundary layer is greater than that for a laminar layer, heat transfer actually is intensified because of the irregular pattern of flow within the turbulent boundary layer (3).

Because the boundary layer acts as an insulator increasing the thermal resistance, reducing the thickness of the film and making it as turbulent as possible is desirable in drying. Two primary methods are available to decrease boundary-layer thickness; one is to increase the air velocity, and the second is to shorten the distance air travels over the surface of the material.

AIR IMPINGEMENT

One effective means of creating desirable boundary layer is by impingement of air. Under this system, air forced from orifices impinges at a 90-degree angle on the surface being dried. By using jets rather than parallel flow as in conventional dryers, the air attains high velocities from 7,000 to 20,000 feet a minute, and if the distance between the jets is small (Figure 4), the boundary layer remains very thin.

At the point of impingement (A in Figure 4), pressure develops to create horizontal flow of air along the surface. Since the point of impingement is the source of horizontal flow, it is also the origin of the boundary layer, and is comparable to the leading edge for parallel flow over a flat plate. From previous discussion, maximum transfer of heat can be expected to occur at the point of impingement, where the boundary layer is exceedingly thin. The heat-transfer coefficient will decrease with distance from the center line of the jet as the boundary layer develops (2, 4).

High velocities of air and close spacing of orifices are the primary reasons why rapid rates of drying can be obtained with air impingement.

The air-impingement apparatus built at Oregon State University's Forest Research Laboratory to study effects of boundary layer is pictured in Figure 5. The air supply is furnished by a Roots



Figure 5. Apparatus for air impingement built to study drying with air at high velocity.

- A--Positive-displacement blower
- B--Air heating unit C--Orifice meter

D--Draft gauge E--U-tube manometer F--Pressure plenum



Figure 6. A typical plate made to study drying by air impingement.



Figure 7. Air-impingement apparatus with one side removed to show the copper plate and water reservoir used in studies of heat transfer.

- C--Orifice meter
- E--U-tube manometer
- F--Pressure plenum

G--Copper heat-transfer plate H--Water reservoir positive-displacement blower (A) and heated by a steam jacket (B). Air passing through the system is measured by an orifice meter (C), equipped with a U-tube manometer (E). By knowing the mass air flow and pressure in the plenum (F), velocity of the air jets can be computed.

A typically perforated plate with 64 orifices is shown in Figure 6. Several differently perforated plates are being studied to determine the effects of size and spacing of orifices, and total area of the perforations. In Figure 7, one side of the apparatus has been removed to show the copper plate (G) for transfer of heat and the water reservoir (H) on which it tests. The copper plate is used for studies of heat transfer, and will be replaced by wood veneer for the study of drying rates. (The perforated plate attached to the under side of the pressure plenum is not visible). The reservoir is supported on a shaft that can be raised and lowered to attain the desired spacing between the perforated plate and the heat-transfer plate. Cool water enters the bottom of the reservoir, and after coming in contact with the copper plate, is drained off at the top. Consequently, by noting the change in temperature of water passing through the reservoir, heat transferred from copper plate to water can be calculated easily. In turn, the heat-transfer coefficient between air and plate can be computed by formula 4, if temperatures of air and plate are known.

Recent work reported by Milligan and Davies substantiates the rapid rates for drying predicted for high-velocity air impingement. With air at a velocity of 9,000 feet a minute and a temperature of 550° F, 1/8-inch veneer of Douglas-fir heartwood with moisture content of 35 per cent was dried to 5 per cent moisture content in 0.95 minute. With a conventional veneer dryer, the approximate time required for drying would be 13 minutes. Reports indicated that rapid drying was achieved without discoloration, reduction in strength, or impaired gluability (5).

In the future, continued research in the field of drying by air impingement and of wood seasoning in general could provide radical changes in present drying methods. We have just begun to develop possibilities available to us. These potentials can be realized only through well-designed research applied by the forest products industry.

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