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Title: Heat and Mass Transfer Rates Associated with the Drying of Southern Pine and Douglas Fir Veneer in Air and in Steam at Various Temperatures and Angles of Impingement

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Abstract approved: James R. Welty

Southern pine and Douglas fir veneer samples were dried in air under the following conditions: air temperatures were 350, 600, and 750°F; air velocities were 50, 100, and 150 feet per second, and angles of impingement of air against the veneer surfaces were 0°, 45°, and 90°. The resulting drying curves were compared with drying curves obtained under similar conditions using steam as the drying medium.

Statistical analyses were performed to estimate magnitudes of differences in veneer drying times associated with the two drying media, the three angles of impingement, and the two species of wood. Air was found to be more effective than steam as a drying medium at the 350°F operating temperature. For the 600°F and higher operating temperatures, steam was found to be more effective than air. Under

all drying conditions, Southern pine dried faster than Douglas fir.

Effective heat transfer coefficients representing the convective effects of both heat and mass transfer associated with drying veneer were computed in two ways: based on the experimental data, and based on theoretical considerations. Experimental internal diffusion coefficients were also computed.

Diffusion of water from the interior of the veneer to the veneer surfaces was found to be the controlling factor on the rate of veneer drying during all but a brief period in the initial stage of the drying process.

Heat and Mass Transfer Rates Associated with the Drying of Southern Pine and Douglas Fir Veneer in Air and in Steam at Various Temperatures and Angles of Impingement

by

Walter William Laity

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

HEAT AND MASS TRANSFER RATES ASSOCIATED WITH THE DRYING OF SOUTHERN PINE AND DOUGLAS FIR VENEER IN AIR AND IN STEAM AT VARIOUS TEMPERATURES AND ANGLES OF IMPINGEMENT

INTRODUCTION

Veneer sheets, which are usually peeled from fresh-cut or water soaked logs, must be dried to a moisture content of about 5% or less as part of the process of preparing the veneer for gluing to form plywood panels (2, p. 1). Drying times in excess of ten minutes are common for veneer dried in present industrial dryers. To reduce the moisture content of 1/8 inch thick Douglas fir veneer from 106% to 5% in a conventional dryer, for example, a drying time on the order of 20 minutes is necessary (13, p. 28). This thesis is one of several projects which have been undertaken in recent years to obtain experimental and theoretical information for possible application to improving the design of veneer dryers.

In most conventional veneer dryers, air, or a mixture of air and steam, is circulated parallel to the surfaces of the veneer sheets which are conveyed through the dryer and held flat by a series of steel rollers (4, p. 449). Steam which forms a part of the drying medium comes from moisture which has evaporated from the veneer. Drying temperatures are generally maintained within the range from 300° F to 400°F (4, p. 449).

Research projects in veneer drying which were completed prior to the start of the work described in this thesis involved investigations into the effects of angular impingement of the drying medium against veneer surfaces, and the use of drying temperatures and velocities well beyond the limits imposed in conventional dryers. Among the projects which have been completed are the following: Milligan and Davies (13) dried several species of veneer at temperatures up to 500°F under conditions of perpendicular impingement of the drying medium; Atherton (2) dried Douglas fir samples in steam flowing at ten feet per second parallel to the veneer surfaces with drying temperatures to 800°F; and South (15) dried Southern pine and Douglas fir samples in steam under conditions of 45° impingement, 90° impingement, and parallel flow, with steam velocities to 150 feet per second and temperatures to 800°F.

Little, if any, experimental information is available for use in comparing drying times of veneer in steam with drying times in air under conditions which are otherwise the same. Experimental work for this thesis was directed toward obtaining data for quantitative comparisons of air and steam as drying media, under a wide variety of operating conditions. In addition, experimental and theoretical heat and mass transfer parameters were evaluated for Southern pine and Douglas fir veneer exposed to air as the drying medium.

DESIGN OF EXPERIMENT

Objectives

The following objectives were established for this experiment:

1. To determine heat and mass transfer parameters and drying rates for Douglas fir and Southern pine veneer in air as the drying medium under various conditions of velocity, angle of impingement, and temperature.

2. To evaluate and compare the results of 1., above, with similar work, using superheated steam as the drying medium, which was completed by South (15).

Variables

The variables which were investigated in this experiment are as follows:

1. Species of wood - Southern pine and Douglas fir.

2. Drying media - Air and steam, each used individually for drying veneer samples.

3. Velocities of drying media - 50, 100, and 150 feet per second.

4. Angles of impingement of drying media on veneer surfaces - 0°, 45°, and 90°.

5. Temperatures of drying media -

   a. For steam: 350^{o}, 600^{o}, and 800^{o}F.

   b. For air: 350^{o}, 600^{o}, and 750^{o}F.

It should be noted that the highest temperature at which veneer samples were dried in air is 50^{o} less than the highest temperature at which samples were dried in steam. This discrepancy is due to limitations in the heat exchanger used to heat the air, for temperatures on the primary side of the heat exchanger reached maximum allowable limits before the air passing through the secondary side could be heated to a steady state temperature of 800^{o}F.

Experimental Material and Equipment

To permit valid comparisons between South's data for steam dried veneer and data from this experiment for air dried veneer, the conditions under which the two experiments were run had to be as alike as possible. Accordingly, veneer samples used in this experiment were cut to the same size, stored under the same conditions, and dried in the same test sections as the samples used by South. The same temperature instrumentation, scales, and techniques for determining moisture loss were used for the two experiments.

Possible sources of variation which could affect the validity of comparisons between this experiment and South's experiment are differences in physical properties of veneer samples used in the two experiments, and differences in flow instrumentation. Although the same species of veneer were used in both experiments, the samples for this experiment were obtained over a year later than the samples for South's work. Consequently, logs from which samples for the two experiments were obtained were probably grown in different geographical locations, and, hence under different conditions.

The differences in flow instrumentation for the two experiments are not considered a serious source of variation, since standard instruments having widely recognized reliability (a pitot tube for this experiment and a flow orifice for South's experiment) were used. Tests were conducted to determine whether the two instruments would give comparable results when used to measure flows under the same conditions.

To ascertain whether the drying characteristics of veneer samples used in this experiment differed to any appreciable extent from the veneer samples used in South's work, representative test points throughout the operating range of the work completed by South were rerun in steam using veneer samples obtained for this experiment.

Size of Experiment

The total number of conditions at which drying curves were obtained for Southern pine and Douglas fir in air as the drying medium is the product of the numbers of temperatures, velocities, and angles of impingement which were selected for this experiment, as follows:

Number of drying conditions = 3 x 3 x 3 = 27

At each condition, three drying curves were obtained for each species of wood. Results of the three replications were used in statistical analyses of the data, and the three replications at each condition were averaged to form the drying curves included in this thesis.

The total number of samples of each species required to obtain three curves at each drying condition ranged from 9 for the highest temperature runs, to 24 for the lowest temperature runs. For the 27 drying conditions, 402 samples of each species, or a total of 804 samples, were dried in air. An additional 212 samples were dried in superheated steam, to obtain drying curves for comparison with those obtained by South.

Thus, 1, 016 veneer samples were used in this experiment.

APPARATUS

A sketch of the apparatus used to dry veneer samples is shown in Figure 1. This is the same apparatus used by South (15) for drying samples in steam, except for modifications which were incorporated to permit use of either air or steam as the veneer drying medium. Component parts of the apparatus are discussed in the following paragraphs.

Heat Exchanger

To heat the drying medium, the concentric pipe, counterflow heat exchanger designed by Atherton (2) was used. In operation, air discharged from a positive displacement blower flowed past a propane burner which was installed in the blower outlet piping, and then through the annulus of the heat exchanger. The drying medium to be heated, either air or steam, flowed countercurrently through the inner pipe of the heat exchanger.

Means of Supplying Air or Steam for Drying Veneer

Air as a drying medium was supplied from the positive displacement blower and associated piping shown in Figure 2. By varying the speed of the blower motor, course adjustments of air flow rate could be made. Fine adjustments were obtained by means

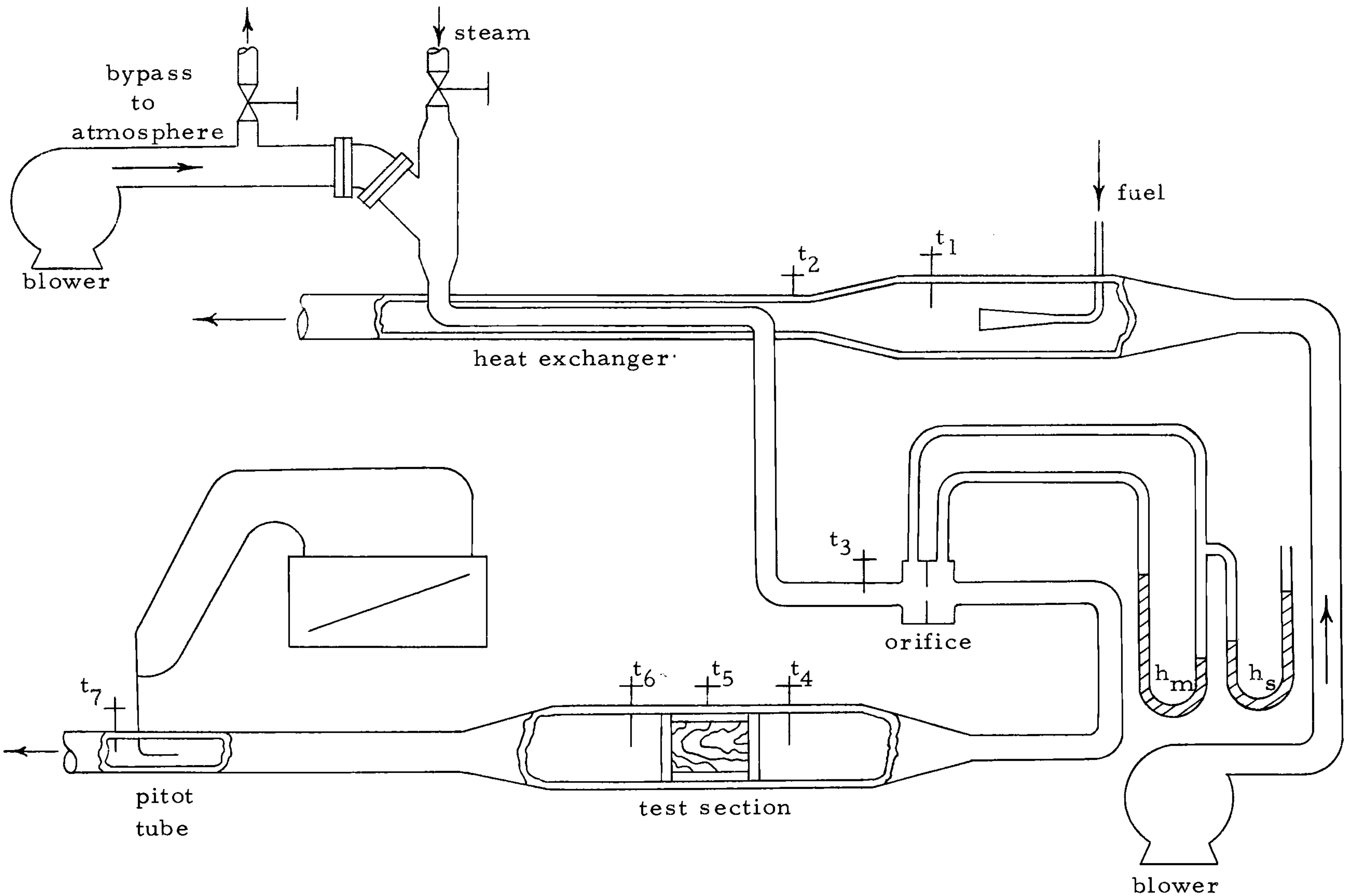


Figure 1. Veneer drying apparatus.

of the bypass valves shown in Figure 2, through which air from the blower could be diverted directly to the atmosphere.

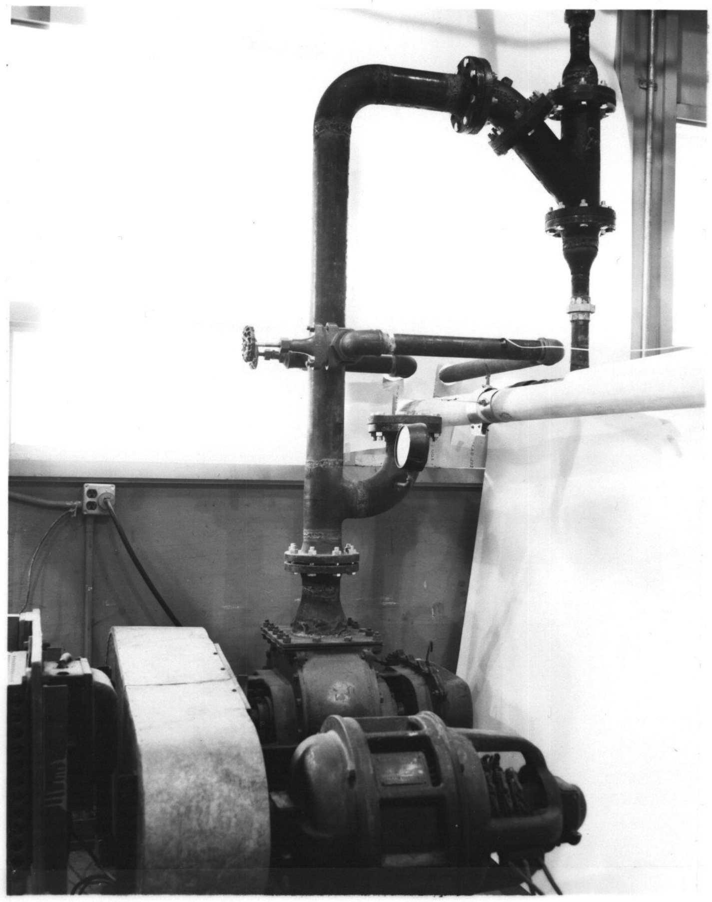


Figure 2. Blower and piping for supplying air to veneer drying apparatus.

When supplying steam to the drying apparatus, the 45° elbow shown in Figure 2 was removed, and the flange on the wye to which the elbow was attached was blanked off. Steam was supplied from a 50 psig steam main through a pipe attached to the vertical branch of the wye, and steam flow was controlled by means of a valve not shown in the figure.

Test Sections for Drying Veneer

Two test sections, both designed by South (15), were used for drying the veneer samples. One of the test sections, shown in Figure 3, was used for parallel flow past the veneer samples; the other, shown in Figure 4, was used for 45^{o} and 90^{o} impingement of the drying medium on the veneer samples. Both test sections were interchangeable in the drying apparatus. The drying medium entered each test section through the piping on the right as shown in Figures 3 and 4, and exhausted through the piping on the left. Glass wool at least two inches thick was used to insulate each test section.

The parallel flow test section was designed to accept samples 6 inches long by 4 inches wide by 1/8 inch thick. Samples were placed equidistant between the two sides of the enclosure, using the sample holder shown in Figure 3. (Note: the object shown in Figure 3 which is protruding vertically through the sample holder served only as a prop for positioning the holder for this picture.)

Within the 45^{o} and 90^{o} flow test section, two banks of eight parallel pipes were installed. Small jets, through which the drying medium impinged on the veneer, were drilled in a straight line at one inch intervals along each of the pipes. The pipes penetrated one end of the housing of the test section as shown in Figure 4, and could

Figure 3. Parallel flow test section.

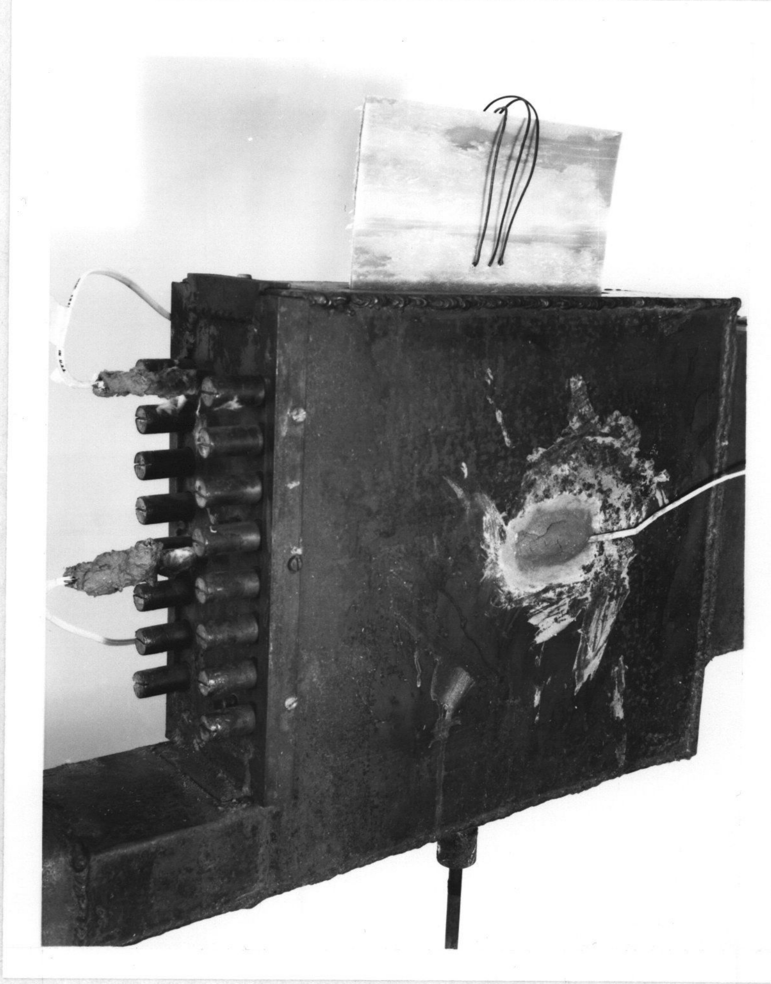


Figure 4. 45^{o} and 90^{o} flow test section.

be rotated so as to change the angle of impingement of the drying medium on the veneer surfaces.

Guides were provided in the 45° and 90° flow test section to locate the veneer samples parallel to and midway between the two banks of pipes. The rod shown in Figure 4 which extended downward from the housing is a sample ejector. The 45° and 90° flow test section was designed to accept 8 inch by 8 inch by 1/8 inch samples.

Temperature Instrumentation for Drying Apparatus

Temperatures at locations shown in Figure 1 were measured using chromel-alumel thermocouples in conjunction with a 12-point General Electric temperature recorder. To provide added assurance in the accuracy of temperatures needed for heat transfer calculations, duplicate thermocouples were used to obtain two or more independent measurements of each of the following: wall temperature of the test section, and temperature of the drying medium at the entrance of the test section.

Each thermocouple used for measuring wall temperature of the test section was forced into a small hole which was slant bored into the wall, and then the metal surrounding the hole was peened over to tightly encase the thermocouple hot junction. Holes for the thermocouples were drilled to a depth which was just short of the depth required to penetrate through the wall, so that the thermocouple hot junctions would not be directly exposed to the drying medium. Thermocouple leads were encased in ceramic insulators to prevent short circuits, and high temperature mortar was placed over each installation to provide protection against breakage of the leads.

The thermocouple leads which extended from the front face of the test section shown in Figure 4 were attached to hot junctions which measured temperature of the drying medium within the test section. These and other thermocouples which were used to measure gas temperatures were housed in small diameter tubes which extended into the gas stream, with the thermocouple hot junctions located a small distance beyond the tubes to be directly exposed to the gas. Leads housed in the tubing were enclosed in ceramic insulators to prevent short circuits.

Temperature Instrumentation Used in Wood Samples

To obtain wood temperature as a function of time when a veneer sample was inserted in the test section, small (24 gauge) copper-constantan thermocouples were used in conjunction with Bausch and Lomb millivolt recorders. Two thermocouples, located on opposite sides of each veneer sample and approximately three inches from the leading edge, were used for parallel flow conditions. For samples dried under 45^{o} and 90^{o} impingement, three thermocouples were used in the following locations: one at the stagnation point directly in front of a jet, a second between two adjacent stagnation points, and the third between the first two. The hot junctions were forced into small holes which were drilled in the samples.

The temperature-time charts obtained for each veneer sample were averaged for heat and mass transfer calculations.

Flow Instrumentation

Flow rates were set using a Dwyer 1/8 inch diameter pitot tube in conjunction with an inclined manometer. The pitot tube was installed in a straight, four inch diameter duct downstream of the test section.

The orifice used by South (15) for measuring steam flows was too small for use in this experiment. Due to the pressure drop across the orifice, air velocities at which tests were to be conducted could not be attained without exceeding the 2.5 psig maximum discharge pressure which was established to prevent damage to the positive displacement blower.

A larger orifice which was compatible for use with the positive displacement blower was installed upstream of the test section, but the piping layout for the larger orifice did not comply with American Gas Association standards which are referenced by Spink (16). Consequently, published orifice coefficients could not be used for flow calculations. Since additional piping would have increased the pressure drop through the apparatus, it was decided to use the larger orifice as a secondary means of measuring flow. Pressure drop across the orifice was noted when each flow condition was initially set using the pitot tube, and this pressure drop was then periodically monitored to ensure that the flow rate remained constant while drying samples at the given test condition.

PROCEDURE

Preparation of Samples

Samples were cut from freshly peeled 1/8 inch thick veneer sheets, which were carefully selected for uniformity of thickness and grain structure so as to minimize variations between samples from each sheet. For parallel flow tests, 4 inch by 6 inch samples were cut with the longer dimension in the grain direction. Samples for the 45^{o} and 90^{o} tests were cut to 8 inch by 8 inch size.

After cutting, samples were soaked, wrapped in plastic bags, and stored in a cold room maintained at $35^{o}F$. This method of storage was utilized to prevent growth of mold on the samples.

Method of Obtaining Drying Curves

Multiple samples, which generally came from the same sheet of veneer and which were stored under the same conditions prior to the start of tests, were used to identify each drying curve. The first sample of a batch allotted for a drying curve was dried for one minute at $350^{o}F$, or for one-half minute at the higher temperature test conditions. At successively greater intervals of one minute or one-half minute, depending on the operating temperature, the remaining samples in the batch were dried. This process was discontinued for each drying curve when the weight losses of two samples dried at successively greater time intervals were approximately the same, or when the time interval was reached at which a sample would burn.

Samples allotted for a drying curve were removed from the plastic bags in which they had been stored, drilled to accept thermocouples, wiped clean of any free water, and individually weighed to the nearest 0.01 gram. Each sample was placed in a new plastic bag immediately after being weighed to prevent any moisture loss prior to actual testing.

Thermocouples were inserted in each sample just prior to placing the sample in the test section, and the sample was then dried for a predetermined interval which was timed with a stopwatch. Immediately upon removal from the test section, each sample was freed of thermocouples, tightly wrapped in a piece of aluminum foil of known weight, and then reweighed. Finally, each sample was dried for at least 15 hours in an oven set at 220°F for subsequent determination of oven-dry weight.

Air flow rates through the test section were determined by taking a pitot tube traverse in a four inch diameter duct downstream of the test section, and then performing a mass balance between the location of the pitot tube and the test section. Details of flow calculations are given in the Appendix.

Steam flow rates were determined by using the same orifice and calculational techniques which were used by South (15).

After establishing a predetermined flow rate and temperature, the test condition was maintained until all samples necessary to obtain drying curves at the test condition were run. For example, samples for four sets of drying curves were run consecutively while maintaining a predetermined test condition when the test section for 45° and 90° impingement was installed. The four sets of drying curves were for the two species of veneer, each dried under the two angles of impingement. By proceeding in this manner, the established test condition was constant for all curves run at that condition.

Comparison of Pitot Tube and Flow Orifice for Measuring Flow Rate

To determine whether the flow orifice used by South and the pitot tube used in this experiment would give equivalent results when used to measure flow rates under the same conditions, tests were conducted with both instruments installed in the drying apparatus. At each of several different air flows, flow measurements were taken independently with both instruments. Results indicate that air flow rates calculated from measurements with the two instruments agree within approximately 8%. Calculations for one of the air flow conditions are included in the Appendix.

No comparisons of the two instruments were conducted in measuring steam flows. Due to varying steam demands elsewhere in the steam system, steam flows to the test section were more difficult to control than air flows. In addition, the effectiveness of the 1/8 inch diameter pitot tube in steam was very limited, since steam tended to condense on the pitot tube and clog the small passages of the instrument.

STATISTICAL ANALYSES

As can be seen from the veneer drying curves, drying times are strongly dependent upon the temperatures at which tests were conducted. The dependence of drying time on such factors as species of wood and type of drying medium is not so obvious. Statistical analyses were therefore performed to estimate magnitudes of differences, if any, in veneer drying times associated with the two drying media, the three angles of flow over the veneer surfaces, and the two species of wood.

Data used in the statistical analyses came from two sources: that for air was taken as part of the experimental work for this thesis, and that for steam was obtained from South's thesis (15).

For reasons discussed previously under Operating Procedures, the maximum air temperature for veneer drying was 750°F, which is 50°F less than the maximum steam temperature of 800°F used by South. Statistical comparisons of the data taken at the maximum air and steam temperatures were not performed, since there was no known correction factor to account for effects of the 50° discrepancy in maximum temperatures. Analyses were performed on data taken at the 350°F and 600°F operating temperatures, since these operating temperatures were the same for both air dried and steam dried veneer.

Three and four-factor factorial analyses of variance were performed using the OSU-03 and OSU-04 computer programs which are included in the Oregon State University program library (21). The programs were run on the Oregon State University C.D.C. 3300 computer. A sample three-factor analysis of variance is included in the Appendix.

Four-Factor Analyses of Variance

At each of two temperatures, $350^{\circ}F$ and $600^{\circ}F$, the effects of the following four factors on veneer drying time were investigated simultaneously:

1. Drying media - air and steam,
2. Angles of impingement on the veneer - 0°, 45°, and 90°,
3. Velocities of drying media - 50, 100, and 150 feet per second,
4. Species of wood - Southern pine and Douglas fir.

Two analyses were performed at each of the two temperatures. First, the above four factors were analyzed with time to dry to a dimensionless moisture content of 10% as the dependent variable. As a check on the results, the four factors were reanalyzed using as the dependent variable the dimensionless moisture content after a drying time of five minutes for the data taken at $350^{\circ}F$, and dimensionless moisture content after a drying time of two minutes for the data taken at 600°F.

Three-Factor Analyses of Variance

To determine whether conclusions regarding comparative veneer drying times in air and in steam would be affected by conducting separate analyses of the drying data for Southern pine and Douglas fir, three-factor analyses were performed with the same factors and dependent variables as described previously for the four-factor analyses of variance, except that species of wood was eliminated as a factor. Hence, at each of two temperatures, 350°F and 600°F, four three-factor analyses were performed: two for Southern pine drying curves and two for Douglas fir drying curves, with moisture losses after a specified time and drying times to a specified moisture considered separately as dependent variables.

Additional three-factor analyses of variance were performed to determine if analyzing air data and steam data separately would affect conclusions from the four-factor analyses of variance regarding the drying times of Southern pine compared to Douglas fir. Factors considered were the same as those described previously for the four-factor analyses of variance, except that the type of drying medium was eliminated as a factor. At each of two temperatures, 350°F and 600°F, four three-factor analyses were performed: two for data taken in air and two for data taken in steam, with the same two dependent variables as those discussed in the preceding paragraph considered separately.

Use of Dimensionless Moisture Content, τ, to Provide a Common Basis for Comparisons of Data

Initial moisture contents varied from sample to sample within species and also between the two species of wood used in the experiment. For example, the average initial moisture content of the Douglas fir samples was approximately 140%, which was approximately 20% less than the average initial moisture content of the Southern pine samples. Veneer samples dried by South (15) in steam also differed in average initial moisture content from samples dried in air for this experiment. To provide a common moisture basis for comparing experimental results, moisture contents for both the samples dried in air in this experiment and the samples dried by South in steam were converted to dimensionless moisture contents, with dimensionless moisture content, τ, defined as follows:

$$\tau = \frac{\text{Moisture content of sample after drying time, } t \; - \; \text{Final equilibrium moisture content}}{\text{Initial moisture content of sample} \; - \; \text{Final equilibrium moisture content}} \times 100$$

The equilibrium moisture content of Douglas fir dried in superheated steam is less than 0.5% at temperatures greater than 350°F (10). Under the assumption that both Southern pine and Douglas fir would have similarly low equilibrium moisture contents when dried in air, the final equilibrium moisture content was considered to be zero in calculations of τ.

Moisture contents which are referred to in the equation for τ were calculated on a "dry" basis, that is,

$$\text{Moisture content} = \frac{\text{Wet weight of sample} - \text{Oven dry weight of sample}}{\text{Oven dry weight of sample}}$$

All drying curves included in this thesis are plotted in terms of τ. For Douglas fir or Southern pine veneer having average initial moisture content in the range of approximately 140% to 160%, the actual moisture content at any arbitrary drying time can be predicted using the appropriate drying curve in conjunction with the equation for τ.

COMPUTATION OF HEAT AND MASS TRANSFER COEFFICIENTS

Effective Heat Transfer Coefficients and Diffusion Coefficients

Prior to presenting the derivations of equations which were used to calculate the effective heat transfer coefficients and diffusion coefficients for the veneer samples used in this experiment, it is necessary to comment briefly on the phenomena involved in drying veneer.

Curves of veneer temperature measured as a function of time in either air or steam as a drying medium exhibited two common characteristics, which are shown diagramatically in Figure 5:

1. Within a few seconds after insertion of a veneer sample into the test section, veneer temperature rose to approximately 212°F. The temperature then remained relatively stable for a period of time which varied inversely with the temperature of the drying medium.

2. An abrupt increase in the rate of veneer temperature rise marked the end of the drying period with relatively stable temperature and the beginning of a period when veneer temperature rapidly rose toward the temperature of the drying medium. It was during this stage of drying that veneer surfaces became charred at the higher drying temperatures.

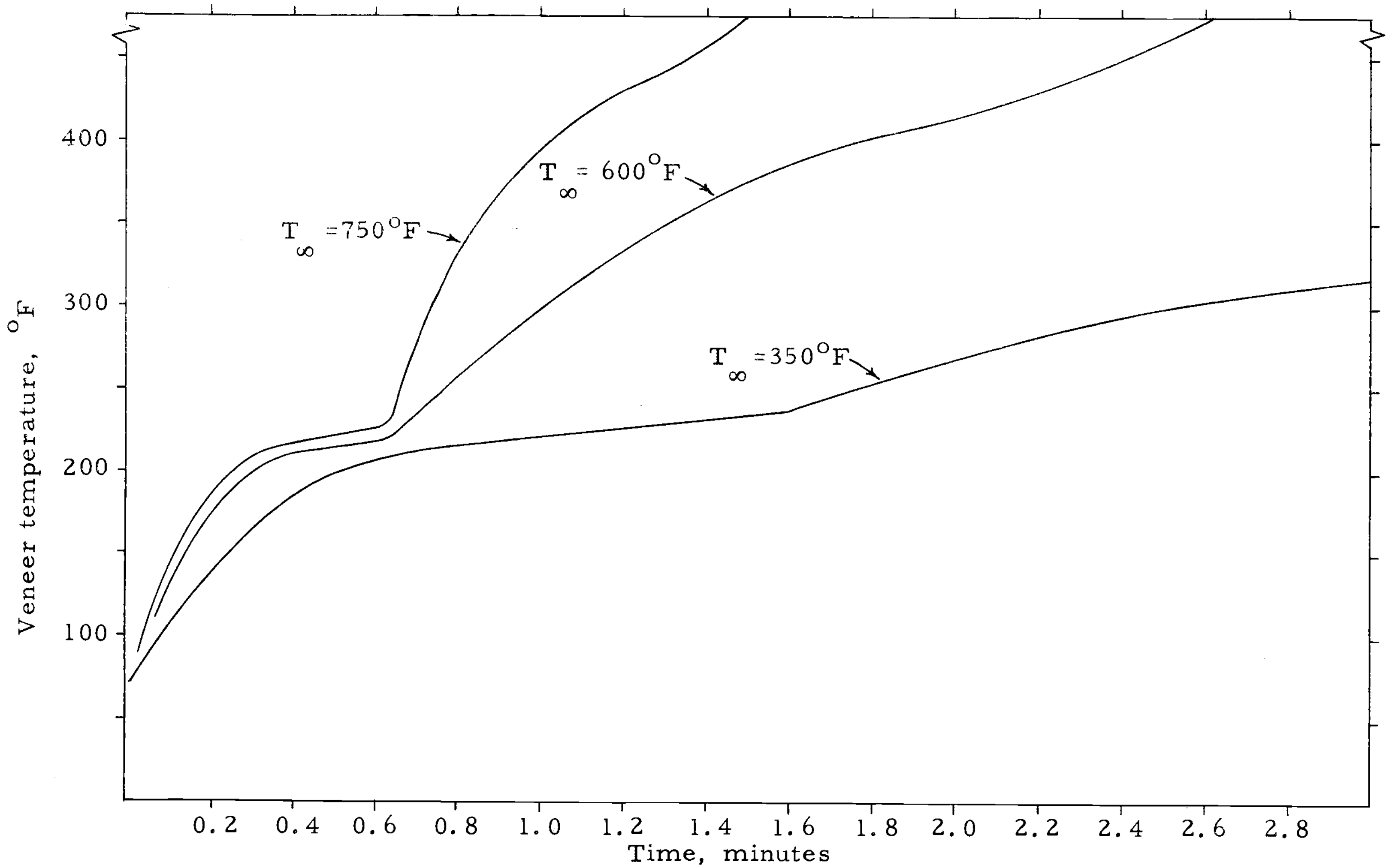


Figure 5. Temperature curves for Douglas fir with air flowing parallel to the veneer surfaces at 50 feet per second.

Changes observed in veneer temperatures during the drying period are related to variations in the rate at which water moves from the interior of the veneer to the veneer surfaces. As long as the veneer surfaces receive water from the interior of the veneer as fast as water is evaporated from the surfaces, the veneer temperature remains constant and the drying rate is governed by the rate of heat transfer from the surroundings to the veneer. This is called the constant rate drying period. When water moves to the veneer surfaces at a rate slower than the rate at which it can be evaporated, the veneer temperature rises and the veneer drying rate is diffusion controlled. This is called the falling rate drying period.

Stamm (17, p. 142-145, 429-435, 441-447) and Tiemann (18, p. 138-144, 221-232) explain in extensive detail the complicated phenomena associated with moisture diffusion through wood. In brief, the affinity of wood for water is inversely proportional to the moisture content of the wood. At the moisture content defined by Tiemann (18, p. 138) as the fiber saturation point, the affinity of water for wood becomes zero. Water is adsorbed by the wood at moisture contents below the fiber saturation point, accompanied by an evolution of heat. The adsorbed water, called bound water, is held as a solid solution within the wood cell walls. When exposed to a saturated atmosphere, wood continues to take on moisture above the fiber saturation point. This additional moisture, called free water, enters the wood by absorption or capillary action to occupy vacancies within the wood structure. Wood having the initial moisture contents of veneer samples used for this experiment contains both bound water and free water.

Included in South's thesis (15, p. 12-26) are derivations of equations for two independent methods of computing an effective heat transfer coefficient, h^o, which represents the convective effects of both heat and mass transfer associated with drying a veneer sample. South also presents the derivation of an equation for computing diffusion coefficients. These equations were formulated jointly by South and Dr. James R. Welty of the Mechanical Engineering Department, Oregon State University.

The following derivations are similar to those presented in South's thesis, with changes made as necessary so that the equations are applicable to veneer samples dried in air.

h^o-Based on Theoretical Considerations

Hartnett and Eckert (7) have presented solutions applicable to the analysis of simultaneous heat and mass transfer for flow past a flat plate. South (15) applied the work of Hartnett and Eckert to the analysis of heat and mass transfer from a veneer specimen for the case of parallel flow. In the following paragraphs, the development of the applicable equations is summarized.

The analysis which follows is for laminar, two-dimensional flow of a constant property fluid, under conditions of negligible compressibility and viscous dissipation effects. Resistance to moisture removal associated with internal diffusion of water through the wood is not taken into consideration, and therefore this analysis applies only during the constant rate drying period described previously.

The applicable equations are as follows:

Continuity: $$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Momentum: $$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial v}{\partial y} = \mu \frac{\partial^2 u}{\partial y^2} - \frac{dP}{dx}$$

Diffusion: $$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2}$$

Energy: $$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2}$$

where: ρ = fluid density

u = velocity parallel to surface (in the x direction)

v = velocity normal to surface (in the y direction)

C = concentration of diffusing fluid

μ = viscosity

T = temperature

D = coefficient of mass diffusion

α = thermal diffusivity

$\frac{dP}{dx}$ = pressure gradient

Included in the solutions to the preceding equations which are presented by Hartnett and Eckert (7) are dimensionless temperature and mass-fraction profiles for the case of laminar flow over a flat plate. The curves, which are shown in Figure 6, are provided for a range of values of the injection parameter, $\frac{v_w}{u_\infty}\sqrt{Re_x}$, where $\sqrt{Re_x}$ is the Reynolds number at a distance x from the leading edge of the flat plate and v_w and u_∞ are as defined in Figure 7. Positive values of the injection parameter denote mass transfer from the plate; negative values denote mass transfer to the plate. The curves are plotted against a dimensionless parameter, η, which relates flow effects near the wall to those in the free stream. Mass fractions of the diffusing gas at the wall and in the free stream are represented by C_{1_w} and C_{1_∞}, respectively, and the temperatures at these two locations are represented by T_w and T_∞. Local values of fluid temperature and mass fraction of the diffusing gas are represented by T and C_1, respectively.

The rate of heat transfer to the surface of a veneer specimen due to conduction through the boundary layer of air as a drying medium may be evaluated as follows:

$$q = k_{air} A_{wood} \left.\frac{\partial T}{\partial y}\right|_{y=0}$$

where the sign convention is such that the direction of positive heat flow is in the negative y direction, as shown in Figure 7.

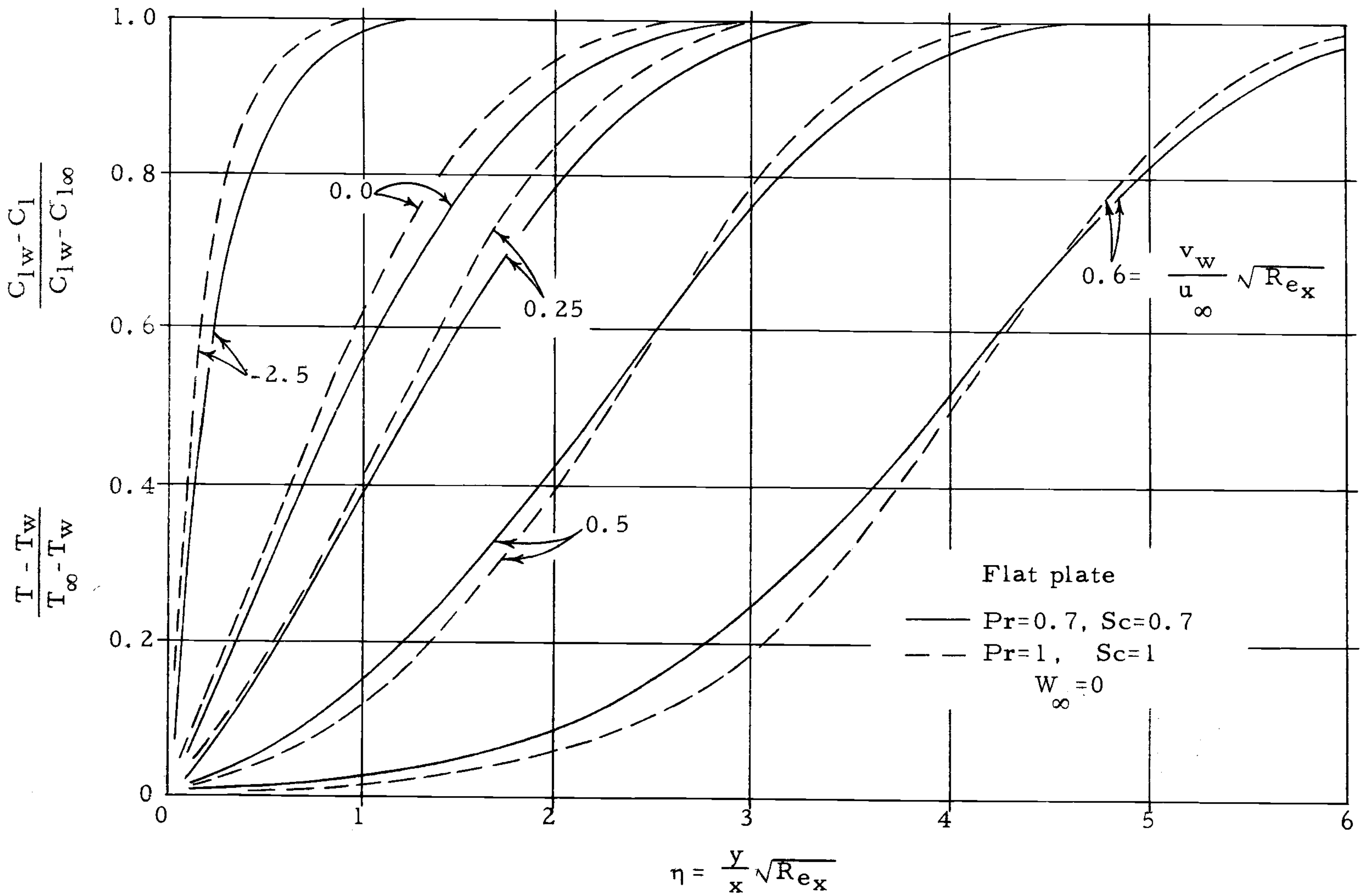
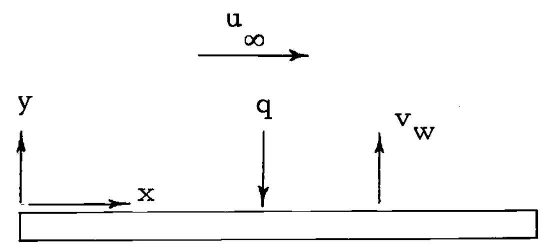


Figure 6. Dimensionless temperature profiles and mass-fraction profiles for laminar flow over flat plate for a range of values of the injection parameter $\frac{v_w}{u_\infty}\sqrt{Re_x}$ for Prandtl numbers of 1.0 and 0.7 (7).



q = rate of heat transfer to veneer
u_∞ = velocity of drying medium
v_w = velocity of moisture leaving veneer surface

Figure 7. Coordinate system for heat and mass transfer analysis of veneer specimen

The temperature gradient at the surface of the specimen may be rewritten in the following form:

$$\left.\frac{\partial T}{\partial y}\right|_{y=0} = \left.\frac{\partial T}{\partial \eta}\right|_{y=0} \left.\frac{\partial \eta}{\partial y}\right|_{y=0} = \left.\frac{\partial T}{\partial \eta}\right|_{y=0} \frac{1}{x}\sqrt{Re_x}$$

Thus,

$$q = k_{air} A_{wood} \frac{\sqrt{Re_x}}{x} \left.\frac{\partial T}{\partial \eta}\right|_{y=0} \tag{1}$$

An alternate way of evaluating the rate of heat transfer from the drying medium to the veneer sample at any position, x, on the surface is by use of the following convection equation:

$$q = \bar{h}_{cx} A_{wood} (T_\infty - T_w) \tag{2}$$

Equating 1 and 2:

$$\bar{h}_{cx} A_{wood} (T_\infty - T_w) = k_{air} A_{wood} \frac{\sqrt{Re_x}}{x} \left.\frac{\partial T}{\partial \eta}\right|_{y=0}$$

from which

$$\bar{h}_{cx} = \frac{k_{air} \sqrt{Re_x}}{x} \left[\frac{1}{(T_\infty - T_w)} \frac{\partial T}{\partial \eta} \Bigg|_{y=0} \right] \qquad (3)$$

where:

$\bar{h}_{cx}$ = convective mass transfer coefficient at position x,

k_{air} = thermal conductivity of air,

and the other terms are as defined previously.

The term in parentheses, which is equal to $\frac{\partial}{\partial \eta} [\frac{T - T_w}{T_\infty - T_w}]$, may be evaluated for a given rate of evaporation from the veneer surface by taking the slope at $\eta = 0$ of the appropriate curve in Figure 6. Since the slopes of the temperature profiles in Figure 6 decrease as values of the injection parameter, $\frac{v_w}{u_\infty} \sqrt{Re_x}$, increase, the magnitude of $\bar{h}_{cx}$ varies inversely with the rate of moisture removal from the veneer.

Solutions to the energy equation are also solutions to the diffusion equation, since the two equations are identical in form. Therefore, using the Hartnett and Eckert solutions in Figure 6, convective mass transfer coefficients may be computed in a manner analogous to the method used to calculate heat transfer coefficients. The equation for computing the convective mass transfer coefficient at any position, x, on the surface of the veneer is as follows:

$$\bar{k}_{cx} = \frac{D_{AB}\sqrt{Re_x}}{x}\left[\frac{1}{\Delta C_s}\frac{\partial C_s}{\partial \eta}\bigg|_{y=0}\right] \tag{4}$$

where D_{AB} is the diffusion coefficient of steam evaporating from the surface of the specimen into air as the drying medium, and ΔC_s is the moisture concentration difference between the surface of the veneer specimen and the free stream.

Values of D_{AB} in the preceding equation may be calculated using an equation presented by Hirschfelder, Bird and Spotz (8), which in this paper will be referred to as the Hirschfelder equation. From a known experimental value, the diffusion coefficient at any temperature and pressure below 25 atmospheres may be predicted by using the Hirschfelder equation in the following form (19, p. 457):

$$D_{AB_{T_2, P_2}} = D_{AB_{T_1, P_1}} \left(\frac{P_1}{P_2}\right)\left(\frac{T_2}{T_1}\right)^{3/2} \frac{\Omega_D @ T_1}{\Omega_D @ T_2} \tag{5}$$

where:

$D_{AB_{T_1, P_1}}$ is a known experimental diffusion coefficient. An observed value of the air-water diffusion coefficient is 0.260 cm^2/sec at a temperature of 298°K and a pressure of one atmosphere (14, p. 274).

Ω_D is the "collision integral," defined as a dimensionless function of the temperature of the intermolecular potential field for one molecule of A and one molecule of B (19, p. 455). Values of

Ω_D are tabulated in reference (9).

To evaluate the term in parentheses in equation 4, the slope of the appropriate mass-fraction profile in Figure 6 is determined at $\eta = 0$.

As an example of how equations 3 and 4 are applied to a specific situation, consider the case where mass transfer from the veneer surface is negligible. For this case the injection parameter, $\frac{v_w}{u_\infty}\sqrt{Re_x}$, is zero and

$$\left[\frac{1}{T_\infty - T_w} \frac{\partial T}{\partial \eta}\bigg|_{y=0}\right] = 0.332 .$$

Therefore, equation 3 becomes

$$\bar{h}_{cx} = 0.332 \frac{k_{air}}{x} \sqrt{Re_x} .$$

By integration, the average heat transfer coefficient for the condition of negligible mass transfer is

$$\bar{h}_c = \frac{1}{L}\int_0^L \bar{h}_{cx} dx = 0.664 \frac{k_{air}\sqrt{Re_L}}{L}$$

where L is the length of the veneer sample in the direction of air flow.

The corresponding mass transfer coefficient is

$$\bar{k}_c = 0.664 \frac{D_{AB}\sqrt{Re_L}}{L} .$$

Having developed methods to calculate predicted values for

$\bar{h}_c$ and $\bar{k}_c$, the effective heat transfer coefficient, h^o, may be computed. As discussed earlier, h^o represents the convective effects of both heat and mass transfer. The effective heat transfer coefficient may be expressed as follows (15, p. 26):

$$h^o_{predicted} = \frac{\text{rate of heat transfer to veneer} + \text{energy rate associated with mass transfer}}{A_{wood}(T_\infty - T_w)}$$

$$= \frac{\bar{h}_c A_{wood}(T_\infty - T_w) + \bar{k}_c A_{wood} \Delta C_s h_{fg}}{A_{wood}(T_\infty - T_w)}$$

In simplified form,

$$h^o_{predicted} = \bar{h}_c + \frac{\bar{k}_c \Delta C_s h_{fg}}{(T_\infty - T_w)} \qquad (6)$$

The preceding equation applies only during the "constant rate" drying period described earlier. Values of $h^o_{predicted}$ were calculated for each of the two species of wood under the nine parallel flow test conditions. Computational details are discussed in the Appendix.

h^o-Based on Experimental Data

In the following paragraphs, an equation for calculating h^o from experimental data is formulated by applying the first law of thermodynamics to the control volume shown in Figure 8. The resulting equation is applicable for any angle of impingement of the drying medium, and the equation also applies during both the constant rate and falling rate drying periods described earlier.

The first law of thermodynamics, in a form applicable to a control volume, may be stated as follows: the net rate of energy

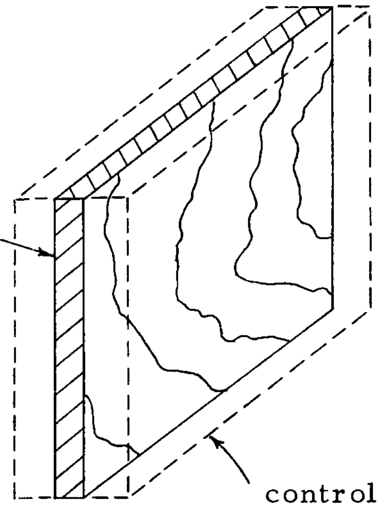


Figure 8. Control volume for veneer sample.

transferred to the control volume equals the net rate of energy leaving the control volume plus the rate of accumulation of energy within the control volume. Mathematically, this expression for the first law of thermodynamics takes the following form:

$$\frac{\delta Q}{dt} - \frac{\delta W}{dt} = \iint_{c.s.} e\rho(\vec{v} \cdot \vec{n})\, dA + \frac{\partial}{\partial t} \iiint_{c.v.} e\rho dv \qquad (7)$$

The first term in the preceding equation, $\frac{\delta Q}{dt}$, represents the heat transferred to the control volume. Within the test section, heat is transferred to a veneer sample by radiation from the enclosure, and by convection from the drying medium. Heat conduction from the sample holder is negligible due to the small area of contact. Since air is practically transparent to thermal radiation, heat transfer by radiation from air to the veneer sample is also negligible. The first term may therefore be expressed as follows:

$$\frac{\delta Q}{dt} = q_{convection} + q_{radiation}$$

$$= h^{o} A_{wood}(T_{air} - T_{wood}) \quad (8)$$

$$+ \sigma A_{wood} \mathcal{F}_{1-2}(T_{walls}^{4} - T_{wood}^{4})$$

where: $\mathcal{F}_{1-2}$ is the view factor from the test section to the wood sample, and

h^{o} is the effective heat transfer coefficient.

Since no work is done by the veneer sample on the surroundings, the second term in equation 7, $\frac{\delta W}{dt}$, is zero.

In the absence of combustion, the only energy leaving the control volume is that associated with the evaporation of water from the veneer. Therefore, the third term of equation 7 becomes

$$\iint_{c.s.} e\rho(\vec{v} \cdot \vec{n})\, dA = \dot{m}_s h_g \quad (9)$$

where: $\dot{m}_s$ = mass flow rate of steam leaving the control surface due to evaporation of moisture within the veneer, and

h_g = enthalpy of saturated steam at the temperature of the veneer surface.

Energy accumulating within the wood, and within water remaining in the wood, is taken into consideration in the last term of equation 7 as follows:

$$\frac{\partial}{\partial t}\iiint_{c.v.} e\rho\, dv = \frac{\partial}{\partial t}(m_{wood}u_{wood} + m_{water}u_{water})$$

$$= m_{wood}\dot{u}_{wood} + \dot{m}_{wood}u_{wood} + m_{water}\dot{u}_{water} + \dot{m}_{water}u_{water}$$

where u_{wood} and u_{water} denote the internal energies of the wood and water. In the absence of combustion, $\dot{m}_{wood} = 0$. The preceding equation becomes

$$\frac{\partial}{\partial t}\iiint_{c.v.} e\rho\, dv = m_{wood}\dot{u}_{wood} + m_{water}\dot{u}_{water} + \dot{m}_{water}u_{water} \quad . \tag{10}$$

Noting that $\dot{m}_s = \dot{m}_{water}$, $u_{water} \simeq h_{water}$, $u_{wood} = Cp_{wood}T_{wood}$, $u_{water} = Cp_{water}T_{water}$, and $(h_g - h_f) = h_{fg}$, equations 9 and 10 may be combined to yield

$$\iint_{c.s.} e\rho(\vec{v}\cdot\vec{n})\,dA + \frac{\partial}{\partial t}\iiint_{c.v.} e\rho\, dv = m_{wood}\frac{d}{dt}(Cp_{wood}T_{wood}) + m_{water}\frac{d}{dt}(Cp_{water}T_{water}) + \dot{m}_s h_{fg} \tag{11}$$

Substituting equations 8 and 11 into equation 7 and assuming constant specific heats, the following equation is obtained:

$$h^{o} A_{wood}(T_{air} - T_{wood}) + \sigma A_{wood} \mathcal{F}_{1-2}(T^{4}_{walls} - T^{4}_{wood}) = \dot{m}_{s} h_{fg} + m_{wood} Cp_{wood} \frac{dT_{wood}}{dt} + m_{water} Cp_{water} \frac{dT_{water}}{dt} \quad (12)$$

Equation 12 can be solved for h^{o}, in terms of quantities which are known from data taken when drying each veneer sample. For each of the two species of wood used in this experiment, values of h^{o} were computed at various stages of drying under all test conditions. Computational details are given in the Appendix.

Average Diffusion Coefficient for Movement of Water Through Wood

As discussed earlier, the rate at which moisture is removed from a veneer specimen during the "falling rate" drying period is governed by the rate of internal diffusion of water from the interior of the wood to the veneer surface. Outlined in the following paragraphs is a method for determining an average diffusion coefficient which applies over the entire time period required to dry a veneer sample. The method can be used to obtain experimental diffusion coefficients for all drying conditions.

At any particular instant of time during the drying period, the rate of transfer of water to the veneer surfaces may be expressed by Fick's first law of diffusion as follows:

$$\frac{\widehat{\dot{m}}}{A} = - \widehat{D_{AB}} \left. \frac{\widehat{\partial C_{w}}}{\partial x} \right|_{surface}$$

where $\widehat{\dot{m}}$, $\widehat{D_{AB}}$, and $\widehat{\frac{\partial C_w}{\partial x}}$ represent instantaneous values for the rate of mass transfer, the diffusion coefficient, and the rate of change of water concentration with respect to distance, and A denotes the surface area of the wood.

Both the concentration profile for water remaining in the wood and the diffusion coefficient for movement of water to the wood surfaces vary during the drying period. To obtain an average diffusion coefficient for any given drying period, a Gurney-Lurie chart (6) may be used in conjunction with known experimental data. The governing equation is Fick's second law of diffusion:

$$\frac{\partial C_w}{\partial t} = \overline{D}_{AB} \frac{\partial^2 C_w}{\partial x^2}$$

where $\overline{D}_{AB}$ is defined by South (15, p. 28) as the average of the instantaneous diffusion coefficients over all of the different concentration gradients which exist as the veneer dries.

Use of Gurney-Lurie charts for solving unsteady state heat and mass transfer problems is discussed in Welty, Wicks, and Wilson (19). In brief, solutions to either of two analogous equations, Fick's second law of diffusion and Fourier's second law of heat conduction, are provided on the Gurney-Lurie charts for certain geometries and boundary conditions. A Gurney-Lurie chart applicable to a flat plate is shown in Figure 9.

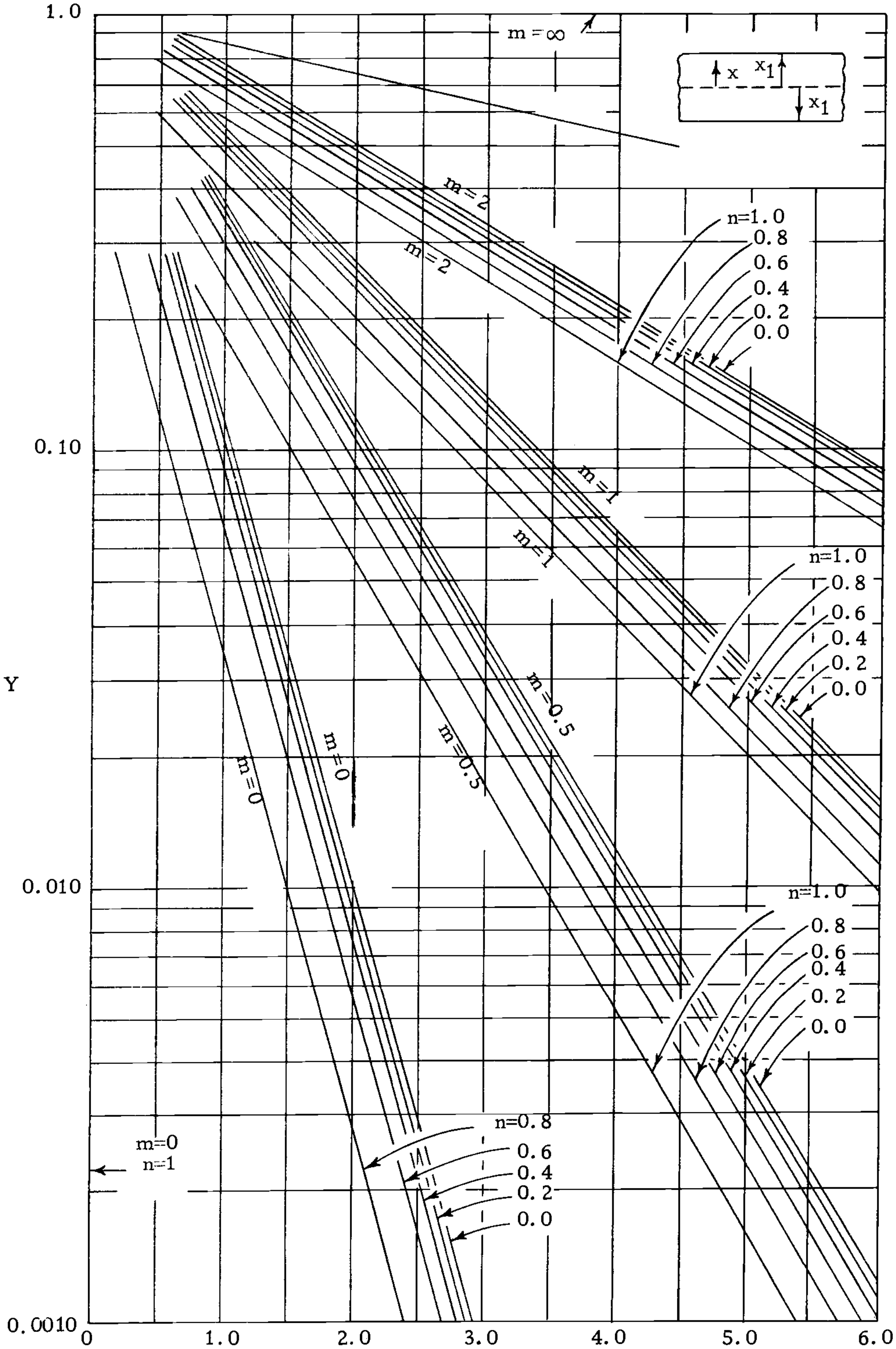


Figure 9. Gurney-Lurie chart for unsteady state transport in a large flat slab (6).

For the case of diffusion through veneer, values for the parameters on the Gurney-Lurie chart are computed as follows:

$$Y = \frac{C_{w_1} - C_{w_f}}{C_{w_1} - C_{w_0}}$$

$$X = \frac{\overline{D}_{AB}\, t}{x_1^2}$$

$$n = \frac{x}{x_1}$$

$$m = \frac{\overline{D}_{AB}}{\overline{k}_c\, x_1}$$

where:

C_{w_1} = concentration of water at the veneer surface,

C_{w_0} = initial moisture concentration in the wood,

C_{w_f} = final moisture concentration after drying,

$\overline{D}_{AB}$ = average diffusion coefficient,

t = time to reach final moisture concentration,

x_1 = half-thickness of the veneer,

x = distance from the center of the veneer to any plane parallel to the veneer surface,

$\overline{k}_c$ = convective mass transfer coefficient at the veneer surface.

Since the diffusion coefficient for water moving through wood is much smaller than the convective mass transfer coefficient at the surface of the veneer, the parameter, m, may be considered to be zero. Based on the assumption that the moisture concentration half-way between the center and either of the two faces of the sample is approximately equal to the average moisture content of the sample, the value of n was taken to be 0.5. A value for X can then be obtained from the Gurney-Lurie chart, and knowing the veneer thickness and the time required to dry the sample under a given set of conditions, D_{AB} can be computed. Sample calculations are included in the Appendix.

RESULTS

Interpretations of the results included in this section are presented in the Discussion section.

Drying Curves for Veneer Samples in Air as the Drying Medium

Curves of moisture loss plotted as a function of time are included in Figures 10 through 19, for veneer samples exposed to air as the drying medium. It is apparent from these curves that drying times of veneer samples are strongly dependent on the temperature and the velocity of the drying medium.

Of the three angles which were established for impingement of the drying medium on the veneer surfaces, the 45^{o} angle was the least effective in this experiment. Differences in drying times associated with the three angles of impingement are summarized in Table I. Comparisons of the effectiveness of parallel flow with perpendicular flow are inconclusive, since neither angle proved to be more effective than the other on a consistent basis.

Comparison of Drying Curves from South's Experiment with Drying Curves from this Experiment for Veneer Dried in Steam

Figures 20 and 21 confirm that drying curves for samples dried in steam in this experiment are virtually identical to drying curves obtained by South (15) under the same drying conditions. Consequently, drying characteristics of the samples obtained for this experiment are assumed to deviate in no significant way from the drying characteristics of samples used by South.

Drying Rates of Veneer in Air Compared to Drying Rates in Steam

Summarized in Table II are the differences in drying times for veneer dried under the same conditions in air and in steam. Results from the statistical analysis of the combined data for Douglas fir and Southern pine indicate that at 350^{o}F, 1/8 inch thick veneer dries to a dimensionless moisture content of 10% approximately 1.1 minutes faster in air than in steam. At 600^{o}F, on the other hand, veneer samples dried approximately 0.4 minutes faster in steam than in air.

Statistical analyses of the drying times were also performed separately for each of the two species of veneer. As shown in Table II, the differences in drying times for Douglas fir in air and in steam do not differ appreciably from the differences in drying times for Southern pine in the two media. Southern pine did, however, dry faster than Douglas fir in both air and steam, as discussed in the following paragraph.

Drying Rates of Southern Pine Compared to Drying Rates of Douglas Fir

Under all conditions of temperature, velocity, angle of impingement, and drying medium, Southern pine dried approximately 0.3 minutes faster than Douglas fir to a dimensionless moisture content of 10%. Differences in drying times for the two species of wood are shown in Table III. Statistical analyses were conducted for the combined data for the two drying media, as well as separately for the veneer drying curves in air and the drying curves in steam. As shown in Table III, the differences in drying times between Southern pine and Douglas fir were smaller in air as a drying medium than in steam as a drying medium.

Charring of Veneer in Air and in Steam

To determine if charring would commence at the 350^{o} operating temperature, several veneer samples were left in the test section for up to 20 minutes, even though the samples dried to a dimensionless moisture content of 5% or less within approximately eight minutes at $350^{o}F$. No charring at the $350^{o}F$ operating temperature was observed for samples exposed to either air or steam as the drying medium.

Charring of veneer samples was observed in both air and steam at operating temperatures of $600^{o}F$ and higher. As shown in Figures 22 through 24, charring commenced at higher moisture contents for veneer samples dried in air than for veneer samples dried in steam. It can be observed from these figures that for samples having equal char, differences in moisture contents for those dried in air and those dried in steam are on the order of 10%.

Effective Heat Transfer Coefficients

Representative values of h^{o} computed from the experimental data taken in air as the drying medium are listed in Table IV. Magnitudes of $h^{o}_{experimental}$ are seen to be directly proportional to the velocity, and inversely proportional to the temperature of the drying medium. In addition, the values of $h^{o}_{experimental}$ are generally lower for samples dried under 45^{o} impingement than for samples dried at 0^{o} or 90^{o} impingement.

Values of $h^{o}_{experimental}$ in Table IV for air dried veneer are similar in magnitude to values of $h^{o}_{experimental}$ presented by South (15, p. 46) for veneer dried in steam at the same temperatures and angles of impingement. Although the differences between $h^{o}_{experimental}$ for veneer dried in the two media are small, the magnitudes of $h^{o}_{experimental}$ for air dried veneer are generally lower than the magnitudes of $h^{o}_{experimental}$ for steam dried veneer.

In Figures 25 and 26, both experimental and theoretical heat transfer coefficients are plotted for air and for steam as the drying media, with data points calculated from the nine combinations of temperature and velocity which were established for drying samples in parallel flow. The data for steam dried veneer are reproduced from South's thesis (15, p. 33). As can be seen from the curves, a sizeable discrepancy exists for air dried veneer between values of h^o predicted from theoretical considerations and values of h^o based on experimental data. Possible reasons for this discrepancy are presented in the Discussion section of this thesis.

Experimental Internal Diffusion Coefficients

Listed in Table V are values of experimental diffusion coefficients for movement of water through Douglas fir and Southern pine samples under all drying conditions established for this experiment. In Figures 27 and 28, diffusion coefficients for samples dried under parallel flow conditions in air are plotted together with diffusion coefficients for samples dried under the same conditions in steam. Diffusion coefficients for samples dried in steam were calculated from South's data.(15).

The diffusion coefficients are plotted in Figures 27 and 28 as a function of the parameter ξ, which is defined by South (15, p. 36) as follows:

$$\xi = \frac{\bar{h}_c(T_\infty - T_{ave})}{\frac{C_1 + C_2}{2}}$$

where: $\bar{h}_c(T_\infty - T_{ave})$ represents the average amount of heat transferred from the drying medium at a temperature of T_∞ to the veneer sample at a temperature of T_{ave}. $\frac{C_1+C_2}{2}$ represents the average moisture content of the veneer sample during the drying period. C_1 is the initial, and C_2 is the final moisture content of the sample.

Since the magnitude of $\bar{D}_{AB}$ is strongly dependent on the average temperature of the wood, the parameter ξ against which $\bar{D}_{AB}$ is plotted in Figures 27 and 28 is made up of the principal factors affecting the average veneer temperature. It may not be clear why a term for the average moisture content of the veneer is included in the equation for ξ. The rate of temperature rise of a veneer sample, and hence the average temperature of the sample during the drying period, is inversely proportional to the average moisture content, due to the fact that the specific heat of water is higher than the specific heat of wood.

Moisture Contents After a Specified Drying Time

As mentioned previously in the Statistical Analysis section, conclusions from analyses with time to dry to a dimensionless moisture content of 10% as the dependent variable were checked by reanalyzing the data using as the dependent variable the dimensionless moisture content after a specified drying time. Mean values of the moisture contents corresponding to the various factors in the latter analyses are included in the Appendix.

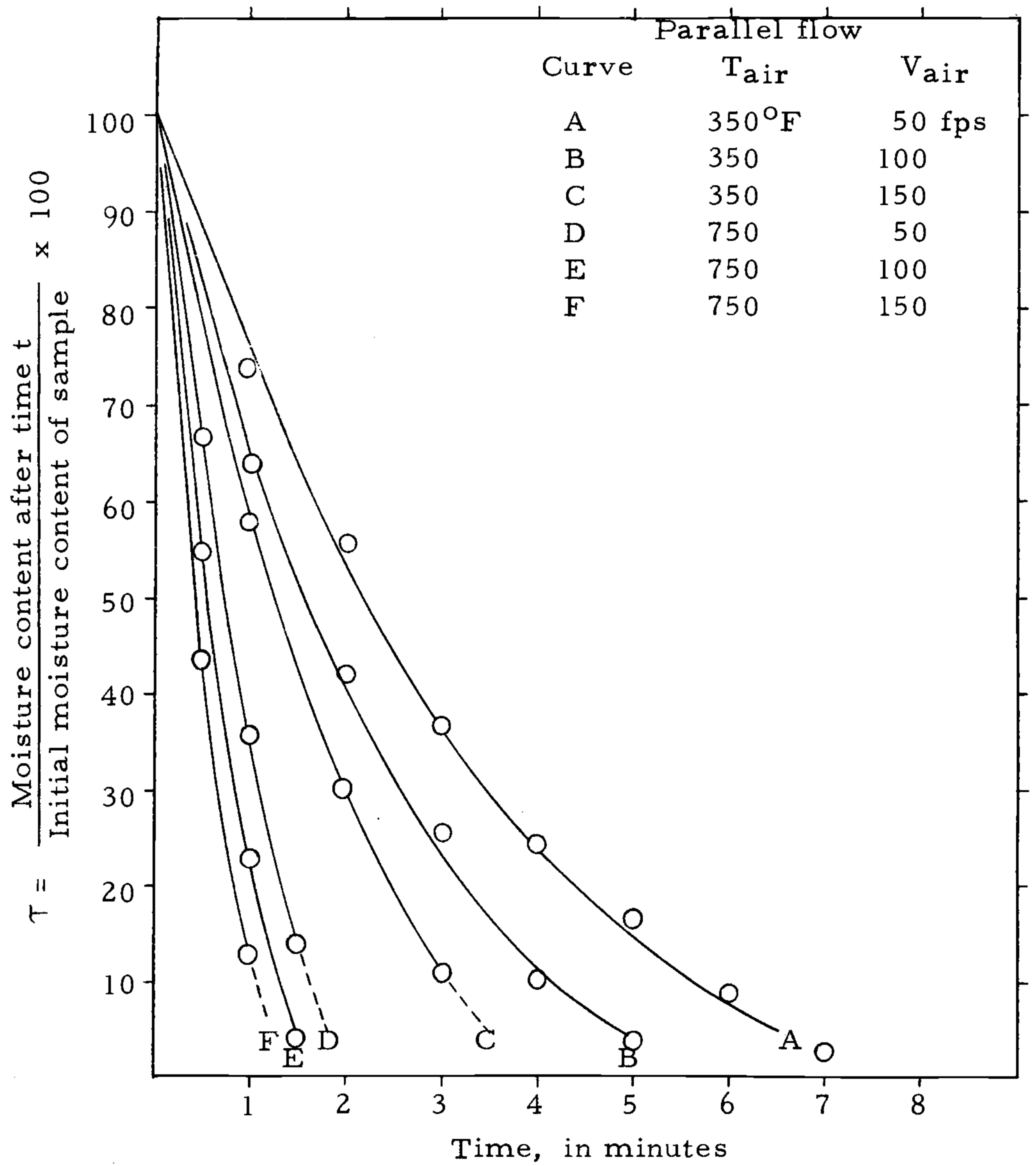


Figure 10. Douglas fir drying curves: Parallel flow of air at 350°F and 750°F.

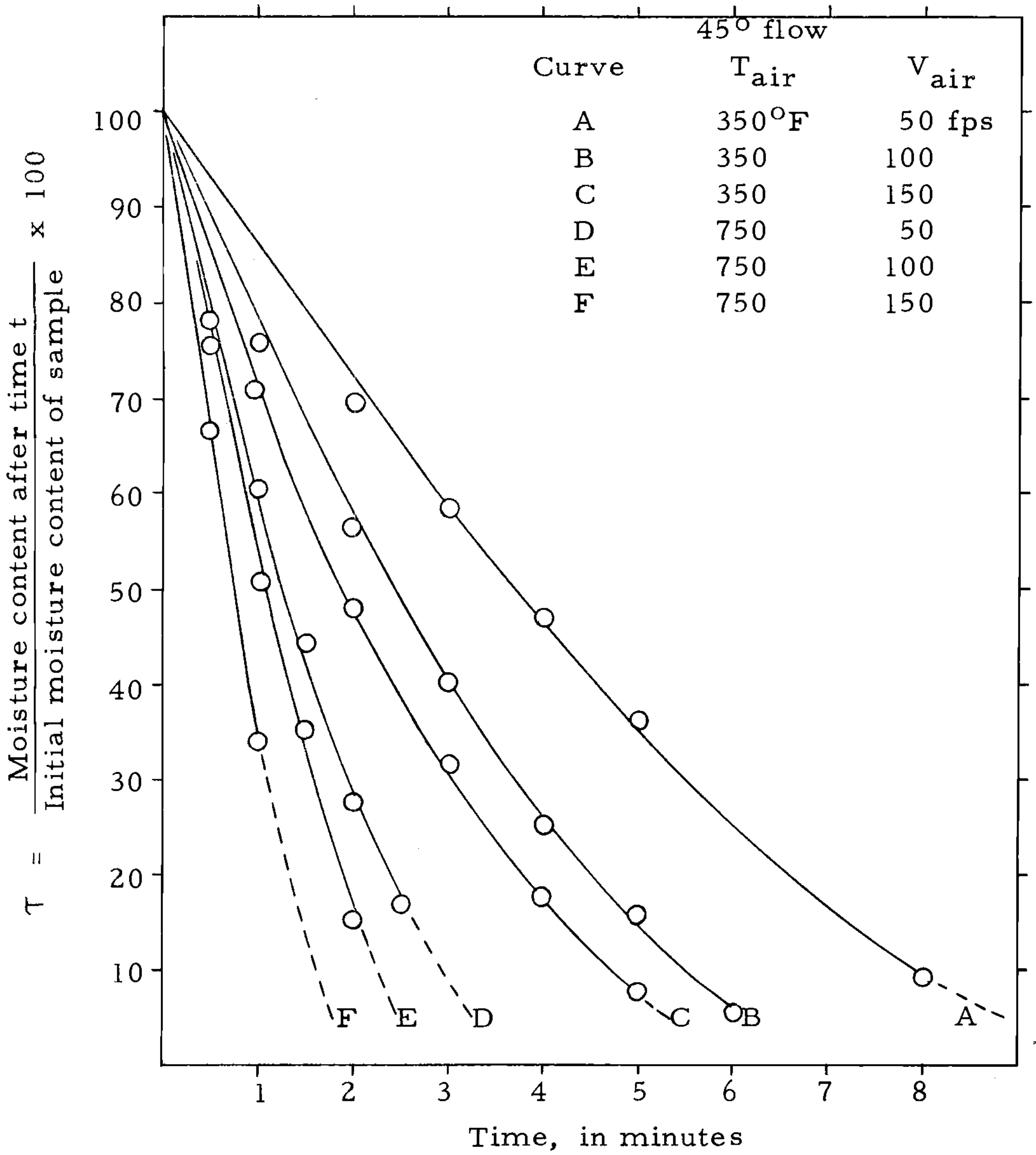


Figure 11. Douglas fir drying curves: 45° flow of air at 350°F and 750°F.

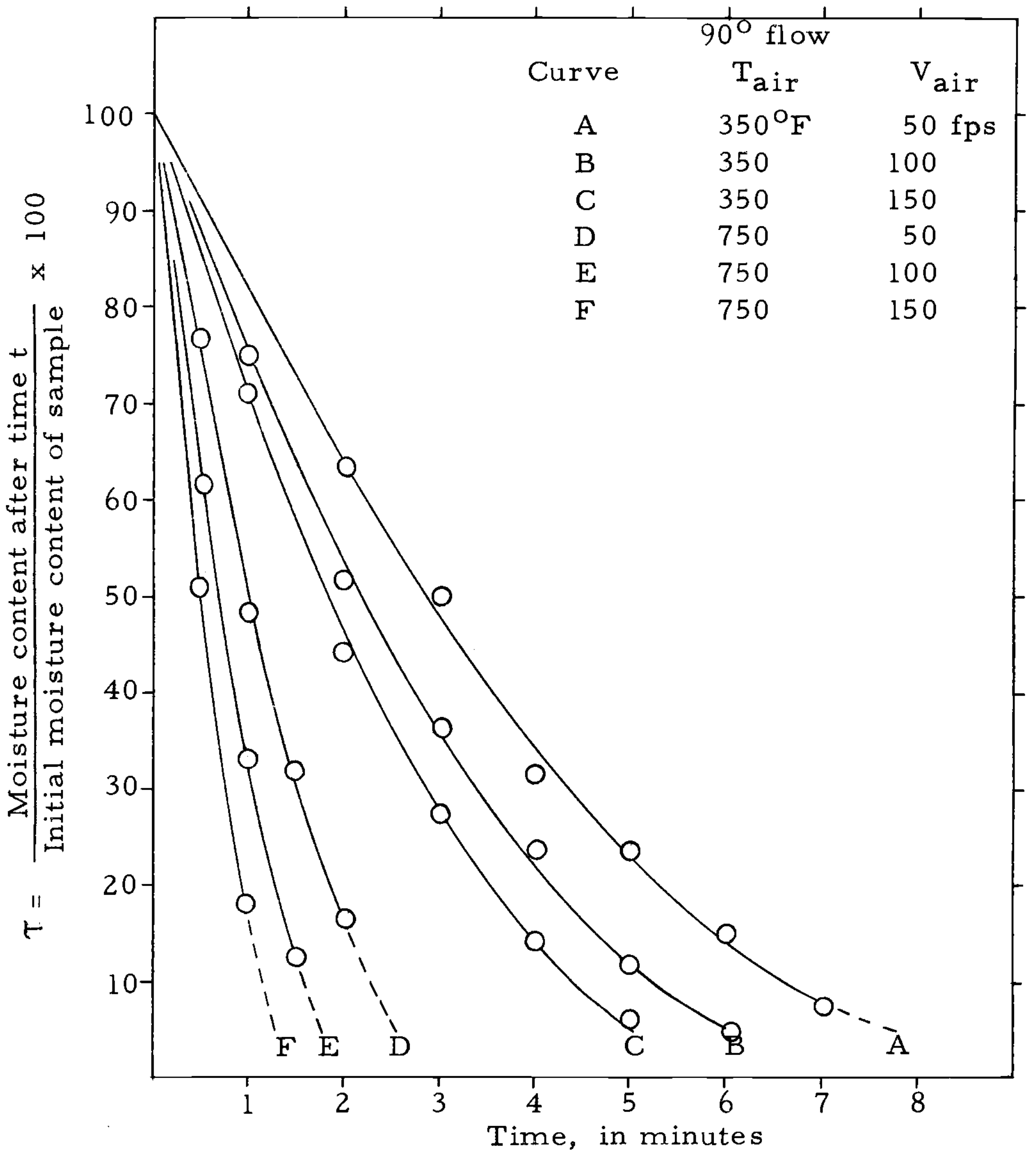


Figure 12. Douglas fir drying curves: 90° flow of air at 350°F and 750°F.

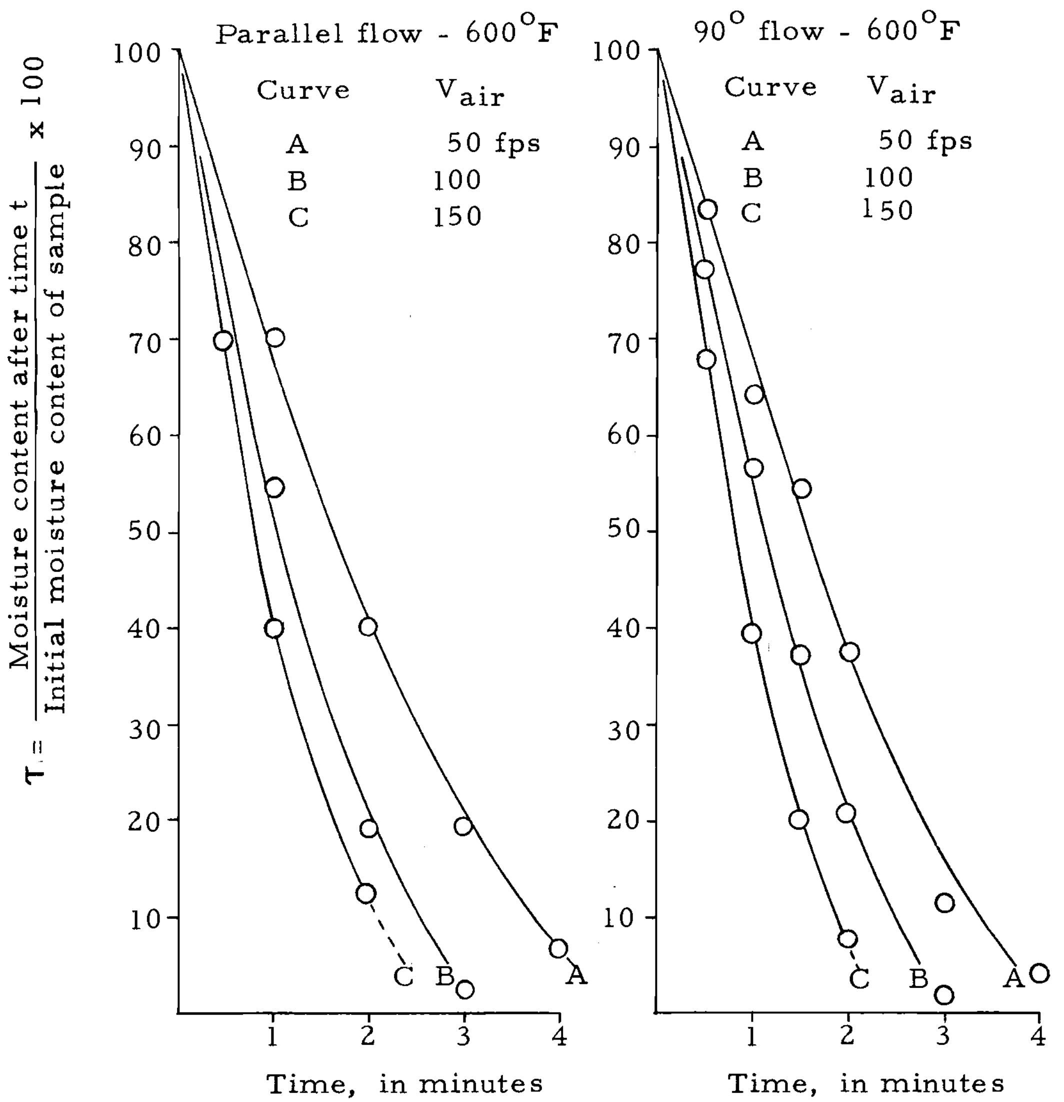


Figure 13. Douglas fir drying curves: Parallel and 90° flow of air at 600°F.

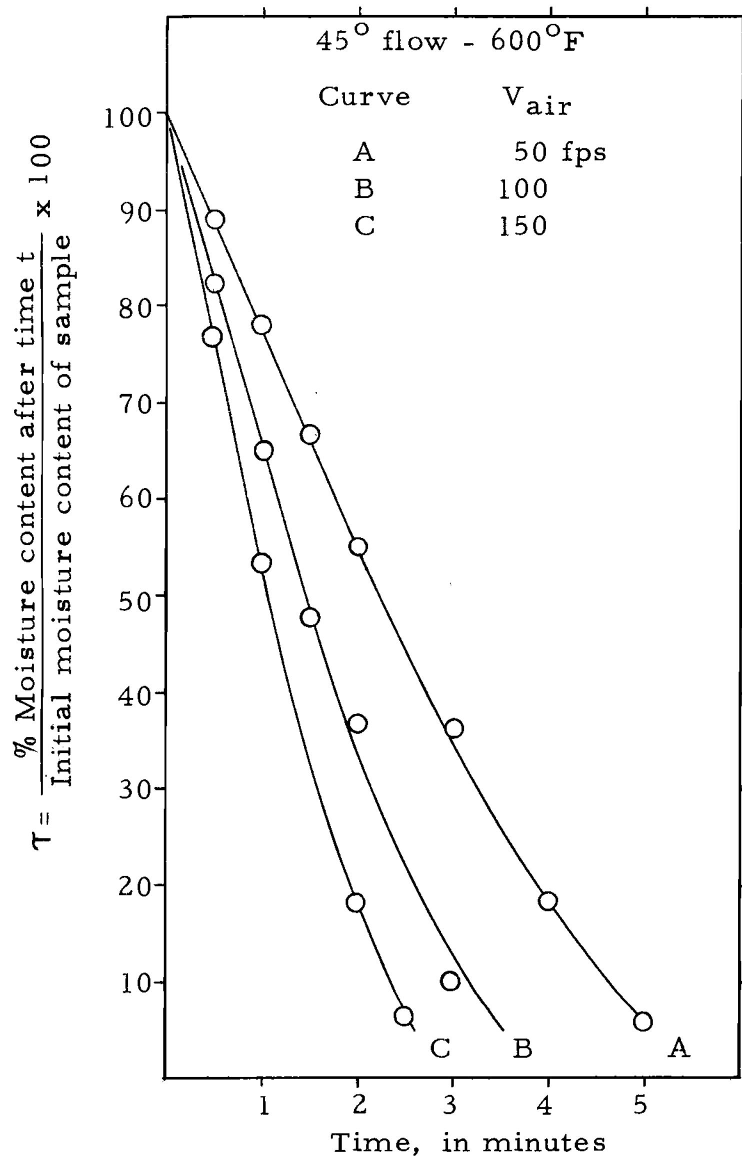


Figure 14. Douglas fir drying curves: 45° flow of air at 600°F.

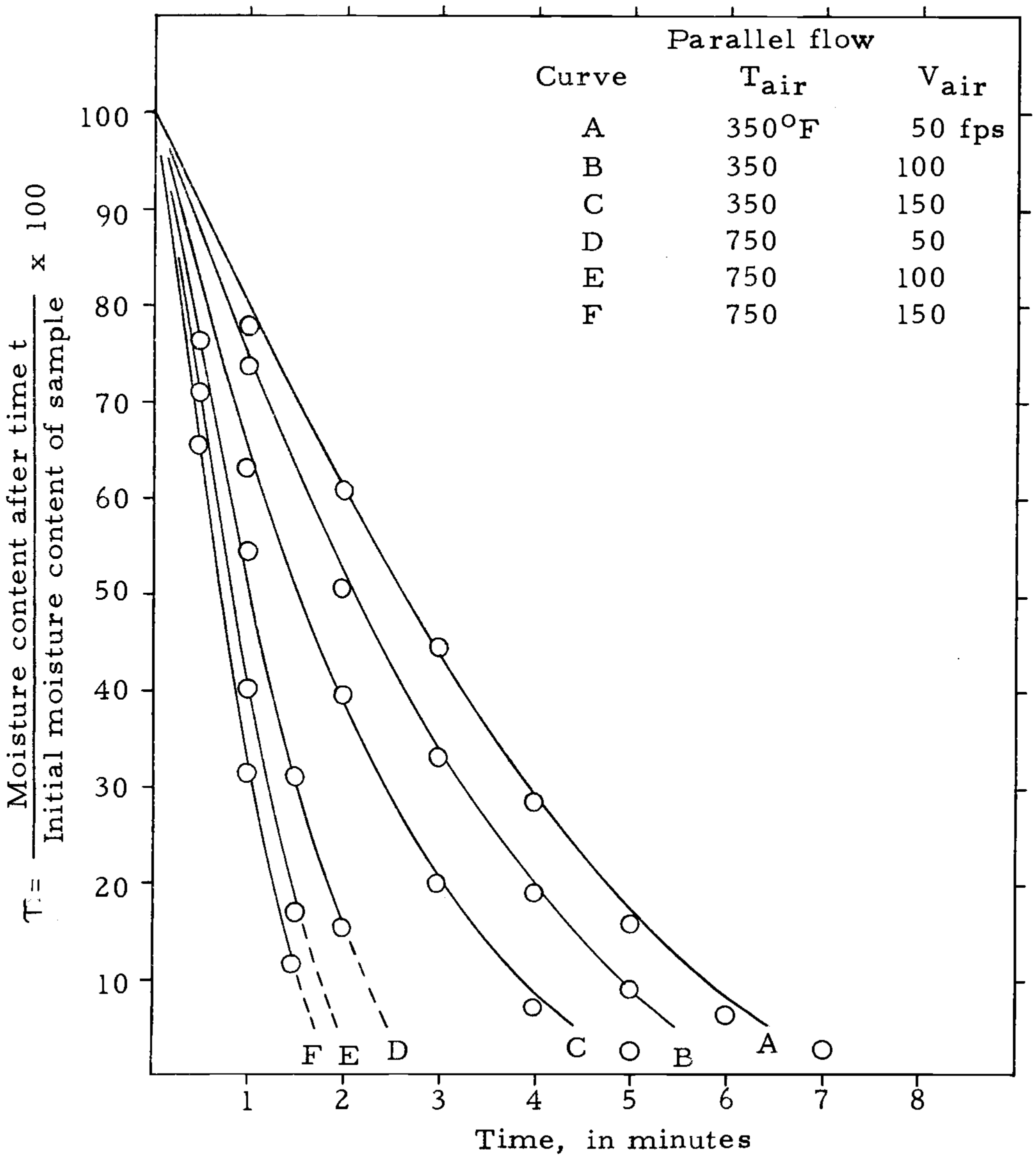


Figure 15. Southern pine drying curves: Parallel flow of air at 350°F and 750°F.

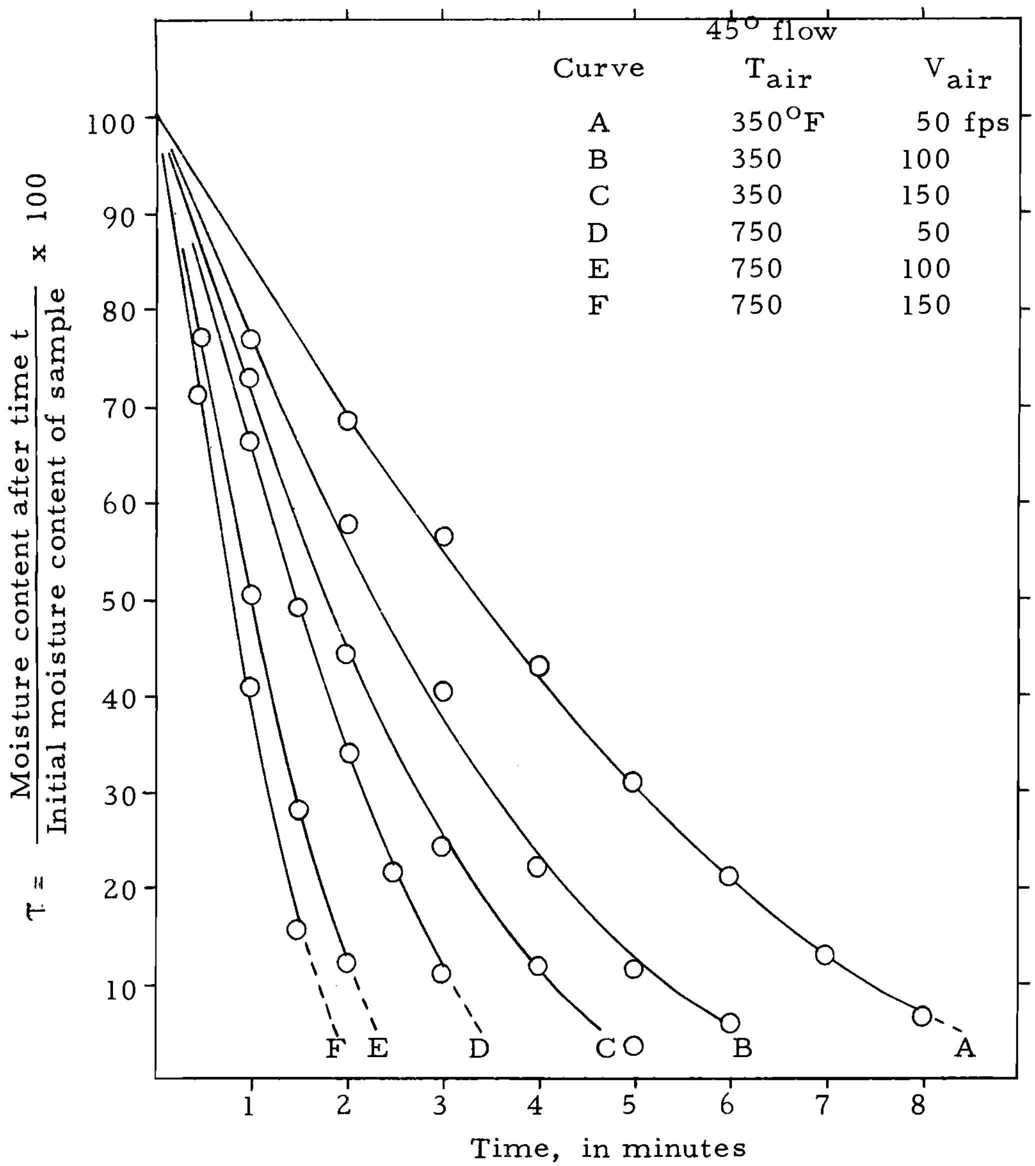


Figure 16. Southern pine drying curves: 45° flow of air at 350° F and 750°F.

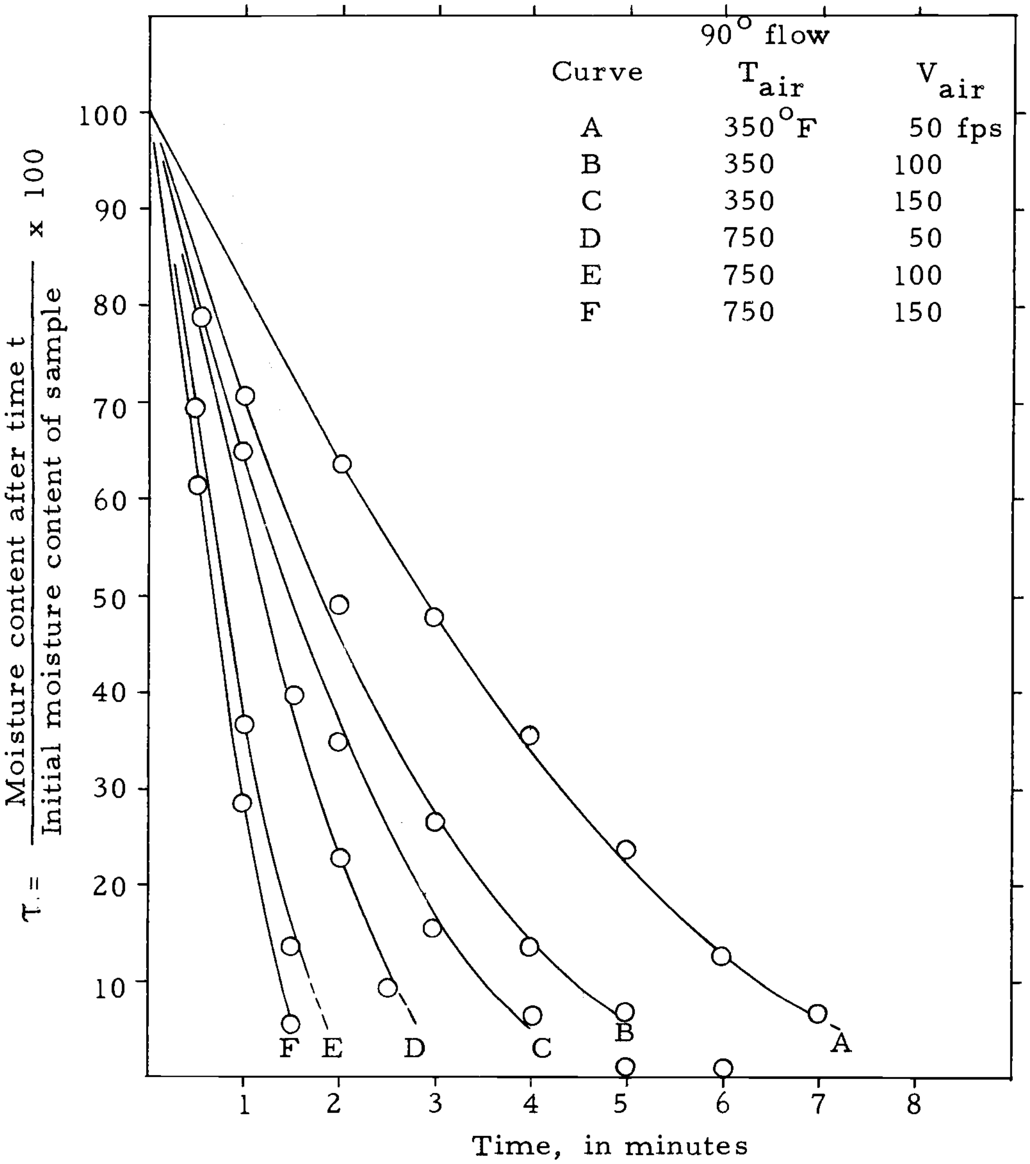


Figure 17. Southern pine drying curves: 90° flow of air at 350°F and 750°F.

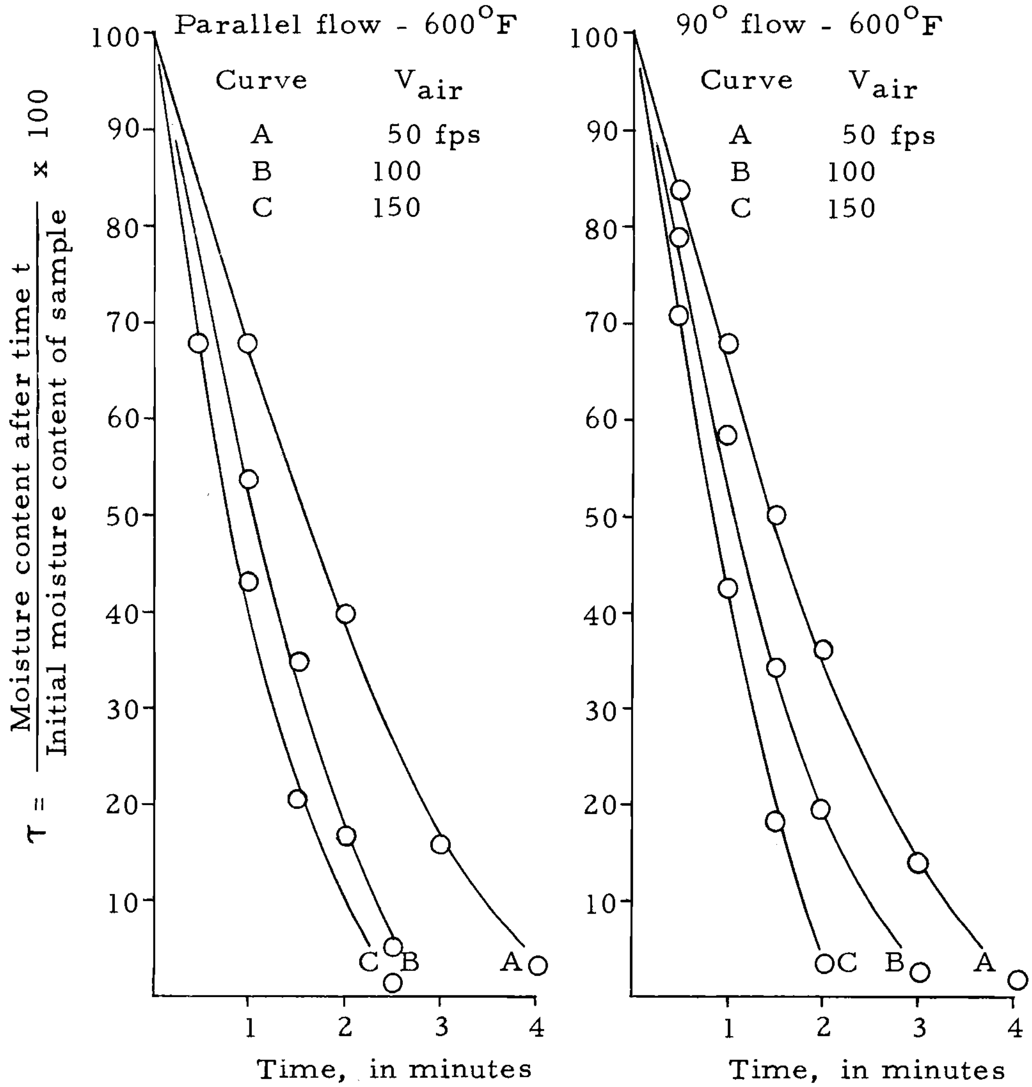


Figure 18. Southern pine drying curves: Parallel and 90° flow of air at 600°F.

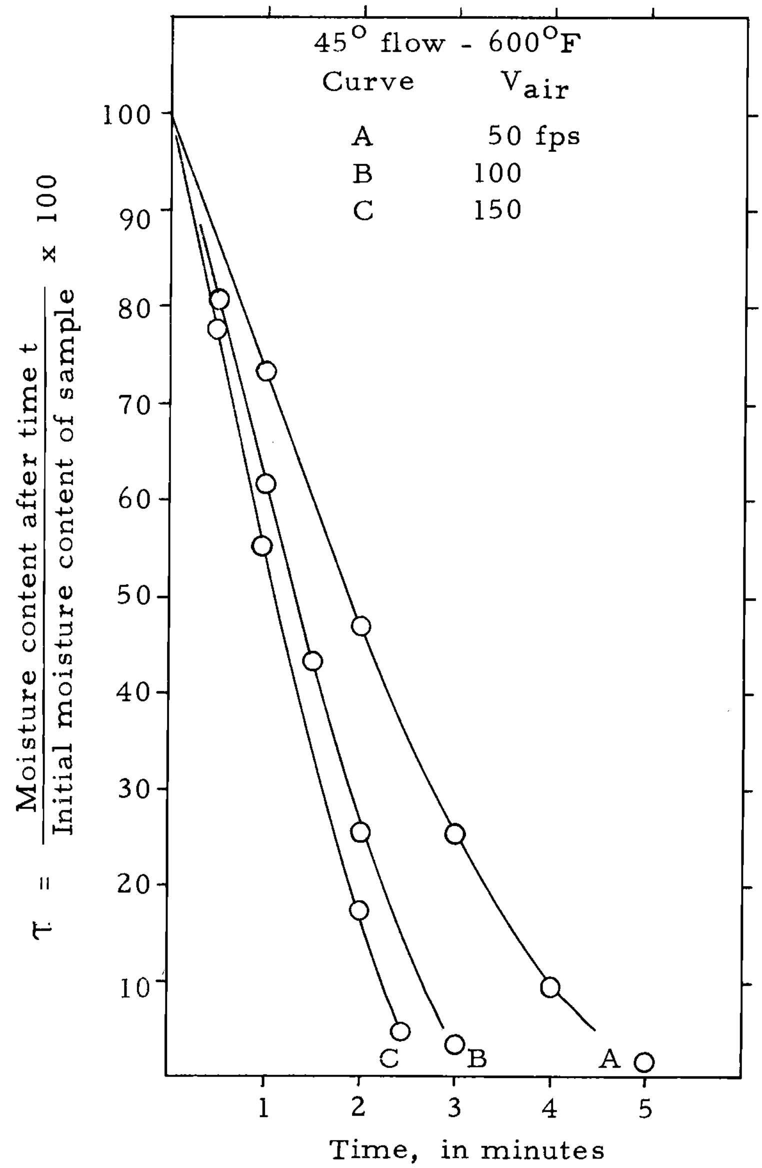


Figure 19. Southern pine drying curves: 45° flow of air at 600°F.

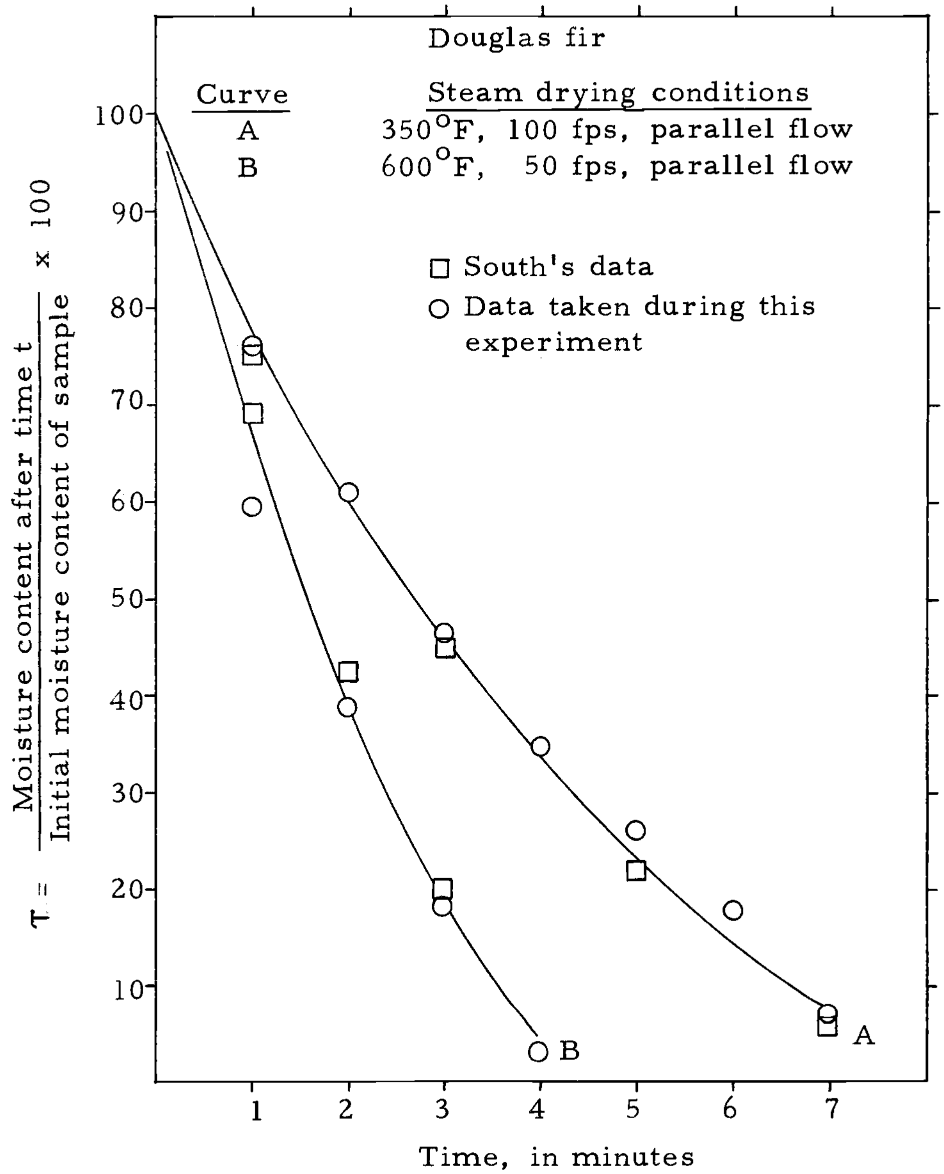


Figure 20. Comparison of drying rates in steam for Douglas fir veneer samples used by South (15) and Douglas fir samples used in this experiment.

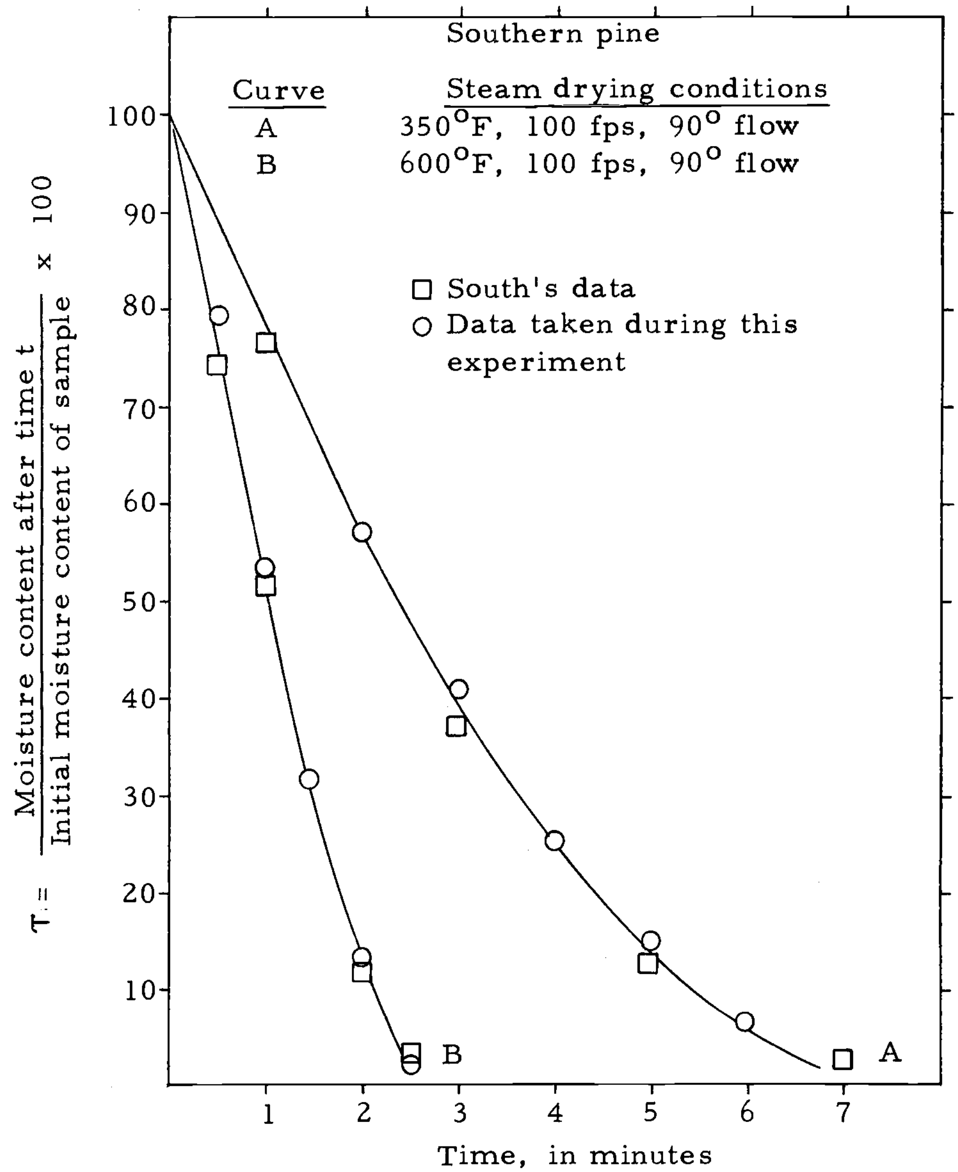


Figure 21. Comparison of drying rates in steam for Southern pine veneer samples used by South (15) and Southern pine samples used in this experiment.

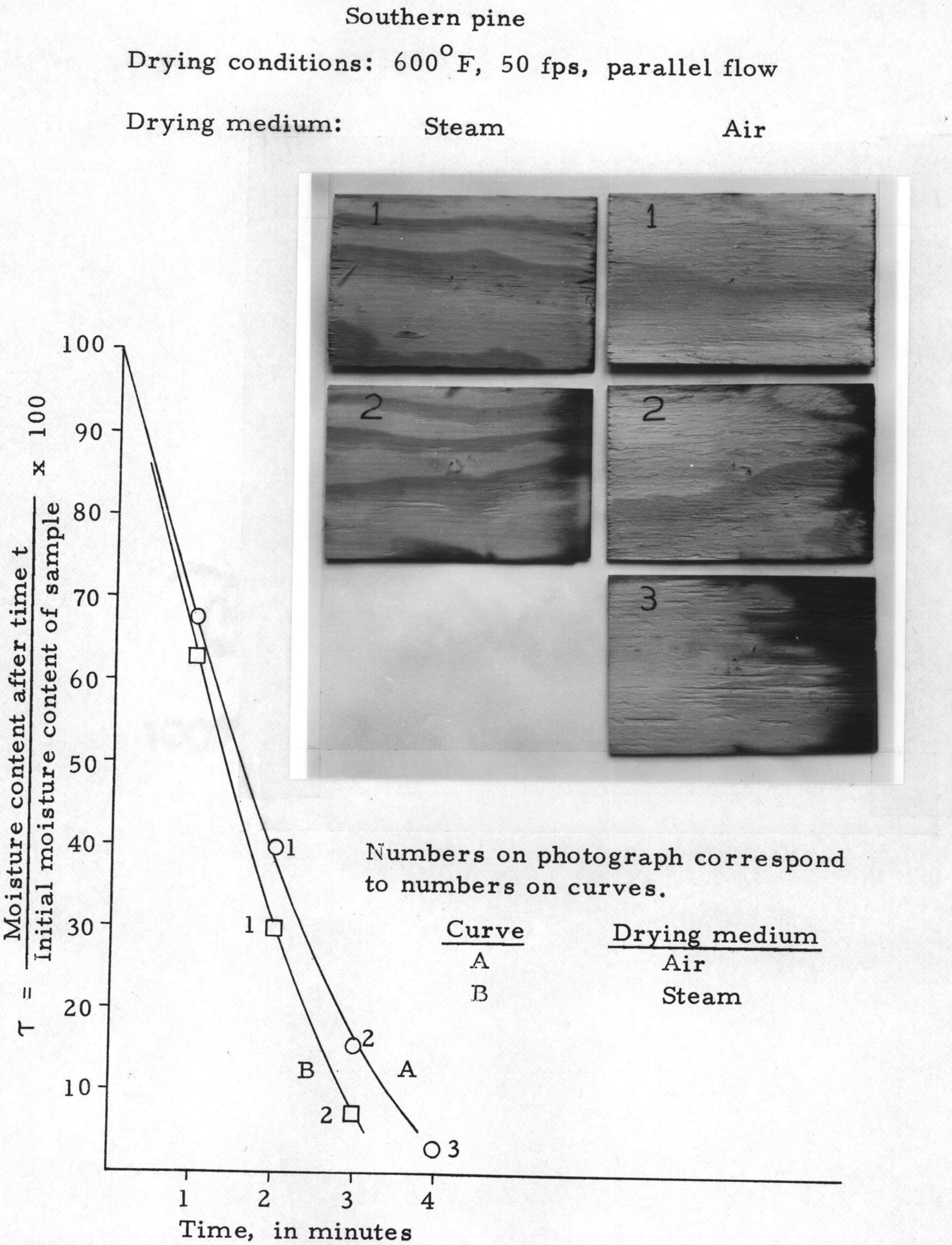


Figure 22. Charring of Southern pine veneer in air and in steam for 600°F, 50 fps, parallel flow test conditions.

Douglas fir

Drying conditions: $600^{\circ}F$, 50 fps, parallel flow

Drying medium: Air Steam

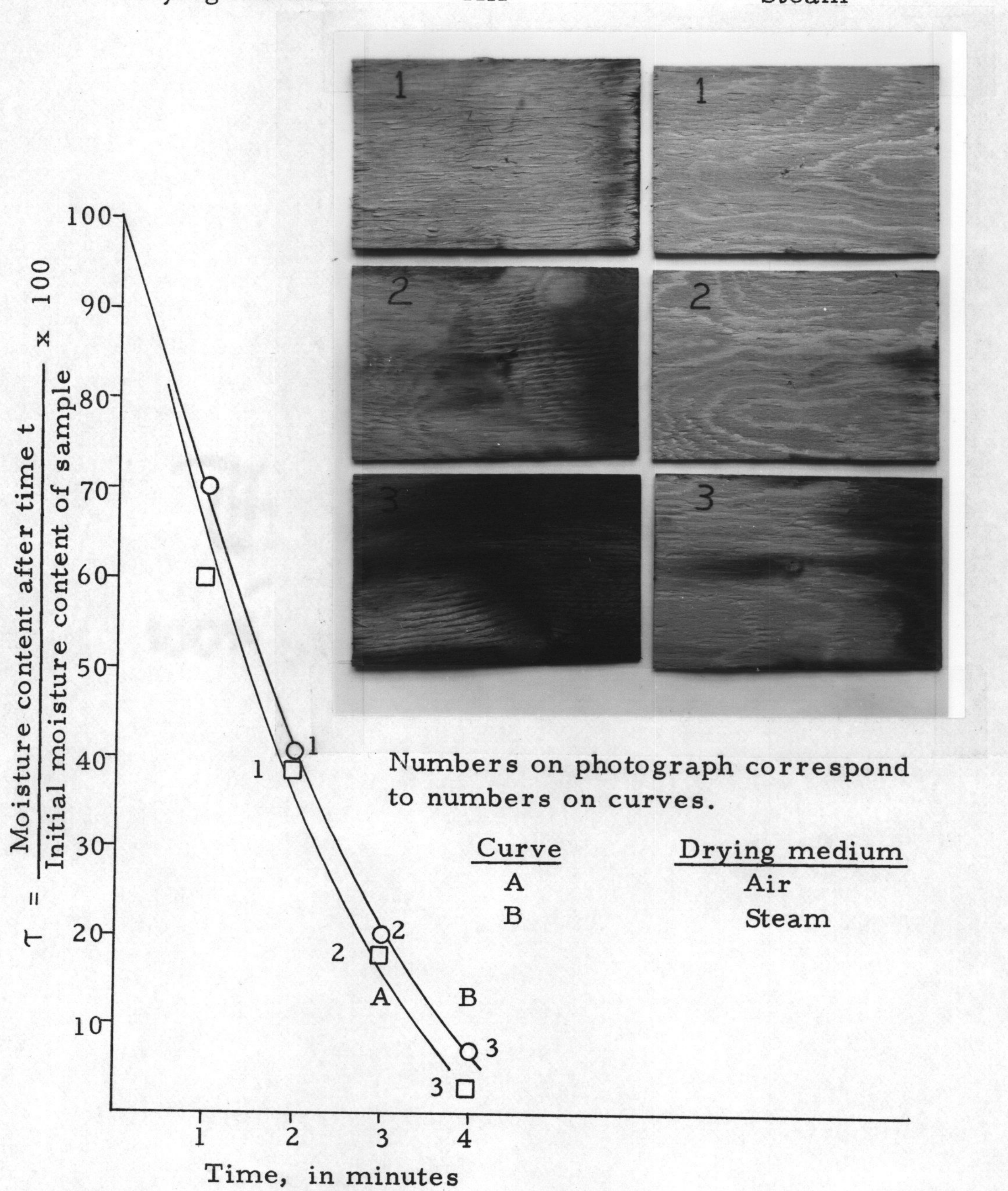


Figure 23. Charring of Douglas fir veneer in air and in steam for $600^{\circ}F$, 50 fps, parallel flow test conditions.

Southern pine

Drying conditions: 600°F, 100 fps, 90° flow

Drying medium: Steam Air

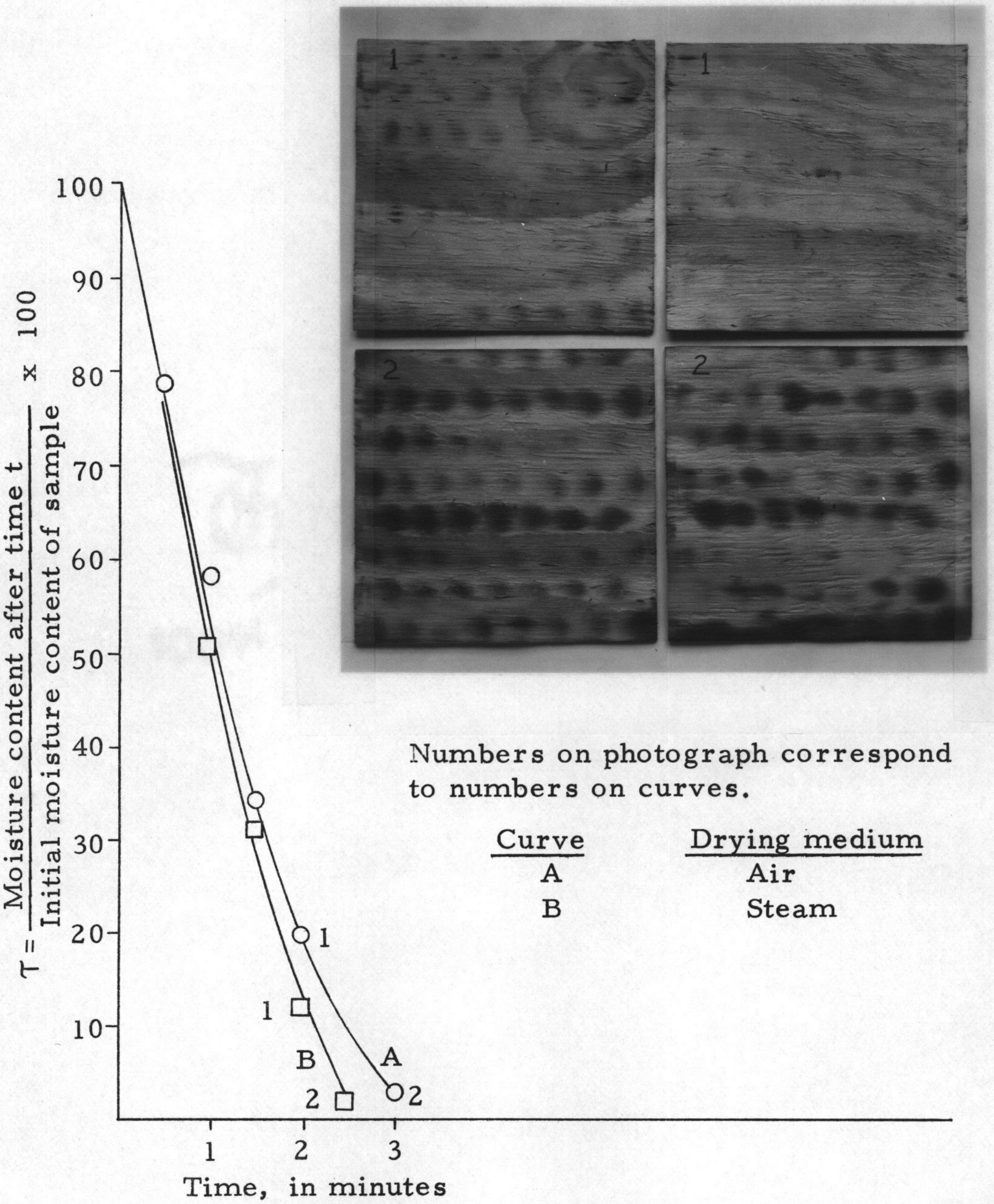


Figure 24. Charring of Southern pine veneer in air and in steam for 600°F, 100 fps, 90° flow test conditions.

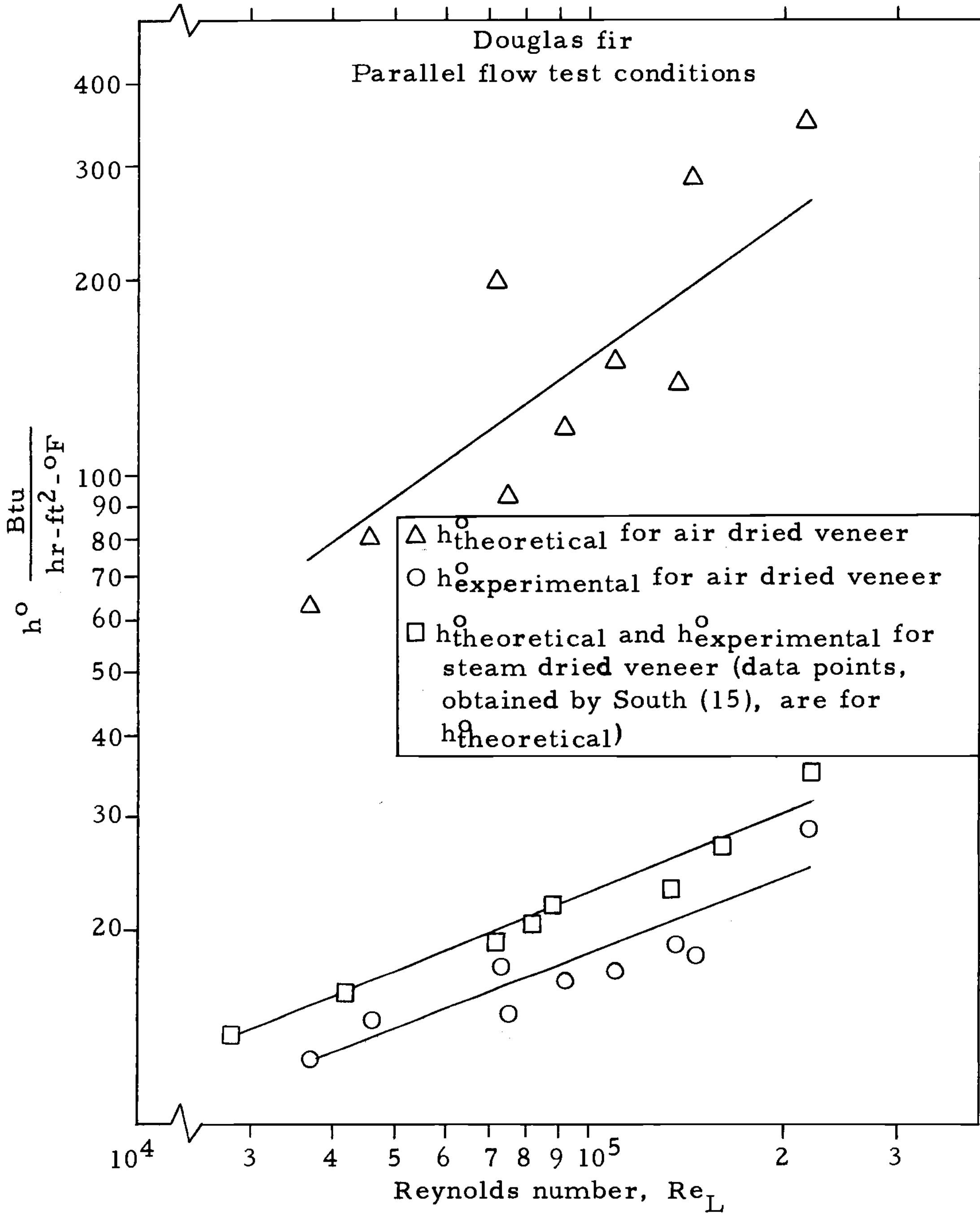


Figure 25. Experimental and theoretical values of h^o for Douglas fir veneer dried in air and in steam.

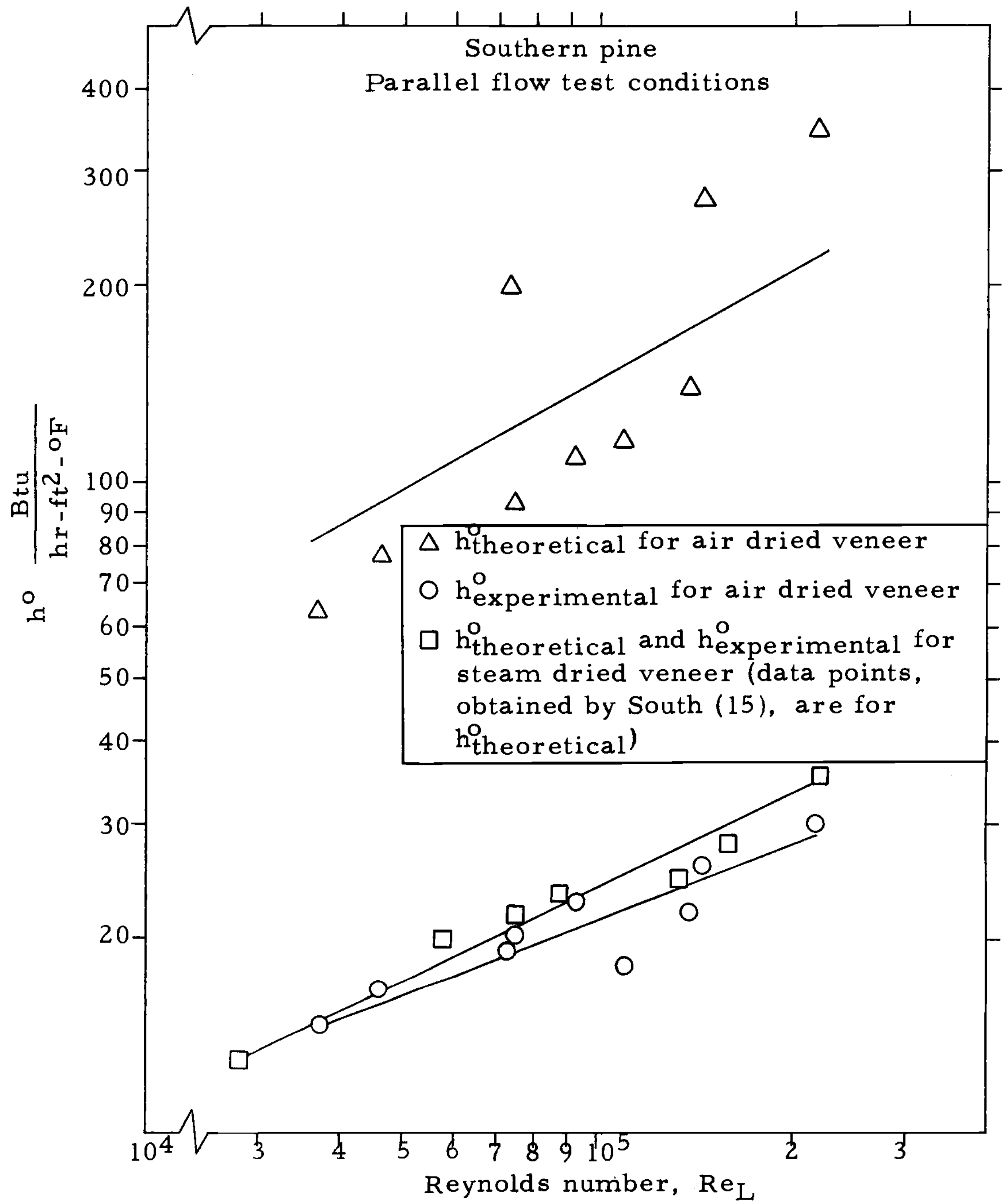


Figure 26. Experimental and theoretical values of h^o for Southern pine veneer dried in air and in steam.

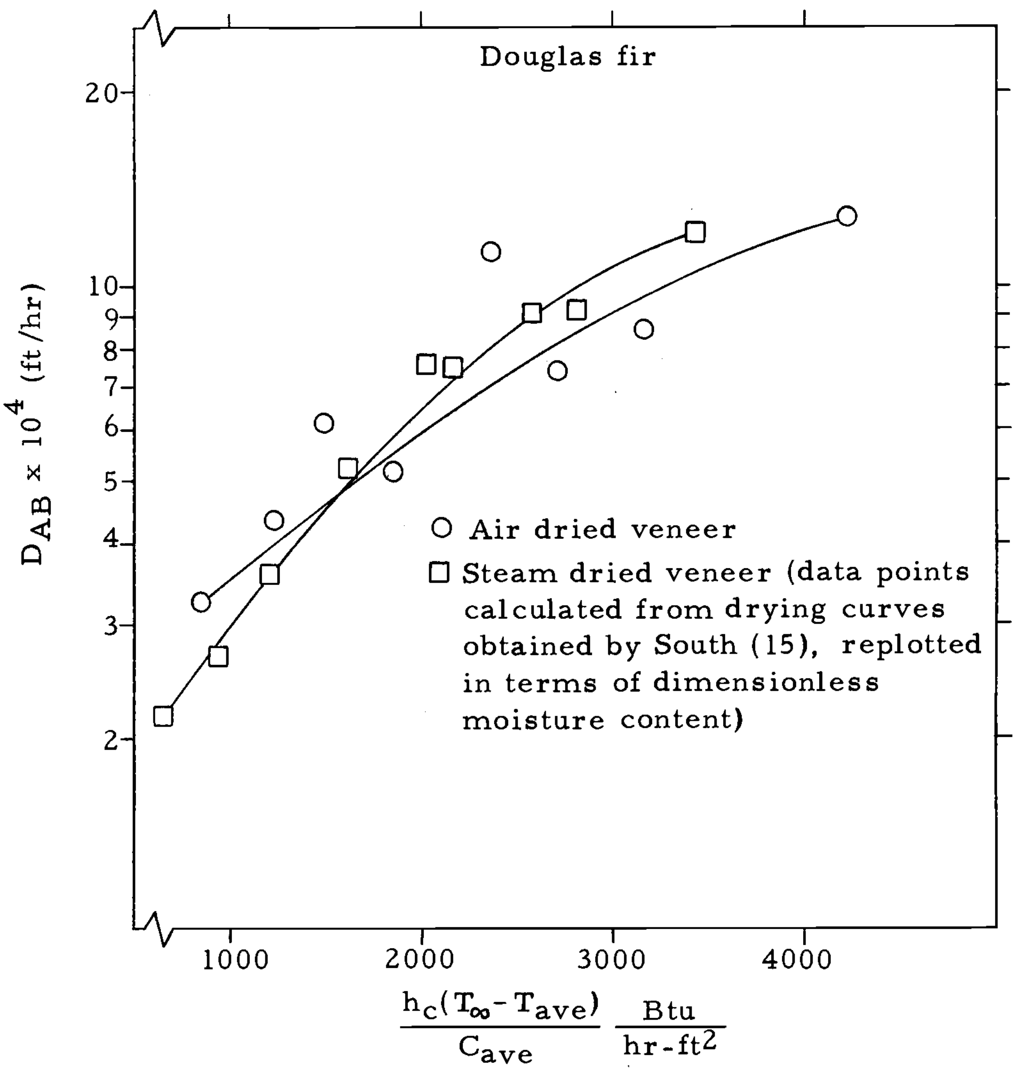


Figure 27. Experimentally determined internal diffusion coefficients for Douglas fir veneer dried under parallel flow test conditions in air and in steam.

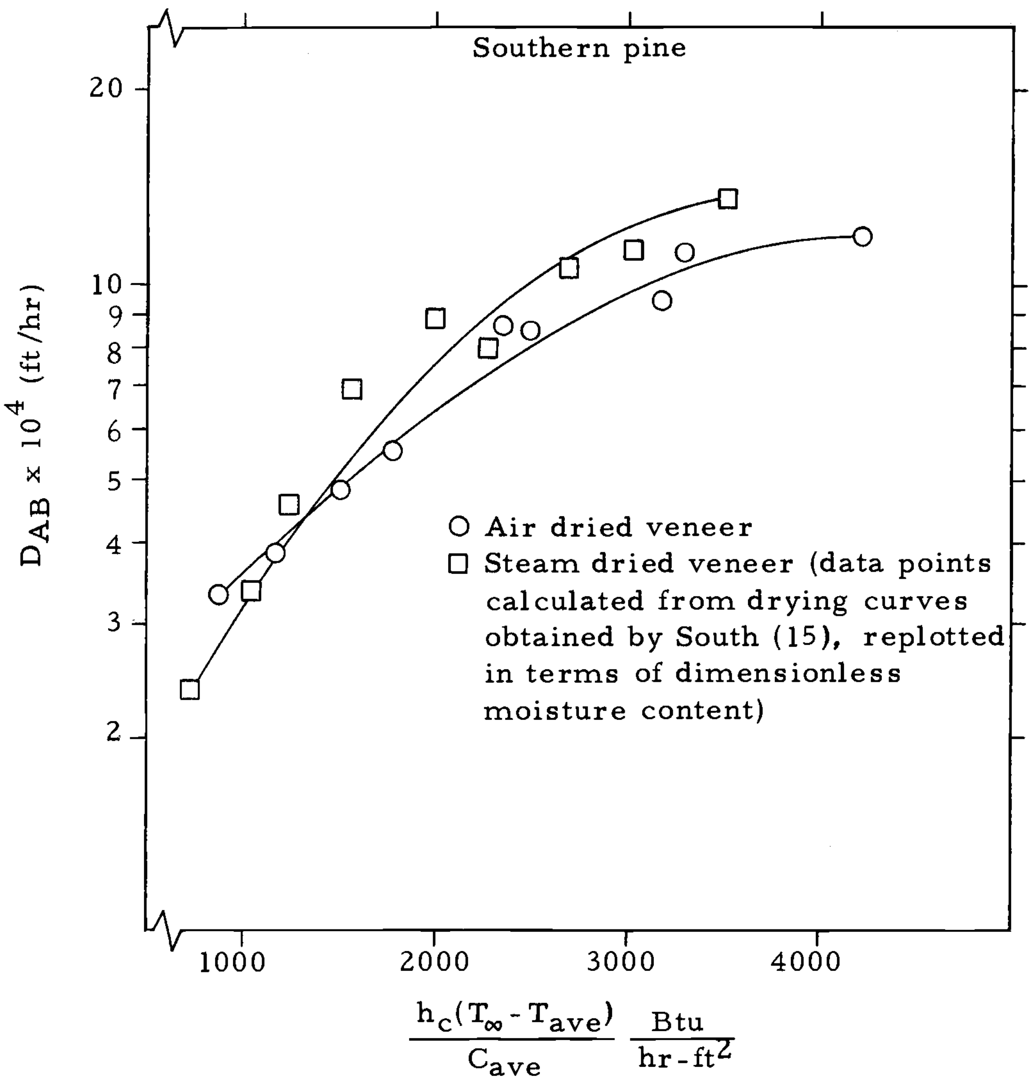


Figure 28. Experimentally determined internal diffusion coefficients for Southern pine veneer dried under parallel flow test conditions in air and in steam.

Table I. Comparisons of times required for veneer to dry under each of three angles of impingement to a dimensionless moisture content, Υ, of 10%.

Note: Mean values of drying times are average values over the three velocities used in this experiment.

Temp.	Factor	Mean drying times at the following angles, in minutes		Differences in mean drying times, in minutes	95% confidence interval for differences in drying times, in minutes	
					Lower limit	Upper limit
350°F	Combined data for both drying media and both species	45° - 6.38	0° - 5.30	1.08	0.94	1.22
		90° - 5.35	0° - 5.30	0.05	-0.09	0.19
		45° - 6.38	90° - 5.35	1.03	0.88	1.17
350°F	Air (both wood species)	45° - 5.80	0° - 4.48	1.32	1.16	1.49
		90° - 5.04	0° - 4.48	0.56	0.39	0.72
		45° - 5.80	90° - 5.04	0.77	0.60	0.93
350°F	Steam (both wood species)	45° - 6.96	0° - 6.12	0.84	0.60	1.08
		0° - 6.12	90° - 5.67	0.45	0.21	0.69
		45° - 6.96	90° - 5.67	1.28	1.04	1.52
350°F	Douglas fir (both drying media)	45° - 6.39	0° - 5.48	0.90	0.69	1.12
		90° - 5.61	0° - 5.48	0.12	-0.09	0.34
		45° - 6.39	90° - 5.61	0.78	0.57	0.99
350°F	Southern pine (both drying media)	45° - 6.37	0° - 5.11	1.26	1.06	1.45
		0° - 5.11	90° - 5.10	0.01	-0.18	0.20
		45° - 6.37	90° - 5.10	1.27	1.07	1.47
600°F	Combined data for both drying media and both species	45° - 2.89	0° - 2.63	0.26	0.21	0.32
		0° - 2.63	90° - 2.41	0.22	0.17	0.28
		45° - 2.89	90° - 2.41	0.49	0.44	0.54
600°F	Air (both wood species)	45° - 3.16	0° - 2.73	0.43	0.35	0.51
		0° - 2.73	90° - 2.58	0.16	0.08	0.24
		45° - 3.16	90° - 2.58	0.58	0.50	0.66
600°F	Steam (both wood species)	45° - 2.63	0° - 2.53	0.10	0.03	0.17
		0° - 2.53	90° - 2.24	0.29	0.22	0.36
		45° - 2.63	90° - 2.24	0.39	0.32	0.46

Table I. (Continued)

Temp.	Factor	Mean drying times at the following angles, in minutes		Differences in mean drying times, in minutes	95% confidence interval for differences in drying times, in minutes	
					Lower limit	Upper limit
$600^{\circ}F$	Douglas fir (both drying media)	45° - 3.07	0° - 2.82	0.25	0.16	0.34
		0° - 2.82	90° - 2.48	0.34	0.25	0.44
		45° - 3.07	90° - 2.48	0.59	0.50	0.68
$600^{\circ}F$	Southern pine (both drying media)	45° - 2.71	0° - 2.44	0.28	0.22	0.34
		0° - 2.44	90° - 2.33	0.10	0.04	0.16
		45° - 2.71	90° - 2.33	0.38	0.32	0.44

Table II. Comparisons of times required for veneer to dry in air and in steam to a dimensionless content, τ, of 10%.

Note: Mean values of drying times are average values over the three angles of impingement and the three velocities of the drying media used in this experiment.

Temp.	Species of wood	Mean drying times in: Air $\overline{X}_A$, min.	Steam $\overline{X}_S$, min.	Differences in mean drying times, in minutes	95% confidence intervals for differences in drying times, in minutes: Lower limit	Upper limit
350°F	Combined data for both species	5.11	6.25	$\overline{X}_S - \overline{X}_A = 1.14$	1.05	1.23
350°F	Douglas fir	5.21	6.44	$\overline{X}_S - \overline{X}_A = 1.23$	1.10	1.36
350°F	Southern pine	5.00	6.05	$\overline{X}_S - \overline{X}_A = 1.05$	0.92	1.18
600°F	Combined data for both species	2.82	2.46	$\overline{X}_A - \overline{X}_S = 0.36$	0.33	0.39
600°F	Douglas fir	2.96	2.63	$\overline{X}_A - \overline{X}_S = 0.33$	0.27	0.39
600°F	Southern pine	2.69	2.30	$\overline{X}_A - \overline{X}_S = 0.39$	0.35	0.43

Table III. Comparisons of times required for Douglas fir and Southern pine to dry to a dimensionless moisture content, τ, of 10%.

Note: Mean values of drying times are average values over the three angles of impingement and the three velocities of the drying media used in this experiment.

Temp.	Drying medium	Mean drying times for: D. fir $\bar{X}_F$, min.	S. pine $\bar{X}_P$, min.	Differences in mean drying times, in minutes	95% confidence intervals for differences in drying times, in minutes: Lower limit	Upper limit
350°F	Combined data for air and steam	5.83	5.53	$\bar{X}_F - \bar{X}_P = 0.30$	0.21	0.39
350°F	Air	5.21	5.00	$\bar{X}_F - \bar{X}_P = 0.21$	0.10	0.32
350°F	Steam	6.44	6.05	$\bar{X}_F - \bar{X}_P = 0.39$	0.24	0.55
600°F	Combined data for air and steam	2.79	2.49	$\bar{X}_F - \bar{X}_P = 0.30$	0.26	0.33
600°F	Air	2.96	2.69	$\bar{X}_F - \bar{X}_P = 0.27$	0.21	0.32
600°F	Steam	2.63	2.30	$\bar{X}_F - \bar{X}_P = 0.33$	0.28	0.38

Table IV. Effective heat transfer coefficients based on experimental data.

h^{o}_{exp} (Btu/hr-ft^2-^oF)							
T_{air} ^oF	V_{air} ft/sec	Douglas fir			Southern pine		
		0°	45°	90°	0°	45°	90°
350	50	17.64	13.08	18.91	19.03	13.36	19.71
	100	18.09	19.62	24.02	25.64	19.11	23.15
	150	28.94	23.09	27.76	29.74	26.52	30.95
600	50	14.50	7.94	11.71	16.57	9.75	11.78
	100	16.87	9.43	12.69	22.54	11.13	14.28
	150	18.90	14.44	18.27	21.98	16.48	18.00
750	50	12.69	8.24	9.68	14.79	8.32	10.04
	100	14.87	11.00	13.13	17.82	10.60	13.77
	150	17.20	14.59	22.17	19.90	14.37	19.30

Table V. Experimental internal diffusion coefficients.

$\overline{D}_{AB} \times 10^4$ (ft^2/hr)							
T_{air} ^oF	V_{air} ft/sec	Douglas fir			Southern pine		
		0°	45°	90°	0°	45°	90°
350	50	3.25	2.40	2.72	3.29	2.51	2.93
	100	4.30	3.43	3.49	3.88	3.49	4.11
	150	6.03	3.94	4.18	4.79	4.54	5.14
600	50	5.08	4.18	5.70	5.55	4.74	5.83
	100	7.40	5.98	7.73	8.44	7.27	7.67
	150	8.44	8.21	10.04	9.37	8.79	10.98
750	50	11.10	6.59	8.44	8.57	6.24	7.68
	100	12.23	8.79	12.05	10.93	9.25	12.19
	150	12.70	12.05	16.22	11.72	11.40	14.06

DISCUSSION

Drying Rates of Veneer in Air Compared to Drying Rates in Steam

Based on convective heat transfer theory, the Nusselt number, and hence the convective heat transfer coefficient, is directly proportional to the Reynolds number for a given flow condition and the Prandtl number of the fluid flowing. The Reynolds numbers for air as a drying medium ranged from 2% higher at 350° to 12% higher at 750° than the Reynolds numbers for steam. Offsetting this Reynolds number effect, however, is the difference in Prandtl numbers between the two fluids, since the Prandtl number for steam is approximately 33% higher than the Prandtl number for air in the temperature range of 350°F to 750°F.

As shown in Table II, the veneer samples dried faster in air than in steam at 350°F. Based on a comparison of the Reynolds numbers and Prandtl numbers for the two fluids at 350°F, steam would be expected to be the most effective of the two drying media from the standpoint of transferring heat to the veneer. When taking into account mass transfer of water vapor from the veneer to the drying medium, however, the faster drying rates obtained in air seem reasonable, since the rate of diffusion of the water vapor is directly proportional to the concentration gradient of water vapor between the surface of the veneer and the drying medium. For dry air, the concentration of water vapor is zero, while for steam, the concentration of water vapor is directly proportional to the density of the steam.

At constant pressure, the density of steam decreases as the temperature increases, with the result that the concentration gradient of water vapor between veneer and steam at $600^{o}F$ is approximately twice as high as the concentration gradient at $350^{o}F$. Consequently, the rate of diffusion of water vapor between the veneer surfaces and steam as a drying medium is less inhibited at $600^{o}F$ than at $350^{o}F$, and steam becomes more effective than air as a drying medium as indicated by the drying times listed in Table II. The greater effectiveness of steam at $600^{o}F$ may be attributed to the higher Prandtl number of steam as compared to air, which is sufficient to override the smaller advantage which air has over steam at $600^{o}F$ due to a higher concentration gradient for diffusion of water vapor from the surfaces of the veneer to the drying medium.

Experimental Internal Diffusion Coefficients

The graphs of experimental internal diffusion coefficients which are plotted in Figures 27 and 28 also demonstrate the relative effectiveness of air compared to steam for drying veneer. At low values of the parameter ξ, the experimental internal diffusion coefficients are higher for samples dried in air than for samples dried in steam. At higher values of ξ, the relative magnitudes of the diffusion coefficients in the two drying media are reversed. The curves in Figures 27 and 28 are directly related to the relative effectiveness of the drying media, since the magnitudes of the diffusion coefficients are inversely proportional to the times required for samples to dry to a dimensionless moisture content of 10%.

Drying Rates for the Three Angles of Impingement of the Drying Medium

A considerable amount of research has been performed to determine heat transfer relationships for surfaces exposed to impinging jets, but little, if any, such work has been accomplished for the case of simultaneous heat and mass transfer. Research into optimization of jets for veneer drying was considered beyond the scope of this thesis, and therefore no attempt was made to improve the performance of the angular impingement test section by varying jet spacing, diameter, or distance from the veneer surfaces. Consequently, comparisons regarding the relative effectiveness of the three angles of impingement used in this experiment should not be considered generally applicable to the design of veneer drying equipment.

Factors which may contribute to differences in drying times between veneer samples dried in parallel flow and samples dried under angular impingement are listed in the following paragraphs. There is no way of drawing general conclusions from the data obtained for this thesis as to what effects, if any, the following factors have on the rate of veneer drying.

1. Moisture evaporating from a sample dried under conditions of parallel flow is readily swept away from the veneer surfaces by flow past the sample. Under conditions of angular impingement, however, moisture transport from the surfaces of a sample may be hindered by the impingement of the drying medium against the sample. Hindrance of moisture removal which may possibly be associated with angular impingement could have contributed to the poor drying rates observed for samples dried under 45^{o} impingement.

2. Under conditions of parallel flow, the boundary layer thickness varies from zero at the leading edge of a veneer sheet to a maximum at the trailing edge. Consequently, local heat transfer and diffusion coefficients vary as a function of distance from the leading edge of the veneer, with the result that a veneer sheet in parallel flow may dry unevenly along the direction of the flow. Local drying rates under conditions of angular impingement would inherently be more uniform over the surface of the veneer, and this factor would tend to make drying rates faster for angular impingement.

3. When samples are exposed to perpendicular impingement,

stagnation points exist at those locations on the sample surfaces which are intersected by the axes of the impinging jets. At each stagnation point, the velocity of the impinging jet abruptly decelerates to zero with an accompanying temperature rise. The stagnation points on veneer surfaces tend to char early in the drying process when exposed to a high temperature drying medium, thus demonstrating that high heat transfer rates are associated with the stagnation points. Milligan and Davies (13) have demonstrated that high drying rates can be achieved without charring when veneer dried under conditions of perpendicular impingement is kept moving through the region of jet flow. Perhaps faster drying rates could have been achieved under conditions of perpendicular impingement in this experiment if there had been more jets in the test section to expose a greater portion of the veneer surfaces to direct impingement of the drying medium.

Comparative Drying Rates of Southern Pine and Douglas Fir

When the densities of the two species are considered, the faster drying times of Southern pine samples as compared to Douglas fir samples are anomalous. Southern pine samples were observed to be more dense than Douglas fir samples in both this experiment and South's experiment. The permeabilities of the two species might be expected to be directly proportional to their densities, in which case Douglas fir samples should have dried faster than Southern pine samples. Differences in observed drying times for the two species indicate that Southern pine is more permeable than Douglas fir, even though the density of the former is greater than that of the latter.

Discrepancies between Experimental and Theoretical Heat Transfer Coefficients for Air Dried Veneer

Lack of agreement between experimental and theoretical heat transfer coefficients plotted for air dried veneer in Figures 25 and 26 is most likely due to discrepancies between the assumed drying conditions and the actual drying conditions rather than to deficiencies in the theory upon which the calculations are based. South (15) obtained excellent agreement between experimental and theoretical heat transfer coefficients for veneer samples dried in steam, thus verifying that the basic theory for the calculations is valid.

The relatively small differences in drying times between air dried veneer and steam dried veneer indicate that the effective heat transfer coefficients in the two media should be about the same. Experimental heat transfer coefficients presented in this thesis for air dried veneer are similar in magnitude to those calculated by South for steam dried veneer, as can be seen from Figures 25 and 26. Calculated values of the theoretical heat transfer coefficients, however, are much higher for air dried veneer than for steam dried veneer. Therefore, discrepancies between experimental and theoretical heat transfer coefficients presented in this thesis for air dried veneer are probably due to deviations between actual and assumed conditions for calculating the theoretical heat transfer coefficients.

As discussed previously, the equation used for computing theoretical heat transfer coefficients is as follows:

$$h^{o}_{predicted} = \bar{h}_c + \frac{\bar{k}_c \Delta C_s h_{fg}}{(T_\infty - T_w)}$$

Based on a comparison of calculations for air dried veneer and steam dried veneer, ΔC_s and $\bar{k}_c$ are the two parameters in the preceding equation which contribute to the high values of theoretical heat transfer coefficients for air dried veneer. ΔC_s, the moisture concentration difference between the surface of the specimen and the free stream, is expected to be larger for air as a drying medium than for steam as a drying medium, due to the differences in composition of the two fluids. Consequently, discrepancies in the heat transfer coefficients most likely originate from calculations of $\bar{k}_c$.

The convective mass transfer coefficient, $\bar{k}_c$, was shown previously to be directly proportional to the external diffusion coefficient, D_{AB}, for mass transport of moisture from the veneer surfaces to the drying medium. Computations of external diffusion coefficients were based on the following assumptions, which are not in complete accordance with the actual drying conditions:

1. The atmosphere into which moisture was diffusing from the veneer surfaces was assumed to be dry air. Under actual drying conditions, the atmosphere surrounding the veneer included an unknown amount of steam which had evaporated from the wood in addition to the air which was supplied as the drying medium. Consequently, the magnitudes of the external diffusion coefficients should be somewhere between the values of diffusion coefficients for steam diffusing into steam and steam diffusing into dry air. In the range of temperatures used in this experiment, the values of diffusion coefficients for steam diffusing into steam are approximately one-half the values of the diffusion coefficients for steam diffusing into dry air, and therefore the presence of steam which was not taken into consideration in calculations of the external diffusion coefficients could partially account for the discrepancies between experimental and theoretical values of the effective heat transfer coefficients.

2. Forces between water at the surface of the wood and the wood itself were assumed to be negligible, so that only the two-component system of water vapor and air was considered in calculating the external diffusion coefficients. This assumption was necessary for use of the Hirschfelder equation, which applies only to binary gas systems. When wood samples were removed for

weighing at various stages of the drying process, the surfaces of the samples were observed to be relatively dry. The hydroscopic attraction of wood for water is inversely proportional to the moisture content of the wood, and therefore adhesive forces not considered in calculating the external diffusion coefficients could have been a significant factor in retarding the rate of mass transfer from the locally dry surfaces of the wood to the drying medium.

3. The wood was assumed to be drying in the "constant rate" period. As discussed earlier in this thesis, the hypothetical "constant rate" period is that portion of the drying interval when internal diffusion of water to the wood surfaces is not a controlling factor, and wood temperature remains constant at 212°F. From curves of wood temperature measured as a function of time, samples of which are shown in Figure 5, it can be seen that "constant rate" drying conditions were approached, but not reached, during the initial drying periods for air dried samples. Departures from "constant rate" conditions were particularly apparent at the 600°F and 750°F operating conditions. Consequently, the retarding influence of internal diffusion on veneer drying rates is not negligible even during the initial drying periods.

Charring of Veneer in Air and in Steam

The fact that charring of the veneer surfaces occurred more readily in air than in steam is most likely due to the much greater quantity of free oxygen in the former drying medium as compared to the latter. High rates of heat transfer associated with the high velocities of the drying media used in this experiment also contributed to the tendency of wood surfaces to char at high temperatures well before moisture contents of the samples had been reduced to low levels.

Atherton achieved rapid drying rates for Douglas fir samples which were exposed to steam flowing at a velocity of 10 feet per second parallel to the veneer surfaces, at steam temperatures up to 800°F. Drying times were three minutes and two minutes to reduce moisture content from about 60% to 5% at temperatures of 600°F and 800°F, respectively (2, p. 30). Unlike samples dried at the same temperatures but at much higher velocities in this experiment, the samples dried by Atherton showed no evidence of charring. Atherton's results indicate that even at high drying temperatures, charring of wood samples can be prevented by maintaining the velocity of the drying medium at a level which will not result in moisture removal from the veneer surfaces at a rate significantly faster than the rate of internal diffusion of moisture to the veneer surfaces.

Charring of the veneer surfaces is a source of error for the experimental work in this thesis. Loss of wood substance as a result of charring was interpreted as moisture loss, since there was no way in this experiment to distinguish between loss of moisture from the wood and loss of wood substance due to combustion. Since charring which occurred was generally confined to a thin layer of the veneer surface, with negligible changes in veneer thickness, the experimental error associated with charring is considered to be small.

CONCLUSIONS

Air Compared to Steam as a Drying Medium

Before discussing conclusions from this experiment regarding the relative effectiveness of air and steam as veneer drying media, it should be noted that factors other than those considered in this experiment could strongly influence the decision as to which drying medium would be most suitable for a particular application. Examples of factors which were not considered in this experiment include economic considerations associated with supplying air or steam to a veneer dryer, and the effects of the two drying media on physical properties of the veneer. Therefore, information beyond that reported in this thesis would be necessary when selecting a drying medium for a specific veneer dryer.

Based on comparisons of veneer drying times in the two drying media, air is more effective than steam when the temperature of the drying medium is 350^{o}F. The effectiveness of air relative to steam should increase at lower temperatures, due to the fact that the diffusion coefficient for mass transfer of water vapor from the veneer surfaces decreases less rapidly as a function of temperature for air as a drying medium than for steam as a drying medium. No charring or other surface degradation of veneer dried in either air or steam was observed at the 350°F drying temperature.

At some temperature between 350°F and 600°F, steam and air are equally effective as veneer drying media. Veneer samples dried more rapidly in steam than in air when exposed to drying temperatures of 600°F and higher. Moreover, veneer samples dried at the 600°F and higher temperatures charred less readily in steam than in air, as shown in Figures 22, 23, and 24.

The preceding conclusions regarding the relative effectiveness of air and steam as drying media hold for all velocities and angles of impingement to which veneer samples were exposed in this experiment. Consequently, the relative effectiveness of air and steam is a function only of the drying temperature.

Governing Mechanism for Veneer Drying

For each of the 27 drying conditions in this experiment, the rate of internal diffusion of water vapor through the veneer was the controlling factor on the rate of veneer drying. This conclusion is based on the following observations:

1. As shown in Figure 5, veneer temperature remained relatively stable as a function of time for only a brief interval during each drying period. If internal diffusion did not become controlling, wood temperature would remain stable throughout the drying interval, for only when the rate of internal diffusion is slower than the rate of

moisture evaporation from the veneer surfaces can the wood temperature rise above the moisture evaporation temperature. The time interval when veneer temperature remained relatively stable was inversely proportional to the temperature and velocity of the drying medium, thus indicating that the controlling influence of internal diffusion on veneer drying rates becomes more pronounced as the rate of heat transfer to the veneer surfaces is increased.

2. Charring of veneer samples commenced at the 600°F and higher temperature test conditions when veneer moisture contents were as high as 40%, as shown in Figures 22 through 24. If the rate of veneer drying were governed by the rate of moisture removal from the veneer surfaces rather than by the rate of internal diffusion, charring would not commence until veneer samples are practically dry.

Milligan and Davies (13), who performed research involving the drying of veneer under a range of temperatures and velocities which overlap the drying conditions in this experiment, concluded that internal diffusion was not a controlling factor for drying rates achieved in their work. Differences in the physical properties of veneer samples used in the two experiments and differences in operating conditions could have resulted in the lack of agreement between conclusions of this study and the study by Milligan and Davies. The principle reason for disagreement, however, may be due to differences in instrumentation for the two studies.

In this experiment, the charts of wood temperature measured as a function of drying time provided the strongest evidence that internal diffusion controls the rate of veneer drying. Milligan and Davies did not take continuous measurements of wood temperature as a function of drying time, nor could they have easily done so since veneer samples were conveyed in several passes through their dryer, rather than being held stationary as in this experiment. Charring of veneer surfaces, which provided a secondary indication in this experiment that internal diffusion was controlling drying rates, did not occur in the work by Milligan and Davies. Therefore, if internal diffusion controlled veneer drying rates in the experiment by Milligan and Davies, it would have been difficult to detect.

Comparative Drying Rates of Southern Pine and Douglas Fir

Southern pine dries more readily than Douglas fir, as confirmed by statistical analyses of the drying curves for both air as a drying medium and steam as a drying medium. Comparative drying times for the two woods are listed in Table III. This conclusion is considered to be applicable to all drying conditions, since the conclusion held without exception over the full range of temperatures, velocities, and angles of impingement used in this experiment.

Applicability of Results to Operation of Veneer Dryers Currently in Use

Many veneer dryers currently in use are operated in the following manner (4, p. 449): air drawn into the dryer is recirculated at a temperature between 300°F and 400°F through a system of fans and ducts, together with moisture which has evaporated from the veneer. The recirculating mixture is either heated by steam coils in the dryer and ducts, or by admitting hot combustion products from burning fuel to the drying system. Air flow rate into the dryer is directly proportional to the flow rate of the air-steam mixture which exhausts through the dryer vent stack. By reducing the damper opening on the vent stack, an atmosphere consisting in large part of superheated steam from the veneer can be built up in the dryer.

Corder (4) concluded from an investigation of veneer dryer ventilating practices that when the intake of air is minimized, the risk of veneer fires is reduced, fuel is conserved, and the dryer atmosphere consisting predominantly of superheated steam from the veneer is an adequate drying medium. Quantitative comparisons of air and steam in this experiment confirm Corder's conclusion regarding the effectiveness of steam, and support his recommendation that air intake into recirculating dryers be minimized.

Applicability of Results to Design of Veneer Dryers

Although further research is necessary to determine the effects of high temperatures and the type of drying medium on the physical properties of veneer, some tentative observations regarding the design of veneer dryers can be made based on experiments which have been completed.

Results of this and other experimental investigations (2, 13, 15) indicate that when designing a veneer dryer to achieve minimum veneer drying times under conditions which will not result in surface charring of the veneer, provisions should be considered for drying the veneer as follows:

1. During the initial drying period, when the veneer is drying under "constant rate" conditions described previously, the veneer should be exposed to high temperature, low velocity steam. Use of steam rather than air minimizes the possibility of surface charring; high temperatures increase the rate of internal diffusion of water to the wood surfaces, and low velocities prevent charring which can occur even in steam when moisture is removed from wood surfaces too rapidly at high temperatures. Based on Atherton's work (2) for veneer samples dried under conditions of parallel flow of the drying medium, steam temperatures as high as $800^{\circ}F$, and steam velocities on the order of 10 feet per second should be appropriate during

this period.

2. When the transitional period of approximately "constant rate" drying is completed and moisture removal from the veneer enters the "falling rate" period, during which the rate of internal diffusion strongly controls the rate of veneer drying, the veneer should be transferred to a second stage of the dryer where the veneer is exposed to moderate to high velocities of the drying medium at a temperature on the order of 300°F to 400°F. The lower temperature prevents charring of the relatively dry wood surfaces during this drying period, and the higher velocity enhances the rate of heat transfer to the veneer, which is necessary for continued diffusion of water to the veneer surfaces. Either air or steam, or a mixture of both, should be satisfactory as the drying medium during this period.

3. To achieve uniform drying over the veneer surfaces, perpendicular impingement of the drying medium is preferable to parallel flow. The veneer should be kept continuously moving beneath the jets, to prevent uneven drying at the stagnation points on the veneer surfaces.

Topics for Additional Research

Among the topics for which information is lacking on which to base design decisions for veneer dryers are the following:

1. Effects of the type of drying medium and the drying

temperature on physical properties of veneer - Adverse effects on the veneer of either high temperatures or a particular drying medium could strongly influence the design of future high speed dryers. An experimental study is underway to evaluate physical properties of Southern pine and Douglas fir veneers dried in air and in steam at the same temperatures used in this thesis.[1]

2. Optimization of jet designs for drying veneer under conditions of angular impingement - Moisture removal is inherently more uniform over the veneer surfaces under conditions of angular impingement than under conditions of parallel flow. The fastest rates of veneer drying may be obtainable under conditions of angular impingement. In a study currently being planned, jet spacing, diameter, angle of impingement, and distance from the veneer surface may be evaluated.[2]

3. Effect of the variation of the local heat transfer coefficient as a function of veneer length for veneer dried in parallel flow - Under conditions of parallel flow, the local effective heat transfer coefficient varies in the direction of flow as a function of distance

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[1]The study, "Gluability and strength of Douglas fir and Southern pine rotary-peeled veneers dried in air and in steam at temperatures to 800°F", is being conducted at the Oregon State University Forest Research Laboratory.

[2]The research is underway at the Forest Products Laboratory, University of California, Richmond, California.

from the leading edge of the veneer. Consequently, a veneer sheet will tend to dry unevenly along the direction of the flow. An experimental and theoretical heat and mass transfer analysis could be performed to analyze the magnitudes of the variations in local effective heat transfer coefficients and moisture contents, to determine the extent of the variations as a function of veneer length.

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APPENDIX

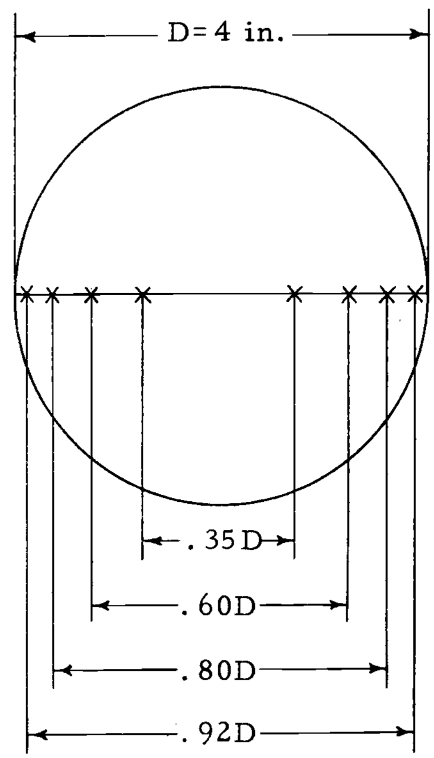
SAMPLE CALCULATIONS

Flow Rate of Air Through the Test Section

To determine the flow rate of air through the test section, a mass balance was performed between the test section and the location downstream of the test section where pitot tube traverses were taken in a four inch diameter duct. After establishing the flow rate for a test condition, the pressure drop across a flow orifice upstream of the test section was noted and then monitored to ensure that the flow rate did not change while veneer samples designated for the test condition were dried.

Velocity pressures across the four inch diameter duct were measured with a 1/8 inch diameter Dwyer pitot tube at the locations recommended in "F. W. Dwyer Bulletin No. B-11." Pressure traverses were measured in the vertical as well as the horizontal direction across the duct for over 50% of the test conditions, to confirm that consistent results would be obtained regardless of the direction of the traverse. The velocity corresponding to each pressure measurement was calculated, and the velocities were then averaged to determine the flow rate in the duct.

Sample calculations which follow are for the 100 feet per second, 600°F test condition in the parallel flow test section. The following data were obtained from the horizontal pitot tube traverse when establishing the aforementioned test condition:



Position (starting from left)	Velocity pressure inches H_2O	Velocity ft./min.
1	0.075	1520
2	0.110	1830
3	0.128	1980
4	0.135	2030
5	0.135	2030
6	0.128	1980
7	0.112	1840
8	0.075	1520
		8 | 14,730
		1841 ft./min.
		= 30.7 ft./sec.

Barometric pressure: 29.8 inches Hg

Temperature at location of pitot tube: 540°F

The velocity corresponding to each pressure measurement may be computed using the following equation:

$$V = 60\,\frac{\text{sec}}{\text{min}}\sqrt{\frac{2\left(g_c\,\frac{\text{lb}_m\text{-ft}}{\text{lb}_f\text{-sec}^2}\right)\left(P_v\text{ inches } H_2O\right)\left(5.2022\,\frac{\text{lb}_f/\text{ft}^2}{\text{inch } H_2O}\right)}{\rho\,\frac{\text{lb}_m}{\text{ft}^3}}}$$

$$= 1,096.2\sqrt{\frac{P_v}{\rho}}\;\frac{\text{ft}}{\text{min}}$$

where: P_v = velocity pressure in inches of water

ρ = air density in lb_m/ft^3 at the location where the traverse is taken. The air density varies with temperature, atmospheric pressure, and relative humidity.

A Dwyer "Air Velocity Calculator," which gives solutions to the preceding equation when the velocity pressure, temperature, barometric pressure, and relative humidity are known, was used to determine the air velocities in this experiment. For all calculations, the air was assumed to be dry.

After determining the average velocity in the four inch diameter duct, the velocity in the test section is calculated from a mass balance as follows:

Mass flow in test secion = Mass flow in duct

$$V_{TS} A_{TS} \rho_{TS} = V_D A_D \rho_D$$

$$V_{TS} = \frac{A_D}{A_{TS}} \frac{\rho_D}{\rho_{TS}} V_D$$

where: $A_D = 0.0873 \text{ ft}^2$

$A_{TS} = 0.0278 \text{ ft}^2$ (parallel flow)

$\rho_D = 0.0394$ (at 540°F and 29.8 inches Hg)

$\rho_{TS} = 0.0372$ (at 600°F and 29.8 inches Hg)

From the pitot tube traverse, $V_D = 30.7$ ft/sec

then: $$V_{TS} = \frac{0.0873}{0.0278} \times \frac{0.0394}{0.0372} \times 30.7$$

$$V_{TS} = 102 \text{ ft/sec}$$

Comparison of Flow Rates Measured Independently Using Flow Orifice and Pitot Tube

At each of several different air flows which were established in the veneer drying apparatus, flow rates were measured independently with the orifice used by South (15) and the pitot tube used in this experiment. These tests were conducted to determine whether the two techniques would give equivalent results. The following calculations are for data taken with the two instruments at one of the flow conditions.

The mass flow rate at the orifice may be calculated from the following equation (1):

$$\dot{m}\,(\text{lb/sec}) = 0.525\,d^2 K\sqrt{\rho\,(P_1 - P_2)}$$

where: d = orifice diameter, inches

ρ = density, lb/ft^3

$(P_1 - P_2)$ = pressure drop across orifice, psi

K is a flow coefficient. Values of K are tabulated in reference (1) as a function of the Reynolds number of the fluid flowing and the ratio of orifice diameter to pipe diameter, β.

By performing a mass balance between the location of the orifice and the location of the pitot tube, the velocity at the pitot tube corresponding to the velocity calculated from data measured at the orifice may be determined. This velocity based on orifice data may be compared with the velocity calculated directly from the pitot tube data, to ascertain the extent of agreement between the two instruments.

The mass balance is performed as follows:

Mass flow at orifice = Mass flow at pitot tube

$$0.525\,d^2 K\sqrt{\rho_0 (P_1 - P_2)} = (\rho V A)_{P.T.}$$

From which the velocity at the pitot tube corresponding to a pressure drop of $(P_1 - P_2)$ across the orifice may be calculated as follows:

$$V_{P.T.} = \frac{0.525\,d^2 K\sqrt{\rho_0 (P_1 - P_2)}}{\rho_{P.T.} A_{P.T.}}$$

Using procedures described previously in sample calculations for flow rates of air through the test section, the following data were obtained from a pitot tube traverse of the four inch diameter duct with air flowing through the apparatus at a temperature of 70°F:

Position	Velocity Pressure inches	Velocity ft/min
1	0.048	885
2	0.060	982
3	0.064	1070
4	0.065	1100
5	0.065	1100
6	0.064	1070
7	0.060	982
8	0.048	885
		8 | 8074
		1010 ft/min
		= 16.8 ft/sec

The corresponding velocity in the two inch diameter pipe in which the flow orifice was installed is:

$$V_{Pipe} = \frac{A_{Duct}}{A_{Pipe}} \times V_{Duct}$$

$$= \frac{0.0873}{0.0233} (16.8) = 62.9 \text{ ft/sec}$$

Reynolds number in the two inch diameter pipe is

$$R_e = \frac{V_{Pipe} D_{Pipe}}{\nu_{air\ @\ 70^\circ F}}$$

$$R_e = \frac{(62.9)\ (2.067)}{(12)\ \ (0.165)} \times 10^3$$

$$R_e = 65,700$$

From reference (1), the orifice flow coefficient corresponding to this Reynolds number is

$$K = 0.6271$$

The pressure drop measured across the flow orifice was 2.5 inches Hg, which is equal to 1.23 psi. Then the velocity at the pitot tube calculated from the pressure drop across the orifice is:

$$V_{P.T.} = \frac{(0.525)(1)^2(0.6271)\sqrt{(0.074)(1.23)}}{(0.074)\ (0.0873)}$$

$$= \frac{(0.525)\ (1)^2\ (0.6271)(0.303)}{(0.074)\ (0.0873)}$$

$$= 15.5 \text{ ft/sec}$$

Thus, the velocity calculated from pressure drop across the flow orifice agrees with the velocity calculated from the pitot tube traverse within $\frac{16.8 - 15.5}{16.8} = 7.7\%$.

Effective Heat and Mass Transfer Coefficients

Calculations for heat and mass transfer coefficients were performed using the Oregon State University C.D.C. 3300 computer. Procedures incorporated into the computer programs for performing the calculations are similar to those used in the following sample calculations.

h^o - Based on Theoretical Considerations

Values for h^o based on theoretical considerations are computed using equation 6:

$$h^o_{predicted} = \bar{h}_c + \frac{\bar{k}_c \Delta C_s h_{fg}}{(T_\infty - T_{wood})}$$

Sample calculations which follow are for Southern pine veneer dried in air flowing parallel to the veneer surfaces at 100 feet per second and 600°F. Since equation 6 is applicable only during the "constant rate" drying period, when veneer temperature remains approximately constant at the evaporation temperature of water leaving the wood surfaces, the surface temperature of the veneer is assumed to be 212°F. Then:

$$h_{fg}(212^oF) = 970 \text{ Btu/lb}$$

$$\Delta C_s = C_{wood\ surface} - C_\infty$$

$$= \rho_{steam\ (212^oF)} - 0$$

$$= 0.0373 \text{ lb/ft}^3$$

From equation 3,

$$\bar{h}_{cx} = \frac{k_a \sqrt{Re_x}}{x} \left[\frac{1}{(T_\infty - T_w)} \left. \frac{\partial T}{\partial \eta} \right|_{y=0} \right]$$

Prior to evaluating the term in parentheses using the curves developed by Hartnett and Eckert which are shown in Figure 6, it is first necessary to compute the value of the injection parameter,

$$\frac{v_w}{u_\infty}\sqrt{Re_x}, \qquad \text{where} \quad v_w = \frac{\dot{m}_s}{\rho_{steam} A_{wood}} .$$

The rate of moisture evaporation from the surface of the veneer, $\dot{m}_s$, is obtained from the slope of the appropriate veneer drying curve, at a location on the curve within the "constant rate" drying period. An equation for calculating $\dot{m}_s$ may be derived as follows:

$$\dot{m}_s \frac{lb}{hr} = \frac{\text{Wet weight}\,|t_1 - \text{Wet weight}\,|\,t_2}{t_1 - t_2}$$

Noting that wet weight $|_{\text{at time } t}$ = dry weight (% moisture $|_{\text{at time } t}$ + 1), the preceding equation may be rewritten in the following form:

$$\dot{m}_s = \frac{\text{Dry weight (\% Moisture}\,|\,t_1 - \text{\% Moisture}\,|\,t_2)}{\Delta t}$$

For the drying conditions in this example, $\dot{m}_s$ = 2.56 lb/hr.

Then

$$v_w = \frac{2.56 \text{ lb/hr}}{(0.0373 \text{ lb/ft}^3)(0.333 \text{ ft}^2)(3600 \text{ sec/hr})}$$

$$v_w = 0.057 \text{ ft/sec}$$

$$u_\infty = 100 \text{ ft/sec}$$

$$Re_x = \frac{u_\infty x}{\nu}$$

Taking x as half the length of the sample,

$$Re_x = \frac{(100\ ft/sec)\ (0.25\ ft)}{5.40 \times 10^{-4} ft^2/sec}$$

$$= 46,296$$

The injection parameter for this example therefore has the following value:

$$\frac{v_w}{u_\infty} \sqrt{Re_x} = \frac{0.057}{100} \sqrt{46,296} = 0.123$$

From Figure 6, the slope at $y = 0$ corresponding to the preceding injection parameter is estimated to be 0.26.

Then

$$\bar{h}_{cx} = \frac{0.26\ k_a \sqrt{Re_x}}{x}$$

$$\bar{h}_c = \frac{1}{L} \int_0^L \frac{0.26\ k_a}{x} \sqrt{Re_x}\ dx$$

$$\bar{h}_c = \frac{0.52\ k_a}{L} \sqrt{Re_L}$$

$$\bar{h}_c = \frac{0.52}{(0.5\ ft)} \left(0.0213 \frac{Btu}{hr\text{-}ft\text{-}{}^oF} \right) \sqrt{92,592}$$

$$\bar{h}_c = 6.74 \frac{Btu}{hr\text{-}ft^2\text{-}{}^oF}$$

From equation 4,

$$\bar{k}_{cx} = \frac{D_{AB}\sqrt{Re_x}}{x} \left[\frac{1}{\Delta C_s} \frac{\partial C_s}{\partial \eta} \Bigg|_{y=0} \right]$$

D_{AB}, the diffusion coefficient for moisture moving from the surface of the veneer into the drying medium, is calculated using the Hirschfelder equation in the following form:

$$D_{AB_{T_2, P_2}} = D_{AB_{T_1, P_1}} \left(\frac{P_1}{P_2}\right)\left(\frac{T_2}{T_1}\right)^{3/2} \frac{\Omega_D @ T_1}{\Omega_D @ T_2}$$

where: $D_{AB_{T_1, P_1}}$ = $0.260\ cm^2/sec$ at 298^oK and a pressure of one atmosphere

$P_1 = P_2$ = one atmosphere

$T_1 = 298^oK$

$T_2 = 600^oF = 589^oK$

Values of Ω_D are tabulated in reference 19 as a function of of $\frac{kT}{\epsilon_{AB}}$, where k is Boltzmann's constant, ϵ_{AB} is the energy of molecular interaction for the binary system AB, and T is the absolute temperature. The parameter ϵ_{AB} may be calculated using the equation $\epsilon_{AB} = \sqrt{\epsilon_A \epsilon_B}$ (19). From reference 19, $\frac{\epsilon_{air}}{k} = 97^oK$, $\frac{\epsilon_{water}}{k} = 356^oK$, and therefore

$$\frac{\epsilon_{AB}}{k} = \frac{\sqrt{\epsilon_{air}\epsilon_{water}}}{k} = \sqrt{\left(\frac{\epsilon_{air}}{k}\right)\left(\frac{\epsilon_{water}}{k}\right)}$$

$$\frac{\epsilon_{AB}}{k} = \sqrt{(97)(356)} = 185.8$$

At $298^\circ K$, $\frac{kT}{\epsilon_{AB}} = \frac{298}{185.8} = 1.605$, and the corresponding value of Ω_D is 1.166. At $589^\circ K$, $\frac{kT}{\epsilon_{AB}} = 3.17$ and $\Omega_D = 0.9352$. Then, substituting into the Hirschfelder equation,

$$D_{AB} = (0.260 \frac{cm^2}{sec})(3600 \frac{sec}{hr})(\frac{ft^2}{(30.480)^2 cm^2})(\frac{589}{298})^{\frac{3}{2}} (\frac{1.166}{0.9352})$$

$$D_{AB} = 3.49 \frac{ft^2}{hr}$$

$$\bar{k}_c = \int_0^L \frac{0.26\ D_{AB}}{L} \frac{\sqrt{Re_x}}{x} dx = \frac{0.52\ D_{AB}}{L} \sqrt{Re_L}$$

$$\bar{k}_c = (\frac{0.52}{(0.5\ ft)}) (\frac{3.59\ ft^2}{hr}) \sqrt{92,592}$$

$$\bar{k}_c = 1,105 \frac{ft}{hr}$$

Substituting into the equation for $h^o_{predicted}$,

$$h^o_{predicted} = 6.74 \frac{Btu}{hr\text{-}ft^2\text{-}^\circ F} + \frac{(1105 \frac{ft}{hr})(0.0373 \frac{lb}{ft^3})(970 \frac{Btu}{lb})}{388^\circ F}$$

$$h^o_{predicted} = 109.7 \frac{Btu}{hr\text{-}ft^2\text{-}^\circ F}$$

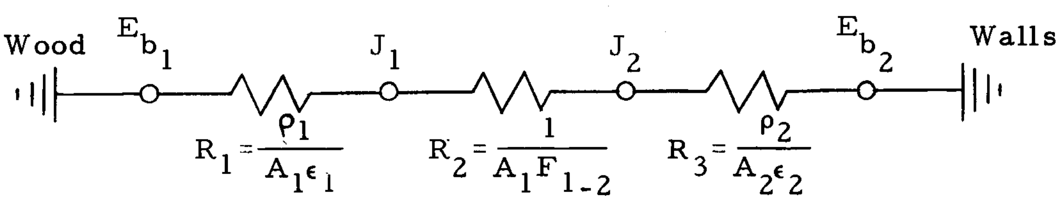
h^o - Based on Experimental Data

Equation 12, the applicable equation for calculating $h^o_{experimental}$, may be written as follows:

$$h^o_{exp} = \frac{(\dot{m}_s)(h_{fg}) + (m_{wood})(c_{p_{wood}})\,\frac{dT_{wood}}{dt}}{A_{wood}(T_{air} - T_{wood})}$$

$$+ \frac{(m_{water})(c_{p_{water}})\,\frac{dT_{water}}{dt}}{A_{wood}(T_{air} - T_{wood})} - \frac{(\sigma)(\mathcal{F}_{1-2})(T^4_{walls} - T^4_{wood})}{(T_{air} - T_{wood})}$$

The gray body shape factor, $\mathcal{F}_{1-2}$, between the wood surface and the surrounding test section may be determined from the following equivalent network:



$$A_1\mathcal{F}_{1-2} = \frac{1}{\frac{\rho_1}{A_1\epsilon_1} + \frac{1}{A_1F_{1-2}} + \frac{\rho_2}{A_2\epsilon_2}}$$

where A_1 and A_2 denote the surface areas of the wood and enclosure, respectively, ρ = reflectivity, and ϵ = emissivity. F_{1-2}, the geometric shape factor between the wood surface and surrounding test section, is unity since the wood is completely enclosed in the test section. Noting in addition that $\rho_1 = (1 - \epsilon_1)$ and $\rho_2 = (1 - \epsilon_2)$, the preceding equation reduces to:

$$\mathcal{F}_{1-2} = \frac{1}{\dfrac{1}{\epsilon_{wood}} + \dfrac{A_{wood}}{A_{walls}\,\epsilon_{walls}} - \dfrac{A_{wood}}{A_{walls}}}$$

South (15) calculated the following values for the gray body shape factor, which were also used in calculations for this thesis:

For the parallel flow test section: $\mathcal{F}_{1-2} = 0.885$

For the 45° and 90° test section: $\mathcal{F}_{1-2} = 0.857$

The following equation from Stamm (17) was used to determine specific heat of wood as a function of temperature:

$$c_{p_{wood}} \left(\frac{Btu}{lb_m\,^{o}F}\right) = 0.2454 + 0.000645\ T_{wood}$$

where T_{wood} is in °F.

From the plots of wood temperature as a function of drying time which were obtained for each sample, the time rate of change of wood temperature, $\frac{dT_{wood}}{dt}$, can be determined. This is assumed to be equal to the time rate of change of water temperature within the wood. The rate at which water evaporates from the surface of the wood, $\dot{m}_s$, is determined from the appropriate drying curve.

The following sample calculation is for Southern pine veneer dried in air flowing at a velocity of 100 feet per second and a temperature of 600°F parallel to the veneer surfaces. For this example, the time dependent quantities discussed in the preceding paragraph were evaluated from the curves of wood temperature and moisture at the points corresponding to 0.35 minutes of drying time. Wood temperature after 0.35 minutes was 224°F. Magnitudes of the other parameters are equal to the values which have been substituted into equation 12 as follows:

$$h^{o}_{exp} = \frac{(2.56\frac{lb}{hr})(962\frac{Btu}{lb})}{(.333\ ft^2)(600^oF - 224^oF)} + \frac{(0.055\ lb)(0.3899\frac{Btu}{lb\text{-}^oF})(9,600\frac{^oF}{hr})}{(.333\ ft^2)(600^oF - 224^oF)}$$

$$+ \frac{(0.067\ lb)(1\frac{Btu}{lb\text{-}^oF})(9600\frac{^oF}{hr})}{(.333\ ft^2)(600^oF - 224^oF)}$$

$$- \frac{(0.1714 \times 10^{-8}\frac{Btu}{hr\text{-}ft^2\text{-}^oR})(0.885)\ [(1060^4 - 684^4)^oR]}{(600^oF - 224^oF)}$$

$$h^{o}_{exp} = 19.67 + 1.64 + 5.14 - 3.32$$

$$h^{o}_{exp} = 23.14\ \frac{Btu}{hr\text{-}ft^2\text{-}^oF}$$

Experimental Internal Diffusion Coefficient, $\overline{D}_{AB}$

The following sample calculations are for Southern pine veneer dried in air flowing perpendicular to the veneer surfaces at 100 feet per second and at a temperature of 350°F.

The following parameters are for use with the Gurney-Lurie chart:

$$m = 0$$

$$n = 0.5$$

$$y = \frac{0 - 5\%}{0 - 100\%} = 0.05$$

From the Gurney-Lurie chart,

$$X = 1.3 = \frac{\overline{D}_{AB} t}{x_1^2}$$

then

$$\overline{D}_{AB} = \frac{1.3\, x_1^2}{t}$$

where: x_1, the half-thickness of the veneer, = 0.0052 ft.

t, the time required for Southern pine to dry from a dimensionless moisture content of 100% to a dimensionless moisture content of 5% under the given drying conditions, is 5.13 minutes.

Substituting,

$$\overline{D}_{AB} = \frac{(1.3)(0.0052\ \text{ft})^2(60\,\frac{\text{min}}{\text{hr}})}{5.13\ \text{min}}$$

$$\overline{D}_{AB} = 4.11 \times 10^{-4}\ \frac{\text{ft}^2}{\text{hr}}$$

Sample Three-Factor Analysis of Variance

An outline of the method of analysis is presented for determining the effects of the following three factors on the moisture content of Southern pine veneer samples dried for two minutes at a temperature of 600°F:

1. Drying media - air and steam.

2. Angles of impingement of the drying media on the veneer - 0°, 45°, and 90°.

3. Velocities of the drying media - 50, 100, and 150 feet per second.

The model equation for a three-factor factorial experiment is as follows (20, p. 466):

$$X_{ijkm} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \epsilon_{ijkm}$$

where:

X_{ijkl} = dimensionless moisture content after a drying time of two minutes at 600°F for the m^{th} Southern pine sample replication (m = 1, 2, 3) dried in the i^{th} medium (i = 1, 2) at the j^{th} angle of impingement (j = 1, 2, 3) and the k^{th} velocity (k = 1, 2, 3).

μ = a constant overall mean drying time.

α_i = the effect of the i^{th} drying medium.

β_j = the effect of the j^{th} angle of impingement.

γ_k = the effect of the k^{th} velocity.

$(\alpha\beta)_{ij}$ = the effect of the interaction between the i^{th} drying medium and the j^{th} angle of impingement.

$(\alpha\beta)_{ik}$ = the effect of the interaction between the i^{th} drying medium and the k^{th} velocity.

$(\beta\gamma)_{jk}$ = the effect of the interaction between the j^{th} angle of impingement and the k^{th} velocity.

$(\alpha\beta\gamma)_{ijk}$ = the effect of the interaction between the i^{th} drying medium, the j^{th} angle of impingement, and the k^{th} velocity.

ϵ_{ijkm} = the m^{th} random effect of the i^{th} drying medium, the j^{th} angle of impingement, and the k^{th} velocity.

This is assumed to be a fixed effects experiment, based on the fact that the levels of the various factors were deliberately chosen rather than being randomly selected from populations of all possible levels of each factor. For example, the two types, called levels, of drying media used in this experiment were selected to investigate the specific effects of each on the drying rate of veneer. Conclusions regarding the drying media are applicable only to the two types which were selected; conclusions do not necessarily apply to the population of all possible types of drying media. The same holds true for the levels of the other factors investigated in this experiment. Had the levels of the various factors been selected at random from populations of all possible levels of each factor, this would have been a random effects experiment, and conclusions would have been more generally applicable to all possible levels of the various factors.

Other assumptions made for the analysis of variance include the following (3, p. 91; 20, p. 444):

1. Effects are additive. One implication of this assumption is that there is no interference among the experimental units (5, p. 19), i.e., the observed rate of moisture removal for samples exposed to one set of conditions is assumed to be unaffected by the particular order in which samples were allocated for the remaining conditions under which the samples were dried.

2. Samples are randomly selected.

3. Experimental errors are independently distributed with a mean equal to zero and with a common variance σ^2.

4. For purposes of establishing confidence limits, and for testing hypotheses concerning levels of the various factors, distributions for both the experimental errors and the populations from which the samples were taken are assumed to be normal.

This experiment may be classified as a completely randomized design. Although samples for each drying curve normally came from the same sheet of veneer, veneer sheets within each species were selected at random for the three replicate drying curves which were obtained at each test condition, and for the various test conditions. The analysis of variance table for a three-factor factorial experiment in a completely randomized design is shown in Table VI.

In Table VI, factors A, B, and C denote drying media, angles of impingement, and velocities of the drying media, respectively.

Table VI. Analysis of variance for a fixed model three-factor factorial experiment in a completely randomized design (20, p. 468).

Source of variation	Sum of squares	Degrees of freedom	Mean squares
Factor A	SSA	a-1	MSA
Factor B	SSB	b-1	MSB
Factor C	SSC	c-1	MSC
Interaction (A x B)	SSAB	(a-1)(b-1)	'
Interaction (A x C)	SSAC	(a-1)(c-1)	'
Interaction (B x C)	SSBC	(b-1)(c-1)	etc.
Interaction (A x B x C)	SSABC	(a-1)(b-1)(c-1)	'
Error	SSE	abc(n-1)	MSE
Total	SST	abcn-1	

The number of levels of factors A, B, and C are denoted by a, b, and c, and the number of replications is denoted by n. For this example, $a = 2$, $b = 3$, $c = 3$, and $n = 3$.

Equations for computing the sum of squares corresponding to each source of variation are available in textbooks on analysis of variance. To calculate the sum of squares for factor A, for example, the following equations are used:

$$SSA = \frac{T_{i\ldots}^{2}}{bcn}$$

$$\text{where} \quad T_{i\ldots} = \sum_{j=1}^{b} \sum_{k=1}^{c} \sum_{l=1}^{n} X_{ijkl}$$

and the other symbols are as defined in the preceding paragraphs.

Hypotheses of the form H_o: $\mu_1 = \mu_2 = \cdots = \mu_k$ may be tested using the analysis of variance table. If a hypothesis of this form, called a null hypothesis, is rejected, then the alternate hypothesis that not all the means are equal is accepted. One of the null hypotheses which may be tested in this sample analysis is the following:

H_o: The means of the moisture contents for Southern pine samples dried in air and Southern pine samples dried in steam for two minutes at 600°F are equal.

To test hypotheses of the form H_o: $\mu_1 = \mu_2 = \cdots = \mu_k$, the F distribution is often used. Such tests required two independent estimates of the variance σ^2 which is assumed to be common to the k populations from which samples are drawn (20, p. 312). A basic assumption for the tests is that the samples are drawn randomly and independently from k normal populations.

The two independent estimates of σ^2 are obtained from the mean squares column of the analysis of variance table. MSE, the error mean square, is an unbiased estimator of σ^2 when the samples are randomly and independently drawn. Choice of the second estimator depends on the hypothesis to be tested. For example, if the hypothesis to be tested is H_o : the means of the moisture contents are equal for samples dried in air and samples dried in steam for a specified time period, then the mean square for factor A in Table VI is selected. When H_o is <u>not</u> true, the expected value of MSA is larger than σ^2. If H_o is true, the ratio $\frac{MSA}{MSE}$ (or $\frac{MSB}{MSE}$, $\frac{MSC}{MSE}$, etc., depending on the null hypothesis to be tested) has the F distribution with (a-1) and abc(n-1) degrees of freedom.

Therefore, to test H_o, the ratio $\frac{MSA}{MSE}$ is compared to an appropriate value of the F distribution which can be obtained from statistical tables. The null hypothesis is rejected if $\frac{MSA}{MSE}$ > $F_{\alpha[(a-1),\ abc(n-1)]}$, where α corresponds to the significance level of the test, and the quantities in the square brackets correspond to the degrees of freedom mentioned in the preceding paragraph.

The analysis of variance table shown in Table VII is reproduced

Table VII. Three-factor analysis of variance for Southern pine veneer dried at 600°F.

Dependent variable: % dimensionless moisture, τ, after 2 minutes.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
MEDI	1	546.5785	546.5785	104.569
ANGL	2	788.7376	394.3688	75.449
VEL	2	7385.4377	3692.7189	706.475
MEDI x ANGL	2	14.2400	7.1200	1.362
MEDI x VEL	2	24.5997	12.2999	2.353
ANGL x VEL	4	74.1597	18.5399	3.547
MEDI x ANGL x VEL	4	105.4611	26.3653	5.044
ERROR	36	188.1707	5.2270	
TOTAL	53	9127.3851		

Means, in terms of % dimensionless moisture content after a drying time of two minutes at 600°F:

	Air	Steam	
MEDI	24.3293	17.9663	
	0°	45°	90°
ANGL	20.4078	26.1544	16.8811
	50 fps	100 fps	150 fps
VEL	36.7756	18.0222	8.6456

from a computer printout. The values given in the "F" column are the magnitudes of the ratios of the mean squares for MEDI, ANGL, etc., to the error mean square. When the F value of 104.569 for MEDI is compared to the tabulated value of $F_{(1, 36)} = 7.41$ at the 99% confidence level, it is apparent that the null hypothesis regarding the equality of moisture contents of veneer dried in air and in steam for a specified period is false. Hypotheses regarding the levels of the other factors may be tested in a similar manner.

Based on the means of the moisture contents for samples dried in the two media, Southern pine samples dried in steam had less moisture than Southern pine samples dried in air after a drying time of two minutes. The difference in moisture contents is significant based on the F test. Therefore, steam was the most effective medium for drying Southern pine at 600°F.

Confidence Intervals

Confidence intervals for differences in drying times and differences in moisture contents corresponding to levels of the various factors investigated in this experiment may be established using Scheffe's method. For any number of linear contrasts among k means, the confidence intervals are calculated by Scheffe's method as follows (20, p. 346):

$$\Sigma m_i \overline{X}_i - \sqrt{F'_\alpha S^2 \Sigma \frac{m_i^2}{n_i}} < \Sigma m_i \mu_i < \Sigma m_i \overline{X}_i + \sqrt{F'_\alpha S^2 \Sigma \frac{m_i^2}{n_i}}$$

where $F' = (k-1) F_{\alpha(k-1, \nu)}$

Quantities represented by the terms in Scheffe's equation are illustrated in the following example, in which a confidence interval is established for the difference in mean values of moisture contents for samples dried in air and samples dried in steam under the conditions specified for the analysis of variance table in Table VII.

The linear contrast of interest in this example is $\mu_A - \mu_S$, where μ_A and μ_S represent unknown population means for moisture contents of Southern pine samples dried for two minutes at 600°F in air and in steam, respectively. From the analysis of variance table, the mean values of the moisture contents for the number, $n = 27$, of samples dried in air and the 27 samples dried in steam for two minutes at 600°F are $\overline{X}_A = 24.329$ and $\overline{X}_S = 17.966$. The samples which were dried in the experiment are assumed to have been randomly and independently drawn from their corresponding populations.

Also from the analysis of variance table, the value of the mean square for error, which is the best estimator of the unknown variance σ^2 assumed to be common to the populations from which samples were selected, is 5.227. This value corresponds to s^2 in Scheffe's equation. The value of ν, the number of degrees of freedom for the variance estimator, is 36.

For a 95% confidence interval, $\alpha = 1 - 0.95 = 0.05$, and the value of $F_{\alpha(k-1, \nu)} = F_{.05(1, 36)}$ is, from statistical tables (20, p. 638), 4.12.

Substituting the preceding quantities into Scheffe's equation, the confidence interval is

$$(24.33 - 17.97) - \sqrt{\frac{(4.12)(5.23)(2)}{27}} < \mu_A - \mu_S < (24.33 - 17.97) + \sqrt{\frac{(4.12)(5.23)(2)}{27}}$$

$$6.36 - 1.26 < \mu_A - \mu_S < 6.36 + 1.26$$

$$5.10 < \mu_A - \mu_S < 7.62$$

With 95% confidence, it can be estimated that differences in mean values of dimensionless moisture contents for Southern pine veneer samples dried at 600°F for two minutes in air and Southern pine veneer samples dried for two minutes in steam fall in the preceding interval.

Confidence intervals for differences in drying times required to reduce veneer moisture content to a specific value are perhaps of greater interest in comparing the effects of various factors, and such confidence intervals are included in the Results section of this thesis. Procedures for calculating the confidence intervals are as outlined in the preceding example. The actual calculations were performed on the Oregon State University C.D.C. 3300 computer.

Mean Values of Dimensionless Moisture Contents from Analyses of Variance with Dimensionless Moisture Content After a Specified Time as the Dependent Variable

As mentioned in the Statistical Analysis section, conclusions from analyses with time to dry to a dimensionless moisture content of 10% as the dependent variable were checked by reanalyzing the data using as the dependent variable the dimensionless moisture content after a specified drying time. The conclusions were the same for each method of analysis. Mean values of the moisture contents corresponding to the various analyses are included in Table VIII.

Table VIII. Mean values of dimensionless moisture content, τ, after specified drying times.

Data analyzed	Drying time, in minutes	Factor		Mean value of dimensionless moisture content, τ, in %
Combined data at 350°F	5	Wood:	S. pine	14.49
			D. fir	17.44
		Medium:	air	13.61
			steam	18.32
		Angle:	0°	13.53
			45°	20.59
			90°	13.78
		Velocity:	50 fps	27.62
			100 fps	13.77
			150 fps	6.51
Southern pine data at 350°F	5	Medium:	air	12.02
			steam	16.97
		Angle:	0°	11.38
			45°	20.40
			90°	11.70
		Velocity:	50 fps	27.61
			100 fps	12.03
			150 fps	3.84
Douglas fir data at 350°F	5	Medium:	air	15.21
			steam	19.66
		Angle:	0°	15.68
			45°	20.78
			90°	15.85
		Velocity:	50 fps	27.62
			100 fps	15.51
			150 fps	9.18
Air data at 350°F	5	Wood:	S. pine	12.02
			D. fir	15.21
		Angle:	0°	9.52
			45°	18.87
			90°	12.46
		Velocity:	50 fps	24.48
			100 fps	10.96
			150 fps	5.40

Table VIII. (Continued)

Data analyzed	Drying time, in minutes	Factor		Mean value of dimensionless moisture content, τ, in %
Steam data at 350°F	5	Wood:	S. pine	16.97
			D. fir	19.66
		Angle:	0°	17.55
			45°	22.32
			90°	15.09
		Velocity:	50 fps	30.75
			100 fps	16.59
			150 fps	7.62
Combined data for 600°F	2	Wood:	S. pine	21.15
			D. fir	25.73
		Medium:	air	25.61
			steam	21.26
		Angle:	0°	22.30
			45°	29.79
			90°	18.22
		Velocity:	50 fps	38.68
			100 fps	20.86
			150 fps	10.78
S. pine data at 600°F	2	Medium:	air	24.33
			steam	17.97
		Angle:	0°	20.41
			45°	26.15
			90°	16.88
		Velocity:	50 fps	36.78
			100 fps	18.02
			150 fps	8.65
D. fir data at 600°F	2	Medium:	air	26.89
			steam	24.56
		Angle:	0°	24.20
			45°	33.42
			90°	19.56
		Velocity:	50 fps	40.58
			100 fps	23.69
			150 fps	12.91

Table VIII. (Continued)

Data analyzed	Drying time, in minutes	Factor		Mean value of dimensionless moisture content, τ, in %
Air data at 600°F	2	Wood:	S. pine	24.33
			D. fir	26.89
		Angle:	0°	22.70
			45°	33.36
			90°	20.77
		Velocity:	50 fps	40.63
			100 fps	22.97
			150 fps	13.23
Steam data at 600°F	2	Wood:	S. pine	17.97
			D. fir	24.56
		Angle:	0°	21.91
			45°	26.22
			90°	15.66
		Velocity:	50 fps	36.72
			100 fps	18.74
			150 fps	8.33