Studies on the drying of wood

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Introduction

In drying of wood many equations have been developed on the moisture movement through wood. Among them, hitherto the diffusion equations [1],[2],[11],[27] or the differential equations [4],[18],[21],[22],[24] similar to the heat conduction equation had been used, and recently yet many other equations [10],[23] are established.

In the range of high moisture content, the movement of free water is mainly due to the capillary force, nevertheless the diffusion equation by the moisture gradient or the differential equation are used. In hygroscopic range besides the above mentioned equations, VOIGT [27] explained it by the capillary movement in cell membrane near the fiber saturation point and by the diffusion equation similar to Stefan' s law, STAMM [23] considering it as a diffusion and an electric stream in wood structure, calculated the drying diffusion constant and KRÖLL [10] explained it as a capillary movement in cell membrane near the fiber saturation point and Knudsen's molecular stream in pit membrane pore in the lower moisture content.

It may be distinctly an error to apply the differential equation in high moisture range, but it comes into problem in hygroscopic range. According to MARTLEY [15], LUDWIG [11], and EGNER [2] , the diffusion coefficient varies with the moisture content, so that the coefficient of differential equation i. e. drying diffusion constant K becomes the function of the moisture content and the actual calculation by its solution is difficult. On the other hand, according to BATEMANN [1], SCHLÜTER [20], STAMM [23], ond KRÖLL [10] it may be considered that the drying diffusion constant is independent upon the moisture content at least from 30 to 10% moisture content.

Thus, for the application of the differential equation some deny it clearly and some have the different opinions even in hygroscopic range as well as in high moisture range, nevertheless the differential equation is often used for the convenience that (1) it represents directly the moisture content of wood (2) other equations can not be directly connected with the relative humidity and the velocity of the drying air, but it can be easily

connected with them (3) at least from 30 to 10% moisture content, it coincides well with the drying process (4) it is convenient for the calculation of the drying time.

At the above mentioned standpoint, the present author treated of the differential equation from the drying process and the moisture gradient, and obtained the influences of the drying air conditions to the drying coefficient. In drying, the heat- and moisture-movement take place together but in the present study only the latter was researched.

1. Differential equation of drying of wood

The general differential equation of the moisture movement through wood is given as the same as that of the heat conduction, that is, when u is the moisture content based on dry weight, the amount of moisture dW which diffuses through the area A in time $d\theta$, is

$$dW = -k\frac{du}{dx} A\ d\theta \cdots\cdots\cdots\cdots(1)$$

where k is the diffusion coefficient (g/cm h) and x the direction of moisture flow. Using equation $V_u = V_0\ (1+0.84\ r_0 u)$ (V_u, V_0 is a wet and dry volume, r_0 is the specific gravity) the differential equation is written in the form

$$\frac{\partial u}{\partial \theta} = \frac{1+0.84\ r_0 u}{r_0}\left(k_r\frac{\partial^2 u}{\partial x^2} + k_t\frac{\partial^2 u}{\partial y^2} + k_l\frac{\partial^2 u}{\partial z^2}\right)$$

$$= K_{ru}\frac{\partial^2 u}{\partial x^2} + K_{tu}\frac{\partial^2 u}{\partial y^2} + K_{lu}\frac{\partial^2 u}{\partial z^2}$$

$$= (1+0.84 r_0 u)\left(K_{r0}\frac{\partial^2 u}{\partial x^2} + K_{t0}\frac{\partial^2 u}{\partial y^2} + K_{l0}\frac{\partial^2 u}{\partial z^2}\right)\cdots\cdots(2)$$

where K ($=k/r_0$) is the drying diffusion constant (cm²/h) and subscript r, t, l, and u and 0 represent the radial, tangential, longitudinal direction and moisture content u, and 0, respectively ; u in $(1+0.84r_0 u)$ is 0-0.3 in hygroscopic range and 0.3 in higher moisture range.

Obviously from equation (2), drying diffusion constant K is the function of the moisture content for a given wood species but its value is approximately equal to 1 in ordinary wood specie as shown in Fig. 1. Hereafter the present author makes in unidirection the investigation whether K is constant or not.
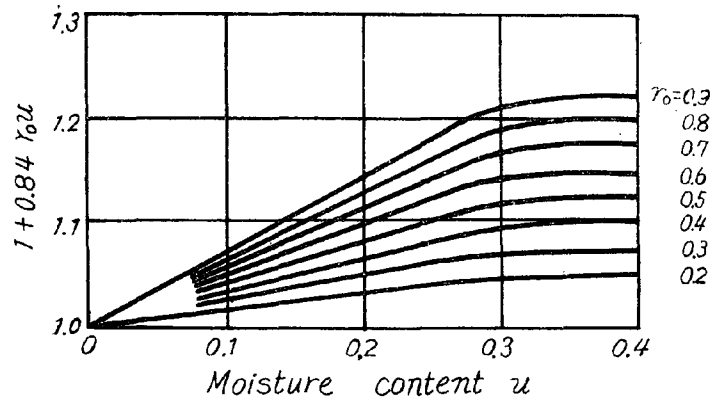
Fig. 1 Values of $(1+0.84\ r_0u)$

11. Differential equation under steady drying conditions

When we assume that the amount of moisture evaporated from the wood surface to the drying air through the fluid film is proportional to the difference between the moisture content at the wood surface and the equilibrium moisture content of the drying air, at the boundary $x = -a$ (ref. Fig. 2),
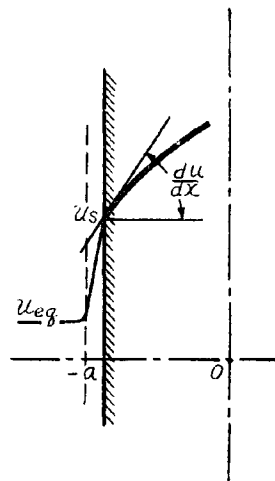

Fig. 2

$$dW = -k\frac{\partial u}{\partial x}A\ d\theta \qquad \text{(from the wood surface)}$$

$$dW = -a\ (u_s - u_{eq})\ A\ d\theta \quad \text{(through the fluid film)} \qquad \cdots\cdots (3)$$

so that
$$\frac{\partial u}{\partial x} = \frac{a}{k}(u_s - u_{eq}) = h\ (u_s - u_{eq})$$

where a is the coefficient of surface evaporation (g/cm^2h) and $h = a/k$.

When the initial moisture gradient in wood is $f(x)$, then

$$\begin{cases} \dfrac{\partial u}{\partial \theta} = K \dfrac{\partial^2 u}{\partial x^2} & \cdots\cdots (4) \\[2mm] \theta = 0 : u = f(x) & \cdots\cdots (5) \\[2mm] x = \mp a : \dfrac{\partial u}{\partial x} \mp h\,(u_x - u_{eq}) = 0 & \cdots\cdots (6) \\[2mm] x = 0 : \dfrac{\partial u}{\partial x} = 0 & \cdots\cdots (7) \end{cases}$$

If we write $v = u - u_{eq}$, equation (4)-(7) are transformed into

$$\begin{cases} \dfrac{\partial v}{\partial \theta} = K \dfrac{\partial^2 v}{\partial x^2} & \cdots\cdots (4)' \\[2mm] \theta = 0 : v = f(x) - u_{eq} = F(x) & \cdots\cdots (5)' \\[2mm] x = \mp a : \dfrac{\partial v}{\partial x} \mp hv = 0 & \cdots\cdots (6)' \\[2mm] x = 0 : \dfrac{\partial v}{\partial x} = 0 & \cdots\cdots (7)' \end{cases}$$

the particular solution, thus

$$v = \frac{1}{a}\sum \frac{\delta_n}{\delta_n + \sin \delta_n \cos \delta_n} e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta}$$

$$\times \cos\frac{\delta_n}{a} x \int_{-a}^{a} F(\lambda) \cos\frac{\delta_n}{a}\lambda \; d\lambda \cdots\cdots (8)$$

where δ_n is nth real root of cot $u = u/ha$.

111. Case where the initial moisture distribution U_0 is uniform

Let $F(\lambda) = U_0 - u_{eq} = V_0$, from solution (8) we have

$$\frac{v}{V_0} = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \cos\frac{\delta_n}{a} x \frac{\sin \delta_n}{\delta_n + \sin \delta_n \cos \delta_n} \cdots\cdots (9)$$

for average moisture content v_{av} at time θ,

$$\frac{v_{av}}{V_0} = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \frac{\sin^2 \delta_n}{\delta_n(\delta_n + \sin \delta_n \cos \delta_n)} \cdots\cdots (10)$$

The water evaporated

$$W = V_0 G_{ab}(1 - v_{av}/V_0)$$

$$= V_0 G_{ab}\left(1 - 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \frac{\sin^2 \delta_n}{\delta_n(\delta_n + \sin \delta_n \cos \delta_n)}\right) \cdots\cdots (11)$$

where G_{ab} is the oven dry weight of wood,

then

$$\frac{dW}{d\theta} = V_c G_{ab} \sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \; K\left(\frac{\delta_n}{a}\right)^2 \; \frac{2\sin^2\delta_n}{\delta_n(\delta_n+\sin\delta_n \cos\delta_n)} \quad \cdots\cdots\cdots (12)$$

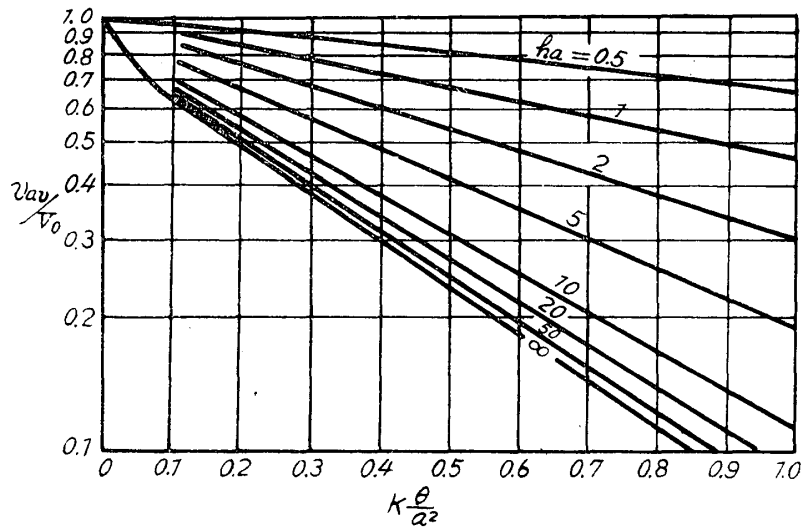Fig. 3 shows the dimensionless diagram of equation (10).

Fig. 3 Dimensionless diagram of eq. (10)

For the drying period θ_{eq} which required till the wood equilibrate with the drying air,

we can take $\qquad e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \fallingdotseq 0.01$ [16]

then

$$\theta_{eq} = \frac{4.6a^2}{K\delta_1^2} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (13)$$

112. Case where the initial moisture distribution is given

as parabola $f(x) = U_m - (U_m - U_s)\left(\frac{x}{a}\right)^2$

Let $\qquad F(x) = V_m - (V_m - V_s)\left(\frac{x}{a}\right)^2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (14)$

then, from equation (8)

$$v = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \cos\frac{\delta_n}{a} x \; \frac{1}{\delta_n+\sin\delta_n \cos\delta_n}$$

$$\times \left[V_s \sin\delta_n - 2(V_m - V_s)\left\{\frac{\cos\delta_n}{\delta_n} - \frac{\sin\delta_n}{\delta_n^2}\right\}\right] \cdots\cdots\cdots (15)$$

and

$$v_{ar} = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2\theta} \frac{\sin\delta_n}{\delta_n(\delta_n + \sin\delta_n \cos\delta_n)}$$

$$\times \left[V_s \sin\delta_n - 2(V_m - V_s)\left\{ \frac{\cos\delta_n}{\delta_n} - \frac{\sin\delta_n}{\delta_n^2} \right\} \right] \cdots \cdots (16)$$

where $V_s = U_s - u_{eq}$, $V_m = U_m - u_{eq}$; the former is the moisture content at the wood surface and the latter is one in the mid-plane.

If the initial moisture distribution satisfies the boundary condition (6)', then

$$\text{from (6)'} \qquad \left(\frac{dV}{dx}\right)_{x=-a} = h V_s$$

$$\text{from (14)} \qquad \left(\frac{dV}{dx}\right)_{x=-a} = \frac{2(V_m - V_s)}{a}$$

therefore $\qquad V_s = \frac{2V_m}{2+ha}$

from parabola $\quad V_{av} = \frac{2V_m + V_s}{3}$

therefore $\quad V_s = \frac{3}{3+ha} V_{av}, \qquad V_m = \frac{3(2+ha)}{2(3+ha)} V_{av} \cdots\cdots\cdots\cdots (17)$

Using these, equation (16) is transformed into

$$\frac{v_{av}}{V_{av}} = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2\theta} \frac{\sin\delta_n}{\delta_n(\delta_n + \sin\delta_n \cos\delta_n)} \frac{3}{3+ha}$$

$$\times \left[\sin\delta_n - ha\left\{ \frac{\cos\delta_n}{\delta_n} - \frac{\sin\delta_n}{\delta_n^2} \right\} \right] \cdots\cdots\cdots (18)$$

and the moisture evaporated

$$W = V_{av}G_{ab}(1 - v_{av}/V_{av})$$

$$= V_{av}G_{ab}\left[1 - 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2\theta} \frac{\sin\delta_n}{\delta_n(\delta_n + \sin\delta_n \cos\delta_n)} \frac{3}{3+ha} \right.$$

$$\left. \times \sin\delta_n - ha\left\{ \frac{\cos\delta_n}{\delta_n} - \frac{\sin\delta_n}{\delta_n^2} \right\} \right] \cdots\cdots\cdots (19)$$

then

$$\frac{dW}{d\theta} = V_{av}G_{ab}\sum e^{-K\left(\frac{\delta_n}{a}\right)^2\theta} K\left(\frac{\delta_n}{a}\right)^2 \frac{2\sin\delta_n}{\delta_n(\delta_n + \sin\delta_n \cos\delta_n)} \frac{3}{3+ha}$$

$$\times \left[\sin\delta_n - ha\left\{ \frac{\cos\delta_n}{\delta_n} - \frac{\sin\delta_n}{\delta_n^2} \right\} \right] \cdots\cdots\cdots (20)$$

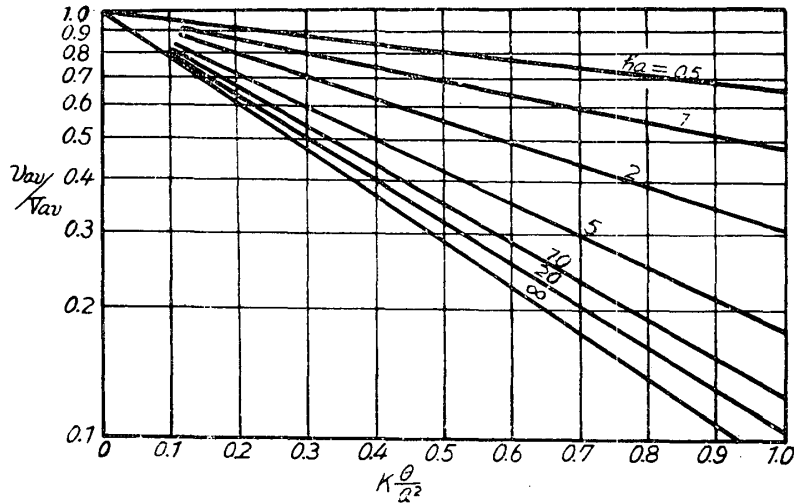Fig. 4 shows the dimensionless diagram of equation (18)

Fig. 4 Dimensionless diagram of eq. (18)

12. Differential equation under unsteady drying conditions

When the drying air conditions vary with time, we may use $u_{eq} = \varphi(\theta)$, but in this case drying diffusion constant K may be not always constant for the change of the drying conditions or the moisture content. Few experimental results have been reported about the relation between K and the drying conditions. KAMEI (1937), BATEMAN (1939), and STAMM (1946) reported the agreeable conclusions that K varies with the temperature, however, there have been an heterodoxy about the relation of K to the relative humidity of the drying air and the moisture content of wood. According to the present author, K varies with the change of the temperature and the relative humidity, but in the lower temperature or the higher humidity the variation is very small and for the change of the moisture content of wood, also, K can be regarded as a constant in practice, and changes of K by some degree give not so large influence on moisture content therefore under the confined unsteady drying conditing assuming K as constant

$$\frac{\partial u}{\partial \theta} = K \frac{\partial^2 u}{\partial x^2} \quad \cdots\cdots (4)$$

$$\theta = 0 \ : \ u = f(x) \quad \cdots\cdots (5)$$

$$x = \mp a \ : \ \frac{\partial u}{\partial x} \mp h \left\{ u - \varphi(\theta) \right\} = 0 \quad \cdots\cdots (21)$$

the particular solution thus

$$u = \frac{1}{a} \sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \cos\frac{\delta_n}{a} \; x \; \frac{\delta_n}{\delta_n + \sin \delta_n \cos \delta_n}$$

$$\times \left[\int_{-a}^{a} f(\lambda) \cos\frac{\delta_n}{a} \lambda d\lambda + 2a \frac{\sin\delta_n}{\delta_n} K\left(\frac{\delta_n}{a}\right)^2 \int_{0}^{\theta} e^{K\left(\frac{\delta_n}{a}\right)^2 \xi} \varphi(\xi) d\xi \right] \cdots\cdots (22)$$

121. Case where the initial moisture distribution is uniform

Let $f(x) = U_0$

$$u = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \cos\frac{\delta_n}{a} x \frac{\sin \delta_n}{\delta_n + \sin \delta_n \cos \delta_n}$$

$$\times \left[U_0 + K\left(\frac{\delta_n}{a}\right)^2 \int_{0}^{\theta} e^{K\left(\frac{\delta_n}{a}\right)^2 \xi} \varphi(\xi) d\xi \right] \cdots\cdots\cdots (23)$$

$$u_{av} = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \frac{\sin^2\delta_n}{\delta_n(\delta_n + \sin \delta_n \cos \delta_n)}$$

$$\times \left[U_0 + K\left(\frac{\delta_n}{a}\right)^2 \int_{0}^{\theta} e^{K\left(\frac{\delta_n}{a}\right)^2 \xi} \varphi(\xi) d\xi \right] \cdots\cdots\cdots (24)$$

122. Case where the initial moisture distribution is parabolic

Let $f(x) = U_m - (U_m - U_s)\left(\frac{x}{a}\right)^2$

$$u = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \cos\frac{\delta_n}{a} x \frac{1}{\delta_n + \sin \delta_n \cos \delta_n}$$

$$\times \left(\left[U_s \sin\delta_n - 2(U_m - U_s)\left\{ \frac{\cos \delta_n}{\delta_n} - \frac{\sin \delta_n}{\delta_n^2} \right\} \right] \right.$$

$$\left. + \sin \delta_n K\left(\frac{\delta_n}{a}\right)^2 \int_{0}^{\theta} e^{K\left(\frac{\delta_n}{a}\right)^2 \xi} \varphi(\xi) d\xi \right) \cdots (25)$$

$$u_{av} = 2\sum e^{-K\left(\frac{\delta_n}{a}\right)^2 \theta} \frac{\sin \delta_n}{\delta_n(\delta_n + \sin \delta_n \cos \delta_n)}$$

$$\times \left(\left[U_s \sin\delta_n - 2(U_m - U_s)\left\{ \frac{\cos \delta_n}{\delta_n} - \frac{\sin \delta_n}{\delta_n^2} \right\} \right] \right.$$

$$\left. + \sin\delta_n K\left(\frac{\delta_n}{a}\right)^2 \int_{0}^{\theta} e^{K\left(\frac{\delta_n}{a}\right)^2 \xi} \varphi(\xi) d\xi \right) \cdots\cdots (26)$$

2. Experimental discussion

21. Experimental method[12]

The schema of the experimental apparatus is shown in Fig. 5, the dryer body was made of galvanized steel plate and was covered with insulating material of 5 cm thick.
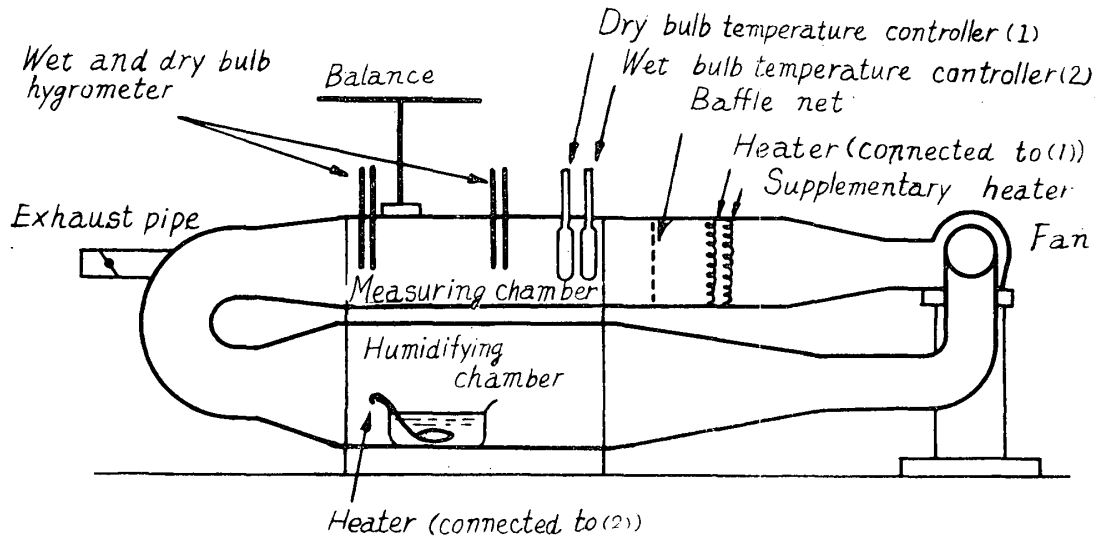

Fig. 5 Experimental apparatus

Heating system. The air was warmed by two unit of Nichrome wire, the one was used to warm the dryer quickly and to maintain a temperature slightly below the desired operating temperature and the other was connected to an automatic dry bulb temperature controller.

Humidifying stystem. Damper placed in the exhaust pipe and the heater placed in hot water bath were used, the heater was connected to an automatic wet bulb temperature controller and used to maintain the desired relative humidity.

Drying air velocity. The air circulation was regulated by the rotating speed of fan to maintain the desired air velocity and was evenly distributed by the baffle net installed ahead of the test section.

The weight of test pieces were directly measured by the balance placed on the dryer body.

Test pieces used in this study were cut from the same stock as 10×20 cm^2 area and 0.2, 0.5, 1.0, and 3.0 cm thickness for the transverse direction (edge grain or flat grain pieces) and 10×20 cm^2 area and 1.3, 2.2, 3.0 and 5.0 cm thickness for the longitudinal direction (end grain pieces) and 15×15 cm^2 or 20×20 cm^2 area for drying of veneer or plywood. Previous to the test, the side surfaces of pieces were covered with synthetic resin for dampproof and one part was soaked in water with the vacuum and pressure treatment and the other saturated in water vapour until they attained the fiber saturation

point. The latter particularly, had been kept to the operating temperature previous to the test in order to avoid the error caused by the temperature difference between wood and the drying air at the beginning of the experiment.

The test pieces for moisture determinations were timely taken out from the apparatus and the small piece (about 3×4 cm) was taken from each centre and cut into several thin
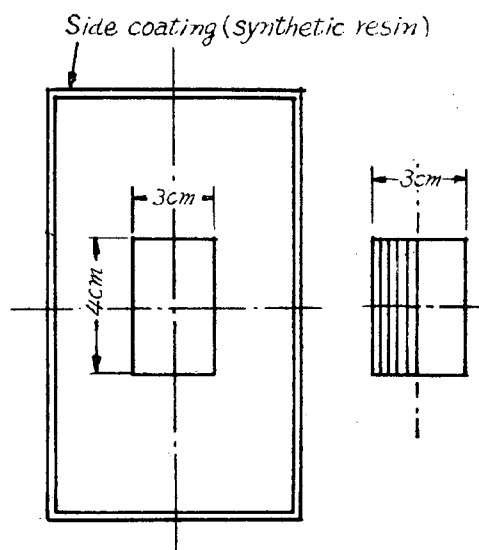
Side coating (synthetic resin)

Fig. 6 Test piece for moisture determination

layer for the moisture gradient (Fig. 6), on the same time, for the purpose of check, the distribution was measured by the electric moisture-meter. In case of need, the temperature gradient was measured by the thermocouple.

22. Drying of timber[12]

221. Drying in the range of high moisture content

The test pieces of *Thujopsis* (HIBA) whose initial moisture distribution was approximately uniform, were dried under the steady air condition of 55°C, 40% and 0.4-0.5 m/s.

The relation between the drying rate and the moisture content were the most typical as shown in Fig. 7. Obviously, in the timber of 0.2 and 0.5 cm thick, the three stages of drying, that is, the constant rate zone, the first and second zone of falling rate appeared, but with increase of thickness the former two disappeared gradually and in the timber of 3 cm thick only the second zone took place from the beginning of the drying. This phenomenon, as HAWLEY[3] had pointed out, shows the fact that the movement of free water is active only in the confined distance and is explained by the temperature-
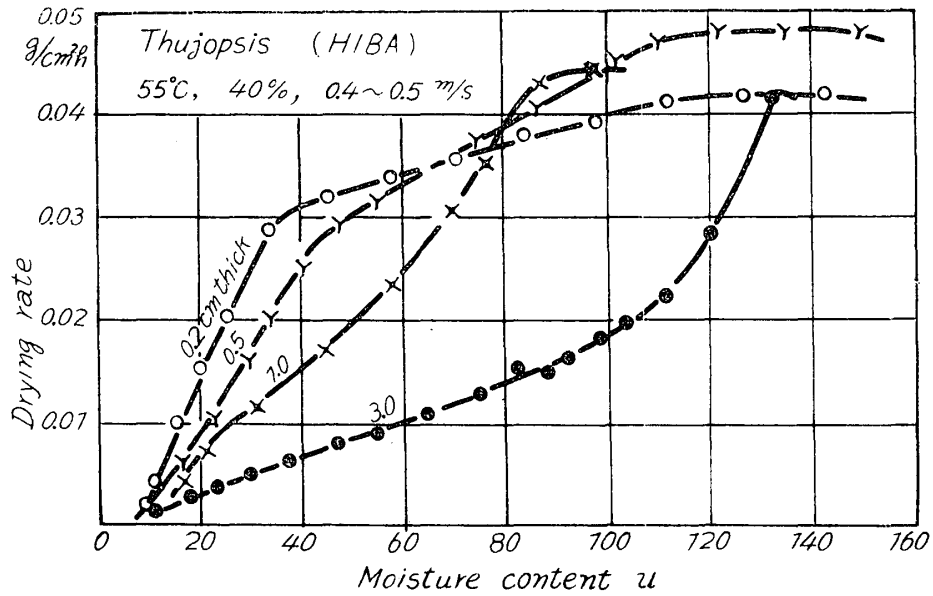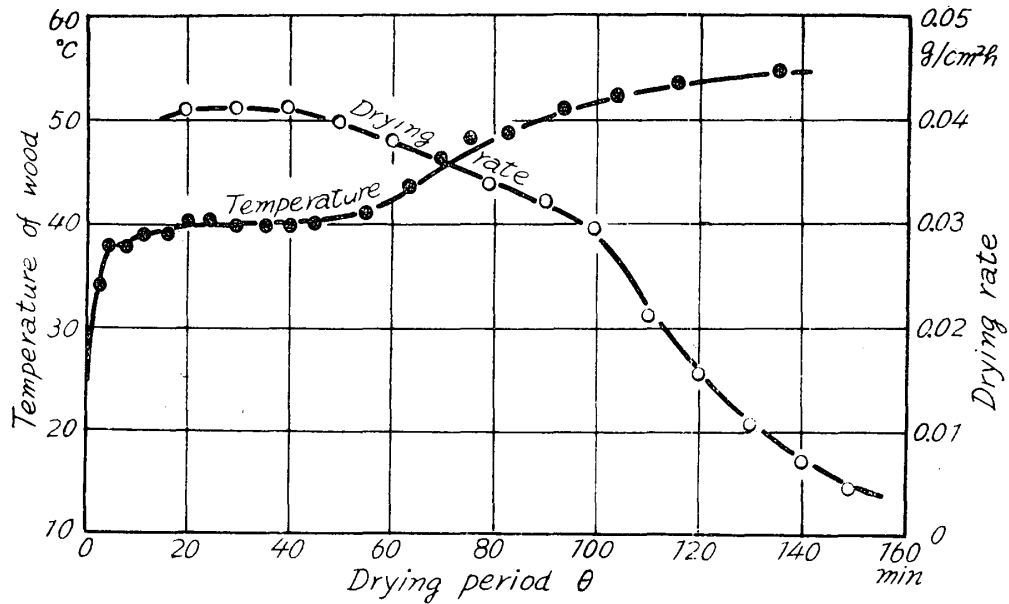
Fig. 7 Drying rate of *Thujopsis* (HIBA)

Fig. 8 Drying and temperature behavior of *Thujopsis* (HIBA. 0,2 cm thick)

drying rate diagram in Fig. 8 and 9, that is, in the timber of 0.2 cm thick, as KEYLWERTH [5] reported on drying of veneer, the temperature of wood during the constant drying rate keeps the wet bulb temperature of the drying air and the constant surface evaporation takes place during this period. In the timber of 3 cm thick, however, this correlation between the drying rate and the temperature of wood disappears. This shows that the movement of free water from the interior to the surface is not so easy as in veneer, and the temperature rising process indicated by KEYLWERTH for timber may
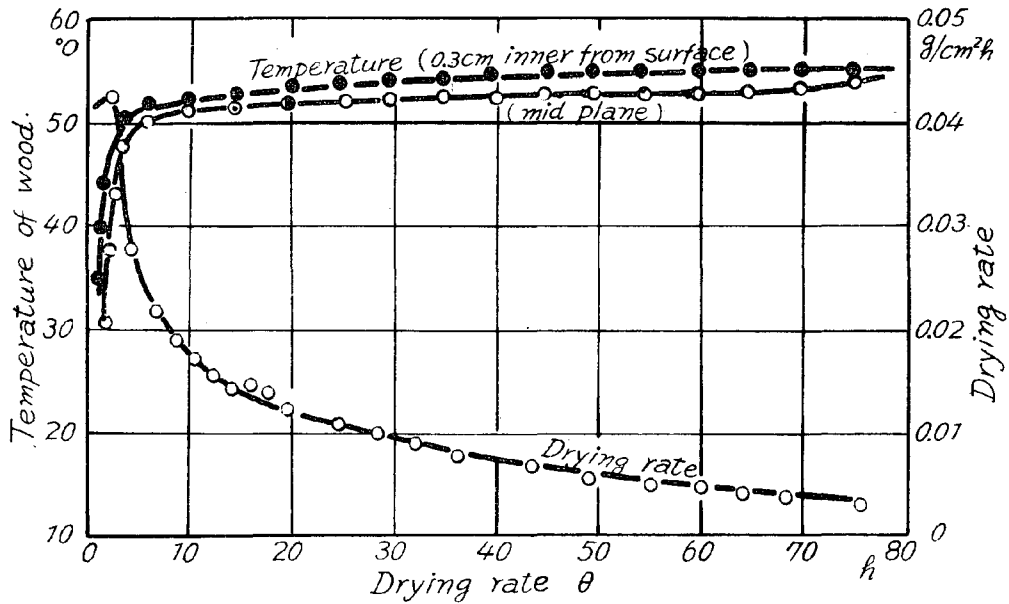
Fig. 9   Drying and temperature behavior of *Thujopsis* HIBA. 3.0 cm thick)
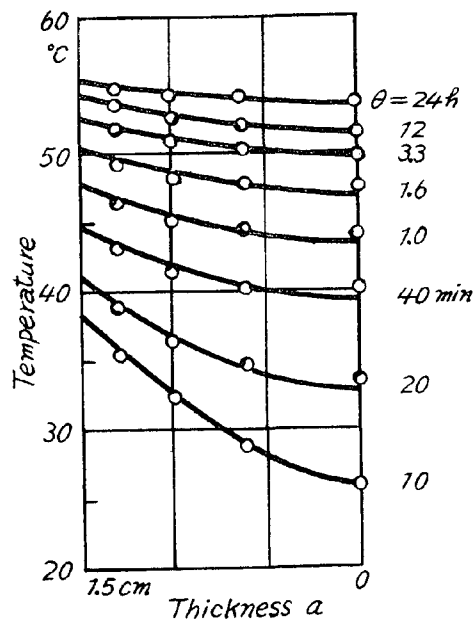

Fig. 10   Temperature gradient in *Thujopsis* (HIBA, 3.0 cm thick)

not occur.   The temperature gradient of *Thujopsis* (HIBA) of 3 cm thick is shown in Fig. 10.

As obvious from the above mentioned result, the mechanism of the drying varies with thickness of wood, and so we can not apply the differential equation in all range from the high moisture content to hygroscopic range and moreover to make it applicable, the plots of v_{av}/V_0 us. $K\theta/a^2$ i. e. θ/a^2 must be all straight lines on a semi-log scale as shown in Fig. 3. In Fig. 11 v_{av}/V_0 is plotted against θ/a^2 for *Cryptomeria* (SUGI) and
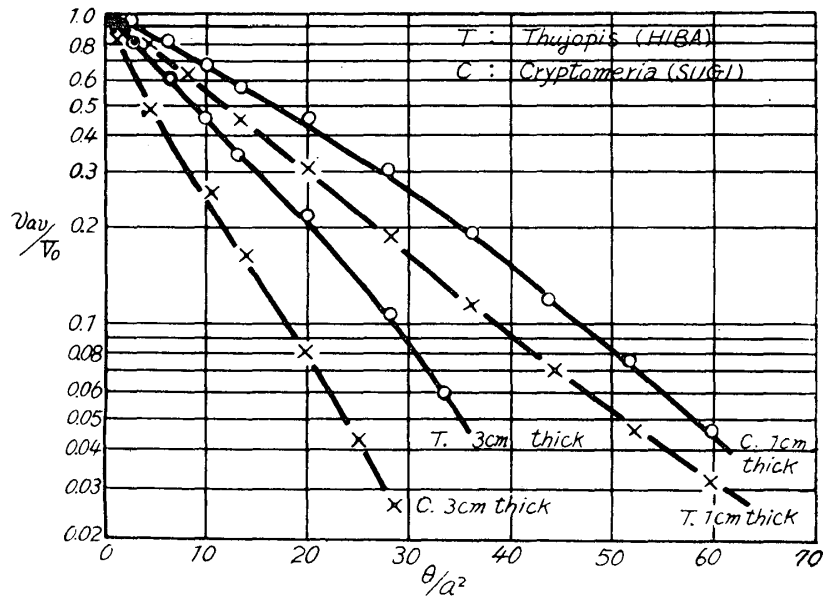
Fig. 11 $v_{av}/V_0 - \theta/a^2$ diagram

Thujopsis (HIBA) of 1 and 3 cm thick, respectively.   The results have not so a good agreement with the differential equation as that of SHERWOOD and KAMEI, and it seems that the differential equation is not applicable in general, to say nothing of high moisture range, even in the case where the second zone of falling rate appears from the beginning of the drying.

222.   Drying in hygroscopic range

222,1   In the transverse direction

222,11   Determinations of the drying diffusion constant *K*

In the case where drying begins from the fiber saturation point, there is the great possibility to apply the differential equation.   The present author used the rectangular slab of *Chamaecyparis* (SAWARA, $r_0 = 0.4$ and HINOKI, $r_0 = 0.41$), *Fraxinus* (TAMO, $r_0 = 0.56$), and *Prunus* (SAWARA, $r_0 = 0.63$) in this study.   As shown in Fig. 12, the relation between v_{av}/V_0 and θ/a^2 agrees well with the differential equation diagram in the range from the fiber saturation point to 10% moisture content, but below 10% moisture content, as KRÖLL[10] stated, the molecular stream may take place instead of the diffusion and no differential equation can be applicable.

As the value of h i. e. ha has never been determined hitherto, the value of K can not be directly obtained here.   The present author has determined ha and K by the
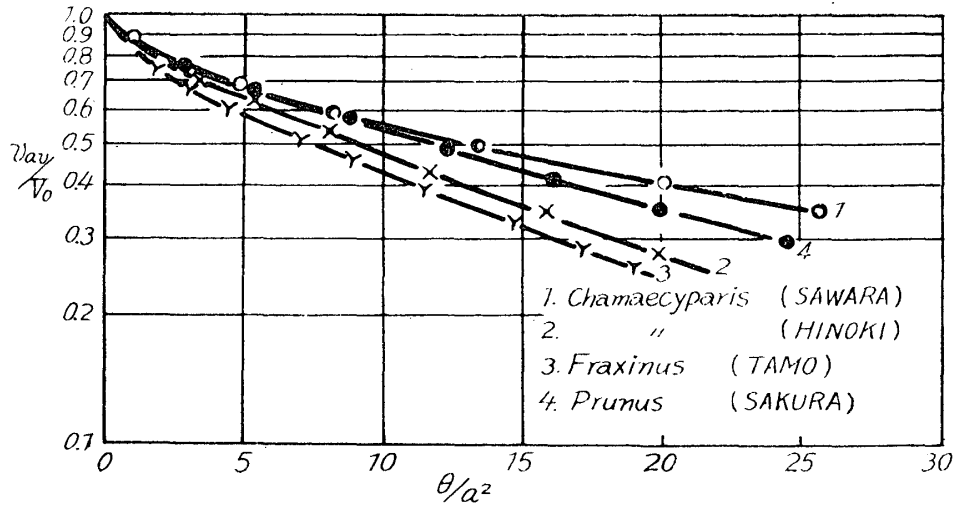
Fig. 12 $v_{av}/V_0-\theta/a^2$ diagram in hygroscopic range

following manner.

As shown in Table 1, K and K_0 for various ha were calculated from the drying data and as the most probable value of ha, the one for which the coefficient of variation of K_0 was minimum was determined (ref. Table 2). On the other hand the moisture distribution was measured and the results were shown as an approximate curve in Fig. 13, from which the moisture content at the wood surface and the mid-plane can be calculated.

Table 1 *Fraxinus* (TAMO) 3 cm thickness

time θ	moisture content u_{av}	v_{av}/V_0	θ/a^2	$ha = \infty$					$ha = 20$			
				$K\theta/a^2$	K	K_0 *	$K_{av}-K_0$	$(K_{av}-K_0)^2 \times 10^{-4}$	$K\theta/a^2$	K	K_0	$K_{av}-K_0$
0	31.9											
0.3	30.0	0.925	0.222	0.004	0.018	0.0158	0.0059	0.348	0.004	0.018	0.0158	0.0092
2.0	27.9	0.844	0.888	0.020	0.0224	0.0198	0.0019	0.0361	0.020	0.0224	0.0198	0.0052
4.0	26.0	0.770	1.776	0.043	0.0242	0.0216	0.0001	0.0001	0.046	0.0259	0.0232	0.0018
7.0	23.9	0.687	3.12	0.072	0.0230	0.0208	0.0009	0.0081	0.092	0.0295	0.0266	0.0016
10.0	22.0	0.613	4.45	0.116	0.0260	0.0236	0.0019	0.0361	0.143	0.0321	0.0292	0.0042
16.0	19.8	0.527	7.11	0.173	0.0243	0.0222	0.0005	0.0025	0.211	0.0296	0.0270	0.002
20.0	18.0	0.456	8.90	0.233	0.0252	0.0242	0.0025	0.0625	0.275	0.0309	0.0284	0.0034
26.0	16.5	0.398	11.57	0.291	0.0252	0.0234	0.0017	0.0289	0.346	0.0300	0.0279	0.0029
33.0	14.8	0.332	14.7	0.358	0.0244	0.0228	0.0011	0.0121	0.414	0.0282	0.0264	0.0014
43.0	13.0	0.262	19.1	0.458	0.0240	0.0226	0.0009	0.0081	0.520	0.0272	0.0256	0.0006

**

$K_{av}=0.0217$ $C.V.=0.107$ $K_{av}=0.0250$ $C.V.=0.161$

	ha = 10					ha = 5						
$(K_{av}-K_0)^2$ ×10⁻⁴	$K\theta/a^2$	K	K_0	$K_{av}-K_0$	$(K_{av}-K_0)^2$ ×10⁻⁴	$K\theta/a^2$	K	K_0	$K_{av}-K_0$	$(K_{av}-K_0)^2$ ×10⁻⁴	$K\theta/a^2$	K
0.846	0.008	0.036	0.0316	0.0002	0.0004	0.019	0.0855	0.0750	0.0236	5.57	0.0390	0.176
0.270	0.029	0.0326	0.0288	0.003	0.0036	0.059	0.0665	0.0590	0.0076	0.578	0.114	0.128
0.0324	0.064	0.036	0.0322	0.0004	0.0016	0.115	0.0648	0.0579	0.0065	0.422	0.194	0.109
0.0256	0.118	0.0378	0.0340	0.0022	0.0484	0.190	0.0610	0.0550	0.0036	0.130	0.293	0.0940
0.176	0.174	0.0392	0.0356	0.0038	0.144	0.259	0.0584	0.0530	0.0016	0.0256	0.388	0.0871
0.04	0.251	0.0352	0.0322	0.0004	0.0016	0.356	0.0500	0.0457	0.0057	0.325	0.520	0.0731
0.116	0.319	0.0358	0.0330	0.0012	0.0144	0.444	0.0500	0.0461	0.0053	0.281	0.644	0.0724
0.0841	0.387	0.0335	0.0311	0.0007	0.0049	0.533	0.0460	0.0427	0.0087	0.757	0.760	0.0659
0.0196	0.471	0.0320	0.0299	0.0019	0.0361	0.644	0.0438	0.0402	0.0112	1.25	0.910	0.0620
0.0036	0.598	0.0313	0.0296	0.0022	0.0484	0.794	0.0415	0.0391	0.0123	1.51	1.11	0.0580

$K_{av}=0.0318 \quad C.V.=0.0548$ $K_{av}=0.0514 \quad C.V.=0.265$

	ha = 2			ha = 1					ha = 0.5				
K_0	$K_{av}-K_0$	$(K_{av}-K_0)^2$ ×10⁻⁴	$K\theta/a^2$	K	K_0	$K_{av}-K_0$	$(K_{av}-K_0)^2$ ×10⁻⁴	$K\theta/a^2$	K	K_0	$K_{av}-K_0$	$(K_{av}-K_0)^2$ ×10⁻⁴	
0.154	0.0706	4.98	0.085	0.384	0.337	0.139	193	0.215	0.968	0.848	0.549	301	
0.113	0.0296	8.76	0.210	0.237	0.209	0.011	1.21	0.425	0.479	0.423	0.124	154	
0.0976	0.014	1.96	0.330	0.186	0.165	0.033	10.9	0.638	0.360	0.321	0.022	4.84	
0.0844	0.0008	0.0064	0.485	0.155	0.139	0.059	34.8	0.920	0.295	0.265	0.034	11.6	
0.0788	0.0048	0.23	0.631	0.142	0.129	0.069	34.8	1.175	0.264	0.239	0.06	36	
0.0667	0.0169	2.86	0.842	0.118	0.108	0.09	81	1.554	0.218	0.199	0.100	100	
0.0668	0.0168	2.82	1.04	0.117	0.108	0.09	81	1.875	0.210	0.193	0.106	112	
0.0612	0.0224	5.02	1.326	0.115	0.107	0.091	82.8	2.200	0.190	0.176	0.123	151	
0.0580	0.0256	6.55	1.460	0.0994	0.0928	0.1052	111	2.600	0.177	0.165	0.134	180	
0.0547	0.0289	8.35	1.775	0.0930	0.0878	0.12	144	3.240	0.170	0.160	0.139	193	

$K_{av}=0.0836 \quad C.V.=0.351$ $K_{av}=0.198 \quad C.V.=0.463$ $K_{av}=0.299 \quad C.V.=0.501$

* $K = K_0(1+0.84 r_0 u)$

**   coefficient of variation of K_0

Table 2 The values of ha determinated from drying process and the
moisture gradient (Transverse direction)

Wood species	ha		$K_{ha=10}$	$K_{ha=2.3}$	K_{av}	ha for K_{av}
	at C. V. minimum*	from eq. (27)				
Chamaecyparis (SAWARA)	10	2.3	0.02	0.045	0.033	3.5
" (HINOI)	2~10	6	0.034			
Fraxinus (TAMO)	10	12	0.032			
Prunus (SAKURA)	10	11	0.020			

* C.V. : coefficient of variation of K_2

Now, take the first term of equation (19) for approximate using, v_s and v_m is given as

$$\frac{v_s}{V_0} = 2e^{-K\left(\frac{\delta_1}{a}\right)^2 \theta} \frac{\sin \delta_1 \cos \delta_1}{\delta_1 + \sin \delta_1 \cos \delta_1}$$

$$\frac{v_m}{V_0} = 2e^{-K\left(\frac{\delta_1}{a}\right)^2 \theta} \frac{\sin \delta_1}{\delta_1 + \sin \delta_1 \cos \delta_1}$$

therefore $\quad \frac{v_s}{v_m} = \cos \delta_1 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$ (27)
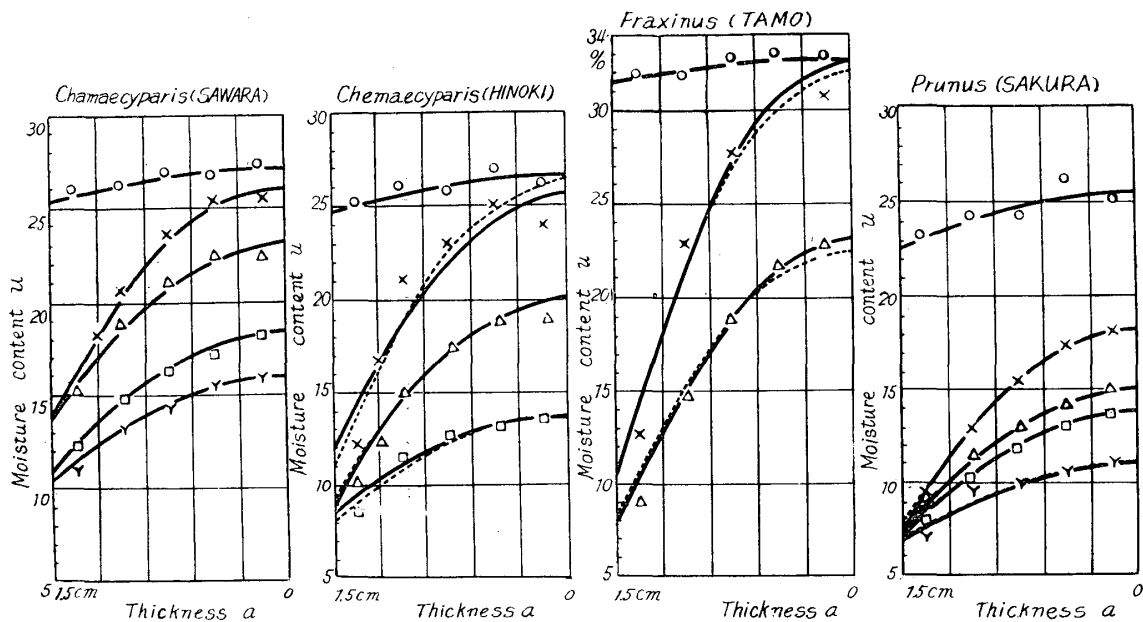
Fig. 13 Gradient of moisture content in transverse direction
(Drying conditions : 55°, 40%, 0.4--0.5m/s)

Using v_s and v_m in Fig . 13, $\cos \delta$, i. e. ha were determined by equation (27). The values of ha thus obtained, as shown in Table 2, have a good agreement with previous one excepting *Chamaecyparis* (SAWARA), and may seem to vary with wood species as will be observed later in the longitudinal direction but the details could not be clarified in here.

Now, using $k = \dfrac{r_0}{100} \dfrac{\dfrac{\partial}{\partial \theta} \int u\, dx}{\dfrac{du}{dx}}$ by Egner's method the values of K_E were obtained

graphycaliy from the moisture gradient as follows (ref . Fig . 14)
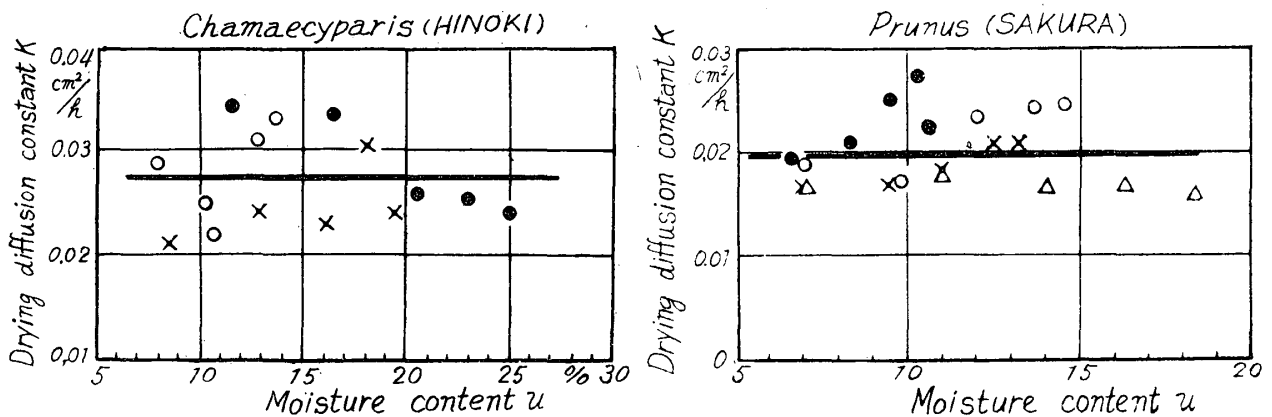
Fig. 14 Relation between the drying diffusion constant K calculated
by Egner's k and the moisture content

for   *Chamaecyparis* (SAWARA) $K_E = 0.034$ cm²/h

//   //   (HINOKI)   //   0.027

//   *Fraxinus*   (TAMO)   //   0.032

//   *Prunus*   (SAKURA)   //   0.0197

Somewhat smaller as K_E is for *Chamaecyparis* (HINOKI), K_E have a good agreement with K_0 for *Fraxinus* (TAMO) and *Prunus* (SAKURA) and with the mean value of K_0 at $ha = 2.3$ and 10 for *Chamaecyparis* (SAWARA) (ref. Table 2), therefore, according to these results the drying diffusion constant is regarded as a constant independently of the moisture content. The dotted line in Fig. 13 is the one calculated by $K = 0.034$, 0.032, and 0.020 for *Chamaecyparis* (HINOKI), *Fraxinus*, and *Prunus* respectively.

222,12 Determinations of the coefficient of the surface evaporation α

From equation (3) the coefficient of surface evaporation is given as

$$\alpha = \frac{dW}{d\theta\, A\, v_s}$$

Then, by the diagram of dimensionless equation (12) a can be obtained as in Table 3, as

Table 3 Transverse coefficient of surface evaporation α
(*Fraxinus*, 3 cm thick, $K_0 = 0.0318$, $V_0 = 0.256$, $G_{ab} = 298$)

θ	θ/a^2	$K\theta/a^2$	Σ of eq. (12)	$\dfrac{dW}{d\theta}$	A	$\dfrac{dW}{d\theta A}$	v_s	α
0.5	0.222	0.00706	0.0504	3.84	401	0.00957	0.119	0.0804
1	0.444	0.0141	0.0456	3.48	399	0.00872	0.0969	0.0900
2	0.888	0.0282	0.0388	2.96	398	0.00744	0.0730	0.102
5	2.22	0.0706	0.0280	2.14	394	0.00543	0.0496	0.109
10	4.44	0.141	0.0204	1.56	389	0.00401	0.0366	0.110
20	8.88	0.282	0.0153	1.17	385	0.00304	0.0253	0.120
30	13.32	0.424	0.0106	0.809	382	0.00212	0.0188	0.113
40	17.79	0.566	0.0080	0.610	379	0.00161	0.0141	0.114

$$\alpha_{av} = 0.105$$

obvious from this table the values of a are nearly constant independently of the moisture content excepting the short period at the beginning of drying. Calculating ha from α_{av} $ha = \alpha_{av} a/k = \alpha_{av} a/Kr_0 = 0.105 \cdot 1.5/0.0318 \cdot 0.56 \doteqdot 9$, this value of ha is nearly agreeable with previously determined ha ($=10$).

From the results of 222, 11, 222, 12, the drying process in hygroscopic range coincides well with the differential equation from the view of the drying rate and the moisture gradient occured in practice. Consequently, even in hygroscopic range the surface moisture content does not reach the equilibrium moisture content u_{eq} given by the drying air and the moisture movement is occured by the correlation between the surface evaporation based on this moisture difference and the internal diffusion. So that the drying diffusion constant K is to say nothing of the temperature, directly influenced by the relative humidity and the velocity of the drying air.

Many results hitherto gave $v_s = 0$ i. e. $u_s = u_{eq}$ in hygroscopic range, in these cases, the thinner the timber is, the steeper the moisture gradient becomes for the same u_m and this is inconsistent with the fact that the thinner the timber is the easier the drying becomes, on the contrary definite value of ha gives above fact the appropriateness. Using $K = 0.034$, 0.032, and 0.020 for *Chamaecyparis* (HINOKI), *Fraxinus* (TAMO), and *Prunus* (SAKURA) respectively, the calculated moisture amount based on equation (11) and the measured values are shown in Fig. 15.
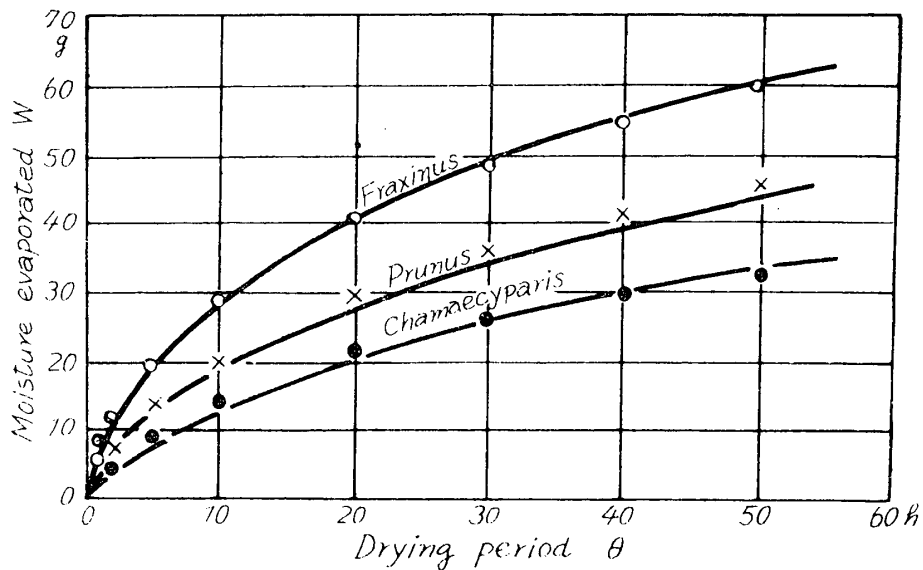
Fig. 15 Evaporatad moisture in drying

222,13 Relation of K and α to the thickness of timber

The similar experiments were done on *Thujopsis* (HIBA) and *Cryptomeria* (SUGI) of 3, 1, 0.5, and 0.2 cm thick from the high moisture content. As the differential equation is applicable after the moisture content of midplane reached the fiber saturation point, determining the time by means of V_{av} for $U_m = 0.3$ and putting $ha = 6$ for 3 cm thick timber (ref. Table 2), consequently $ha = 2$, 1, and 0.4 for 1, 0.5, and 0.2 cm thick respectively, the values of K were obtained as shown in Fig. 16. Obviously in timber
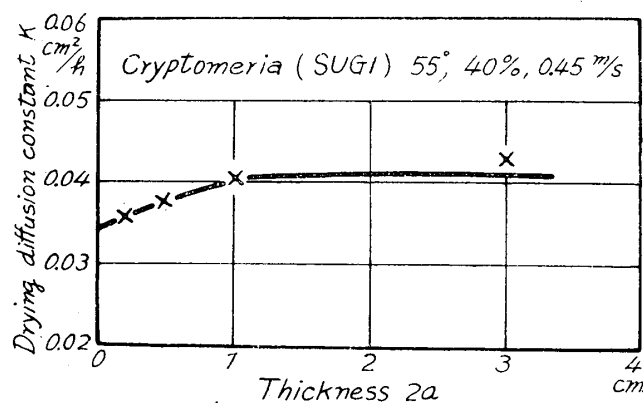
Fig. 16 Relation of transverse drying diffusion constant to the thickness of wood

of below 1 cm thick for which 3 stages of the drying rate appeared the value of K decreases a little with decreasing of thickness. The same inclination is recognized in plate of below 4 cm thick in the longitudinal direction, too (ref. Fig. 24). In both cases this relation between ha and K is shown as Fig. 17 in general. If the drying is controlled by
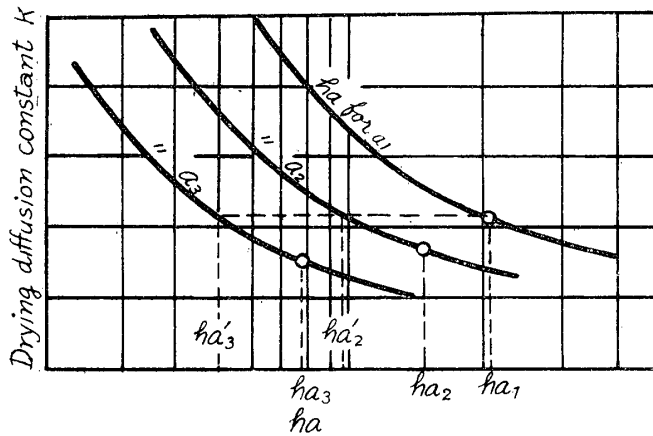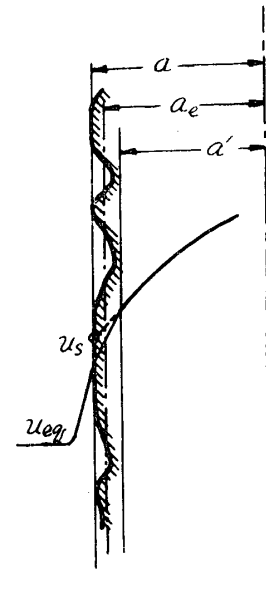
Fig. 17

Fig. 18

the differential equation the values of K must be independently of thickness, that is, smaller value a' must be used instead of a. Now, in the porous material as wood, the effective surface a_e must be somewhat inner than a (ref. Fig. 18). As there are hardly reported on the relation between a_e and a', it may be concluded at least that a_e is connected with dimension of cell. The thickness of aa' obtained from the experiment are about 0.3 - 0.8 mm in radial direction and 2 - 3.5 mm in fiber diretion (the former is as 10 - 25 times as diameter of tracheid and the latter nearly equal to the length of tracheid). From this result, the present author assumes the surface phenomenon similar to the fluid film which may occur in the surface of wood with above order of dimension. The existence of this anomalous thin layer is confirmed a certain extent by the fact that when the wet timber which seems to be pretty dried at the first glance is planed the new wet surface appears again and the fact that when the well dried timber absorbs moisture, after reaching nearly the equilibrium moisture content it shows the remarkable absorption again when it is planed, namely, hygroscopically anomalous thin layer exists at the surface of wood. It is easily imagined that the effect of this layer on K disappears gradually with increase of wood thickness. As to this phenomenon, however, the author can not conclude without more detailed experiments and this may be one of the most interested problems on drying of wood in future.

Now, in wood of below 1 cm thick the apparent value of K varies with the thickness and decreases with the ratio of about 16.7 % / cm to the value of K of 1 cm thick timber

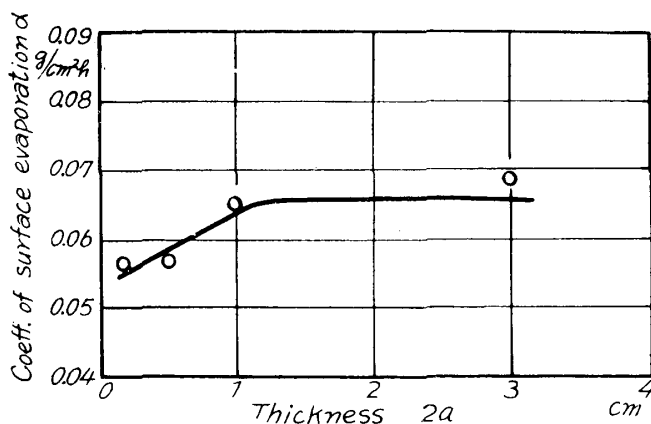and as obvious from Fig . 19 and 24, this ratio is the same as in the coefficient of surface

Fig. 19 Relation of transverse coefficient of
surface evaporation to the thickness of wood

evaporation and in the longitudinal direction below 4 cm thickness. Therefore at 55°C, 40% relative humidity and 0.4 — 0.5 m/s

$$K_2 = K_1 \{1 + 0.167(2a_2 - 1)\} \quad \cdots\cdots\cdots (28)$$

where K_1 is the drying diffusion constant of 1 cm thick timber. The thicker the timber is, the more negligible the effect of anomalous thin layer on K becomes and K shows almost constant value for the timber of over 1 cm thick.

For the coefficient of the surface evaporation α also, as obvious from 222,12, the same relation is given

$$\alpha_2 = \alpha_1 \{1 + 0.167(2a_2 - 1)\} \quad \cdots\cdots\cdots (29)$$

where α_1 is the value of 1 cm thick timber.

As for the relation between the drying time and the thickness under the same drying condition there have been $\dfrac{\theta_2}{\theta_1} = \left(\dfrac{a_2}{a_1}\right)^n$, TUOMALA and EGNER [?] gave $n = 1.7$ and MOLL and KOLLMANN $n = 1.5$.

As obvious from equation (10), (16) and etc. (use the first term approximately), for different thickness $2\,a_1$ and $2\,a_2$

$$K_1\left(\frac{\partial_{11}}{a_1}\right)^2 \theta_1 = K_2\left(\frac{\partial_{12}}{a_2}\right)^2 \theta_2$$

$$\frac{\theta_2}{\theta_1} = \frac{K_1}{K_2}\left(\frac{\partial_{11}}{\partial_{12}}\right)^2\left(\frac{a_2}{a_1}\right)^2 = \left(\frac{a_2}{a_1}\right)^n \quad \cdots\cdots\cdots (30)$$

therefore, $n = 2$ can exist only in the case where $\partial_{11} = \partial_{12}$, that is, $2\,a_1$ and $2\,a_2$ are quite large, and in the practical range of thickness n is somewhat smaller than 2 and below 1 cm n becomes more and more smaller by the decreasing of K. Fig. 20 shows the
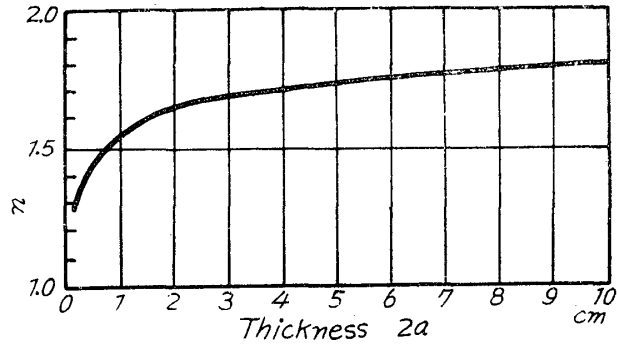

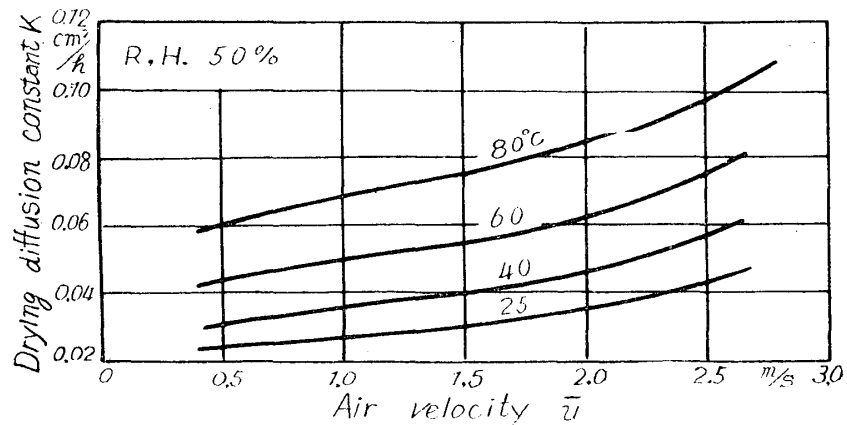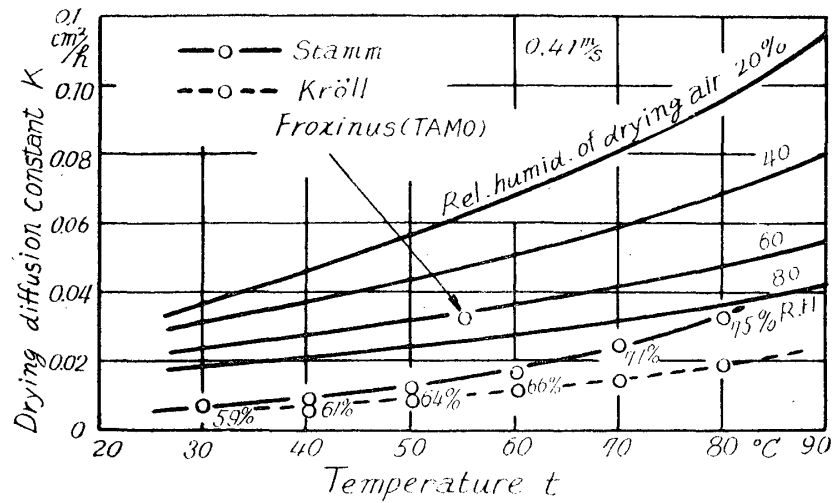Fig. 20 Values of exponent n of eq. (30), from 1 cm to each thickness

Fig. 21 Relation of transverse drying diffusion constant to the drying air conditions (*Fagus*, for timber of over 1 cm thick)

value of n calculated from 1 cm thickness to different thickness. The figure shows that n is 1.3 – 1.8 in the range of 0.2 – 10 cm thick and the value of TUOMOLA and MOLL are all contained in above equation.

222,14 Relation of K and α to the drying air conditions

Fig. 21 and 22 show the relations of K and α to the various drying conditions for timber of over 1 cm thick which were converted by equation (28) and (29) from the data of veneer of *Fagus* (BUNA, $2a = 1.5$ mm) dried at various, steady conditions.
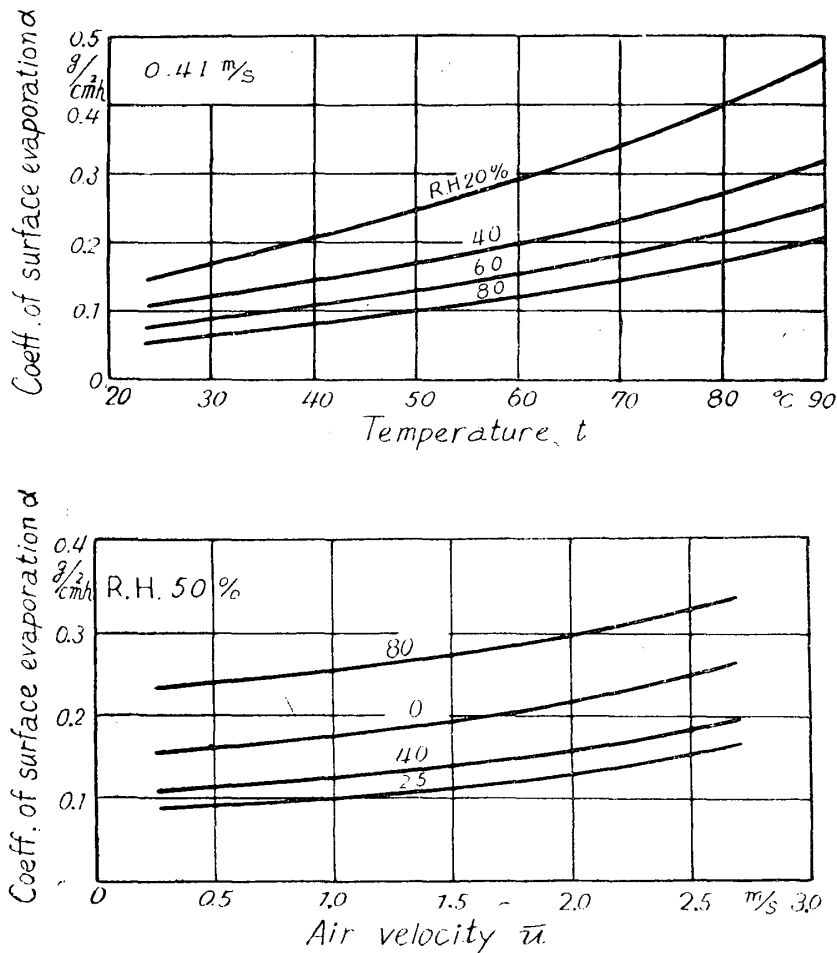

Fig. 22 Relation of transverse coefficient of surface
evaporation to the drying air conditions
(*Fagus*, for timber of over 1 cm thick)

Namely, the drying diffusion constant has the same inclination as the diffusion coefficient which increases generally with increase of the absolute temperature and is in inverse proportion to pressure, and as for the air velocity $\bar{u}$ its influence is slight and K seems to increase in proportion to $\bar{u}^{0.3 \sim 0.5}$ in range of $\bar{u} = 0.5 - 2.0$ m/s.

Thus, the values of K obtained from the definite $h\alpha$ is naturally higher than those which

many researchers obtained under the condition $ha = \infty$, and so the both may not be compared, however, for reference, calculated values of STAMM and KRÖLL were converted into those of the same specific gravity and ploted in Figure.

222,15 Relation of K to the specific gravity

The relation between specific gravity and K converted by equation (28) from the drying data of veneer to the plate of over 1 cm thick are shown later in Fig. 36. Drying diffusion constant decreases linearly in inverse proportion to the increase of specific gravity, but the difference is slight.

222,2. In longitudinal direction[5]

222,21 Drying diffusion constant K_t

The drying data of Chamaecyparis (SAWARA and HINOKI), Fagus (BUNA), and Fraxinus (TAMO), (each initial moisture content is about 50%) give a good agreement with the dimensionless diagram of Fig. 3 only in hygroscopic range (the moisture content 30 – 10%) as similar as in 222,1 and probable ha obtained from the rate of the drying and the moisture gradient shown in Fig. 23 are given in Table 4. According to these results, it is concluded also in longitudinal direction that the differential equation can be applied in hygroscopic range and the surface evaporation based on the moisture difference $(u_s - u_{eq})$ occupies a certain extent. From Table 4 the present author adopted hereafter the value of ha determined from the minimum coefficient of variation of K_0 and showed K_t corresponded to these ha in Table.
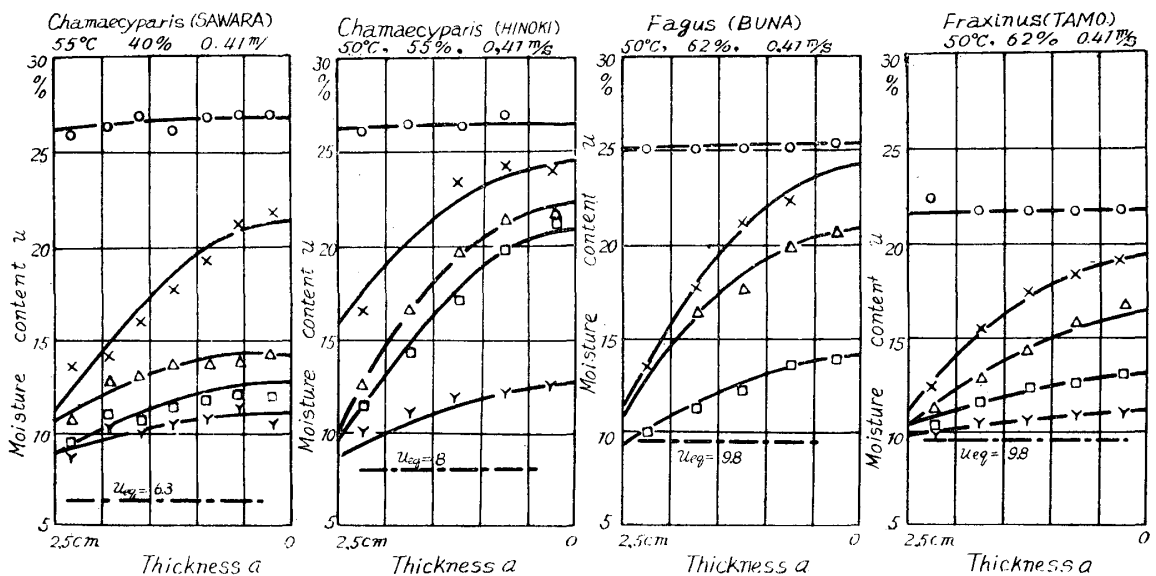

Fig. 23　Gradient of moisture content in longitudinal direction

Table 4 The values of *ha* determined from drying process and the moisture content (Longitudinal direction)

Wood species	*ha*		K_0	Remarks
	at *C.V.* minimum	from eq. (27)		
Chamaecyparis (SAWARA)	2	2.1	0.661	Drying condition 55°, 40%, 0.41m/s
// (HINOKI)	2~5	6	0.457	50, 55, *//*
Fagus (BUNA)	5	11	0.257	50, 62, *//*
Fraxinus (TAMO)	5	7.2	0.257	50, 62, *//*

222,22 Relation of K_l and a_l to the thickness of timber

Test pieces of *Chamaecyparis* (HINOKI) of 5, 3, 2.2, and 1.3 cm thick were dried from about 50% to 10% moisture content. The value of K_l was calculated by equation (18) from the drying data after the moisture content of mid-plane reached 30%, K_l decreases with decreasing of thickness in plate of below 4 cm thick (ref. Fig. 24) and the following equation similar to equation (28) is obtained at 50°C, 55% relative humidity and 0.41 m/s.
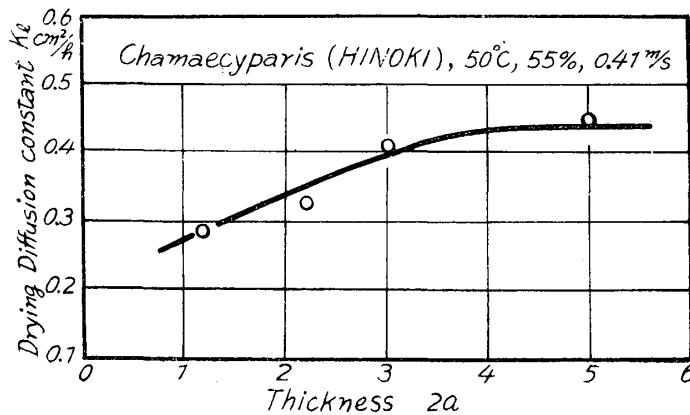

Fig. 24 Relation of longitudinal drying diffusion constant to the thickness of wood

$$K_2 = K_1 \{1 + 0.167(2a_2 - 1)\} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (31)$$

where K_1 is the drying diffusion constant of 1 cm thick plate. For the coefficient of the surface evaporation a_l, similarly

$$a_2 = a_1 \{1 + 0.167 (2a_2 - 1)\} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (32)$$

where a_1 is a_2 of 1 cm thick plate.

222,23 Relation of K_l and a_l to the drying air conditions

To obtain the relation of K_l and a_l to the drying conditions, test pieces of *Fraxinus* (Tamo, thickness 1.3 cm, the initial moisture content 50-60%) were dried. The values of K_l and a_l obtained in hygroscopic range by equation (18) increase, as the same as in transverse direction, with increasing of absolute temperature and are inverse proportional to the relative humidity (Fig. 25, 26), thus
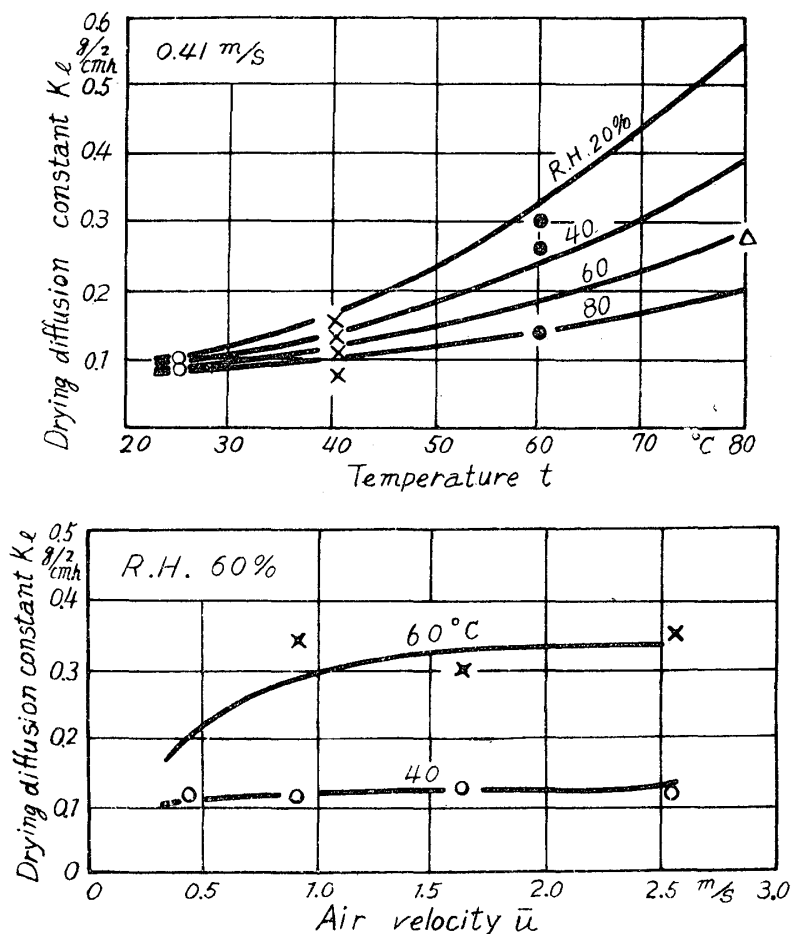

Fig. 25   Relation of longitudinal drying diffusion constant to the drying air conditions (*Fraximus*, for timber of 1.3 cm thick)

$$K_l = n_l \left(\frac{273+t}{273} \right)^{m_l} \left(\frac{1}{H} \right) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (33)$$

where n_l and m_l are the experimental coefficient, H is the relative humidity, and $n_l = 0.876 - 4.0$, $m_l = 5.4 - 9.95$ in the range of the experiment (air temperature 20 - 90°C, relative humidity 20 - 80%).

The above relation is all the same to a_l

$$a_l = n'_l \left(\frac{273+t}{273} \right)^{m'_l} \left(\frac{1}{H} \right) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (34)$$

where $n'_t = 0.85 - 4.0$, $m'_t = 4.4 - 8.9$.

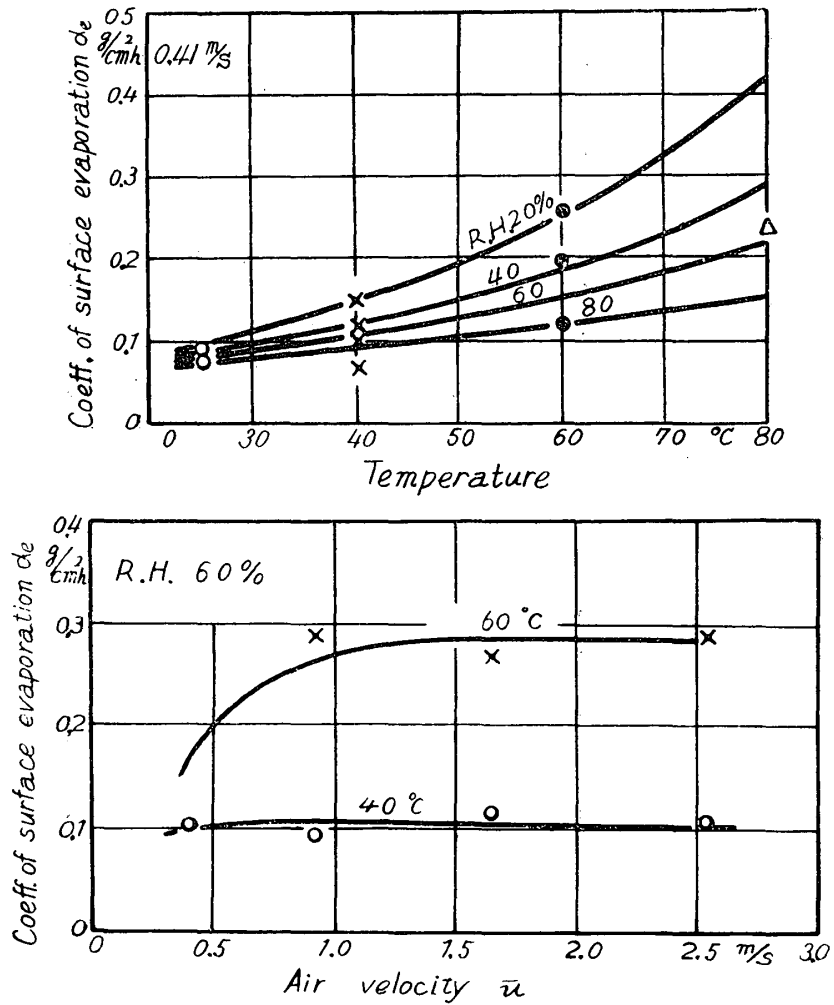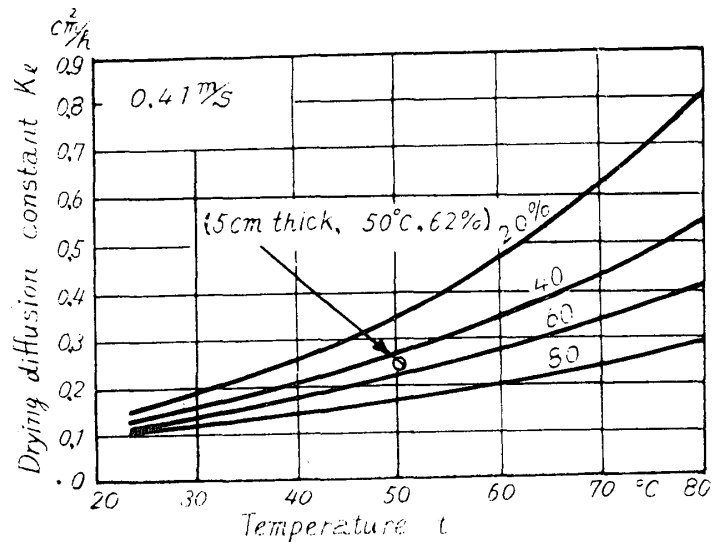Fig. 27, 28 show the converted value for plate of over 4 cm thick.

Fig. 26 Relation of longitudinal coefficient of surface evaporation to the drying air conditions (*Fraxiuus*, for timber of 1.3 cm thick)
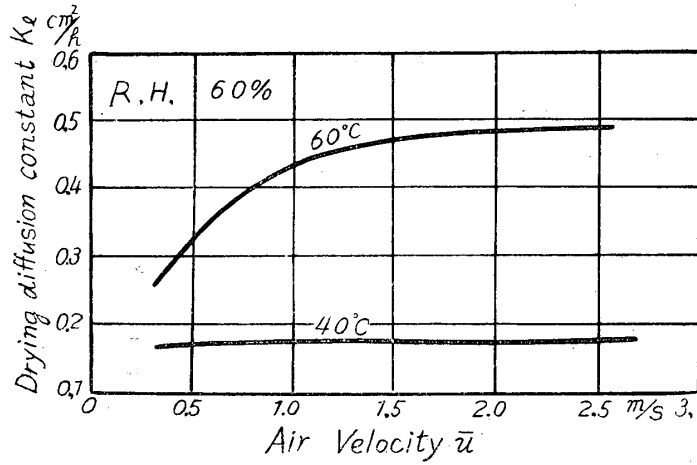
Fig. 27 Relation of longitudinal drying diffusion constant to the drying
air conditions (*Fraxinus*, for timber of over 4 cm thick)
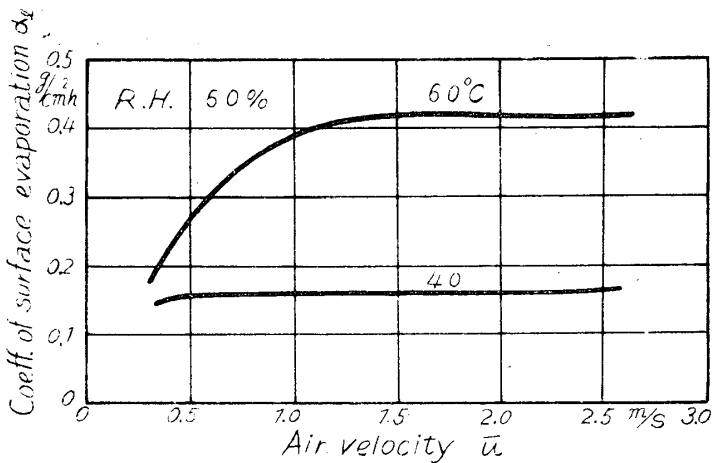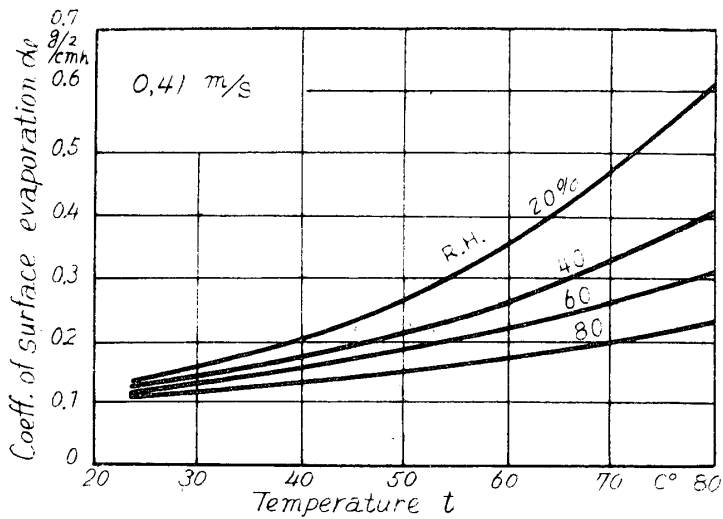

Fig. 28 Relation of longitudinal coefficient of surface evaporation to the
drying air conditions (*Fraxinus*, for timber of over 4 cm thick)

23. Drying of veneer[13]

231 Drying in the range of high moisture content

231,1 Relation of constant rate of drying C to the drying air conditions

Test pieces of *Chamaecyparis* (HINOKI, $2a = 1.6$mm, $r_0 = 0.34$), *Tilia* (SINA, $2a = 1.39$, $r_0 = 0.43$), *Shorea* (Lauaan $2a = 1.24$, $r_0 = 0.48$), *Fagus* (BUNA $2a = 1.54$, $r_0 = 0.56$), and *Betula* (KABA $2a = 1.40$, $r_0 = 0.62$; $2a = 1.34$, $r_0 = 0.67$), (each initial moisture content is about $50-60\%$) were used in this study. As for the drying process of veneer, as already explained in Fig. 7 and 8 in 221, the constant rate zone and the first zone of falling rate take place untill near the fiber saturation point, however, the gradient of the latter is so gentle that it may be considered as a constant rate in practice.

In drying of vereer, PECK[19] and KEYLWERTH[9] established the equation $\dfrac{du}{d\theta} = -cu''$ in all moisture content range (c, u : experimental coefficient) but the results of the present author did not agree with their results. So hereafter the present author will discuss on the range of high moisture content and on hygroscopic range, respectively.

Now, in Fig. 29 an example of drying process under various drying conditions are shown. From these restlts

(1) The constant rate of drying ($\%$/min) takes place until near the fiber saturation point

(2) Constant rate of drying varies with wood species and drying conditions.

Fig. 30 shows the relation between the drying conditions and the average constant drying rate C from initial moisture content to the fiber saturation point for *Fagus*. C, as similar as K, increases with increasing of temperature and decreases as the relative humidity increases and generally

$$C = n''\left(\frac{273+t}{273}\right)^{m''}\left(\frac{1}{H}\right) \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (35)$$

where n'' and m'' are experimental coefficient and $n'' = 16.5 - 22$, $m'' = 4.8 - 6.26$ in the experimented range.

These results are somewhat different from Tuomola's experimental result[6].

As for the relation between the coefficient of heat transfer h' and the mean air velocity $\bar{u}$, ZÜRGES[24] gave for rough face and $\bar{u} < 5$ m/s

$$h' = 5.32 + 3.68\bar{u} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (36)$$

and KEYLWERTH[9] gave

$$h' \propto \bar{u}^{0.5-0.8} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (37)$$
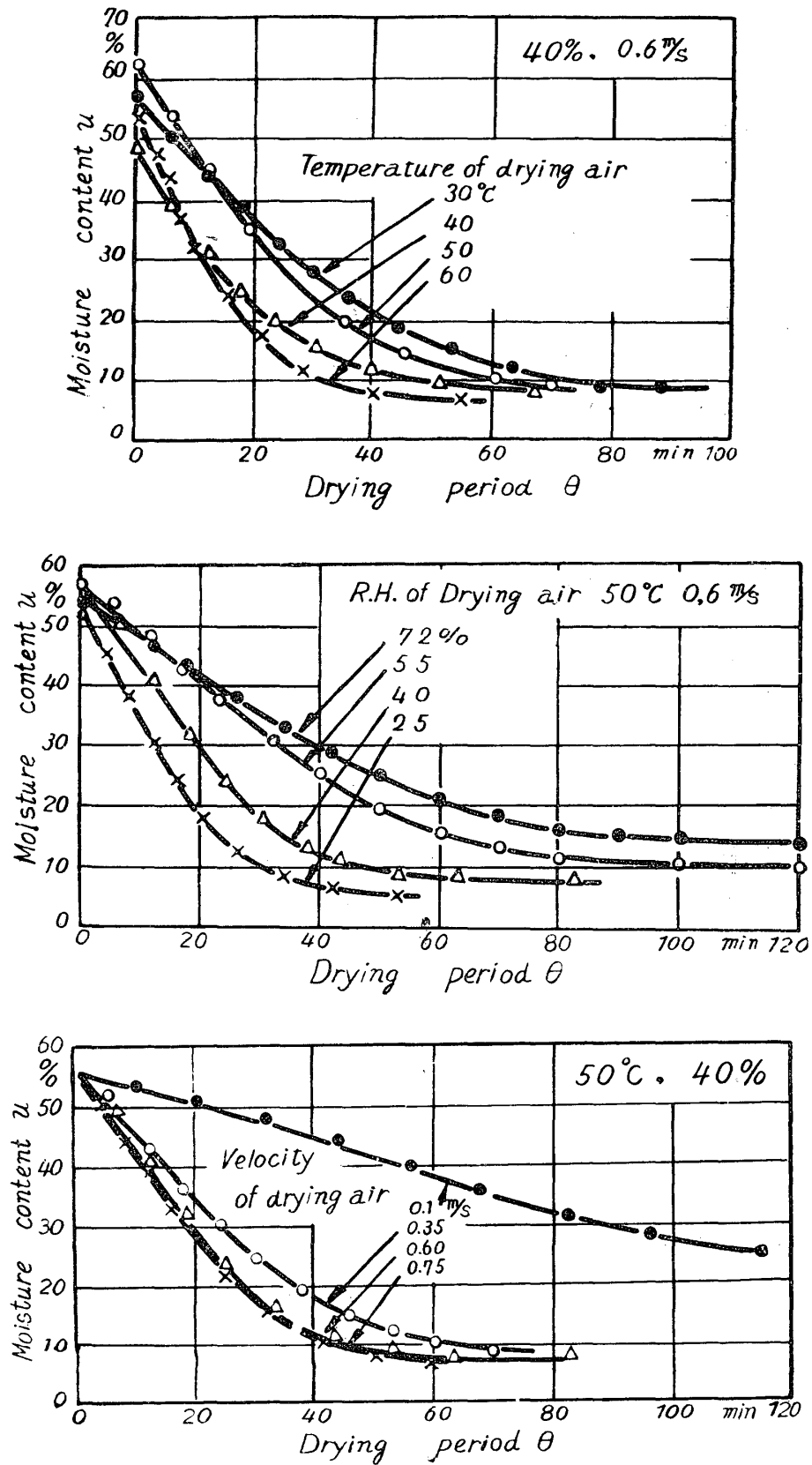
Fig. 29 Drying process of veneer under various drying conditions
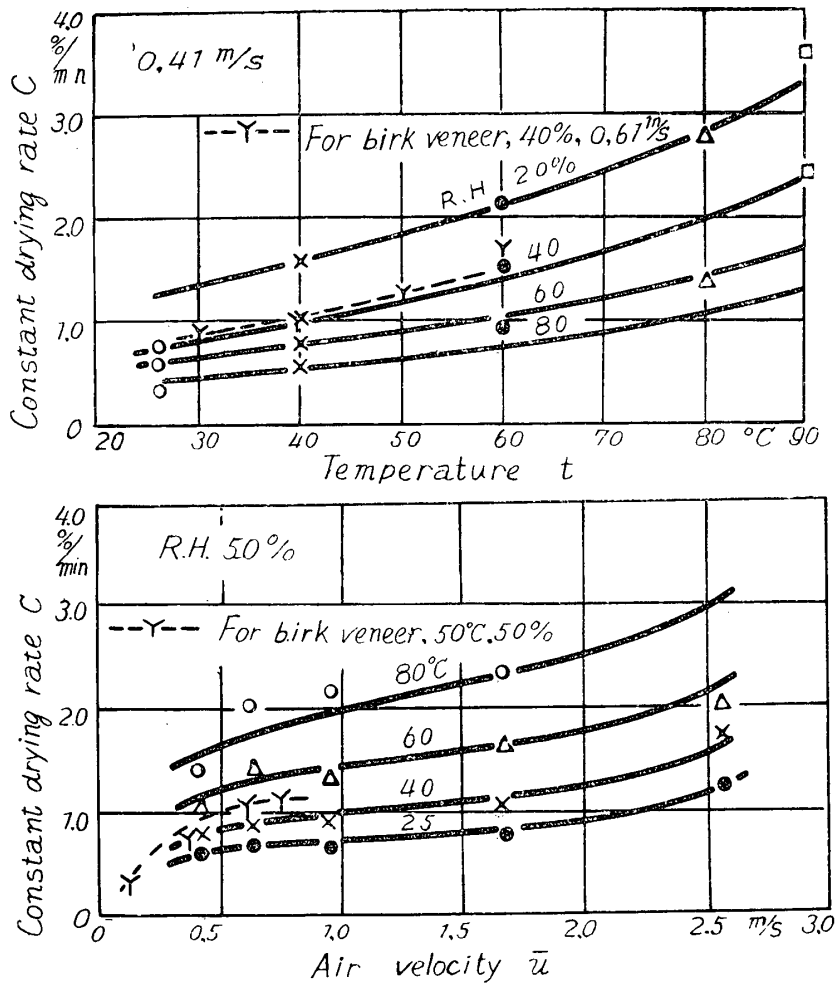(*Betula*, KABA, 1.4 mm thick veneer)

Fig. 30   Relation of constant drying rate to the drying conditions

If there is a proportional relation between the coefficient of heat transfer and the amount of moisture evaporated, above relation may be established between C and $\bar{u}$, however, in the present experiment C is nearly proportional to $\bar{u}^{0.5-0.5}$ in the extent of $\bar{u} = 0.5$-2.0 and the influence of air velocity on C is smaller. This result gives the same inclination with Kamei's experimental result which showed that in below 2 m/s constant drying rate is hardly influenced by the air velocity.

According to present experiment, it may be considered that the effect of air velocity is remarkable in below 0.5 m/s or over 2 m/s, but in the extent of 0.5-2 m/s the effect is slight.

Fig. 31 shows the amount of moisture evaporated in drying of veneer and hatched points on curves show the time when veneer reached the fiber saturation point in mid plane.

231,2 Relation of C to specific gravity

Fig. 32 shows the relation of specific gravity and the constant rate of drying obtained
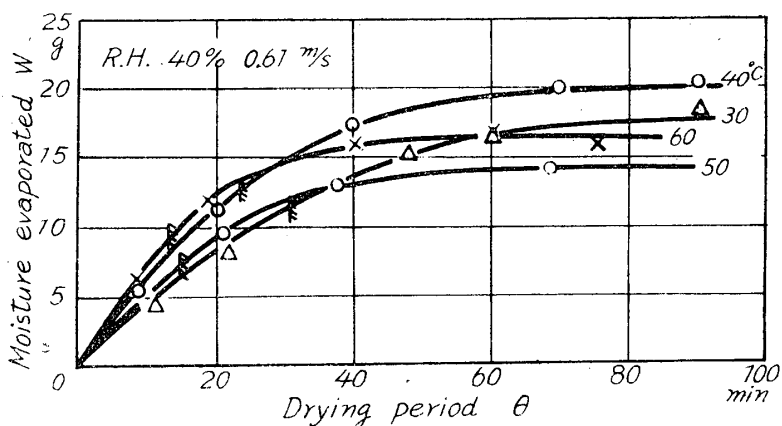
Fig. 31   The curve if the amount of the evaporated moisture
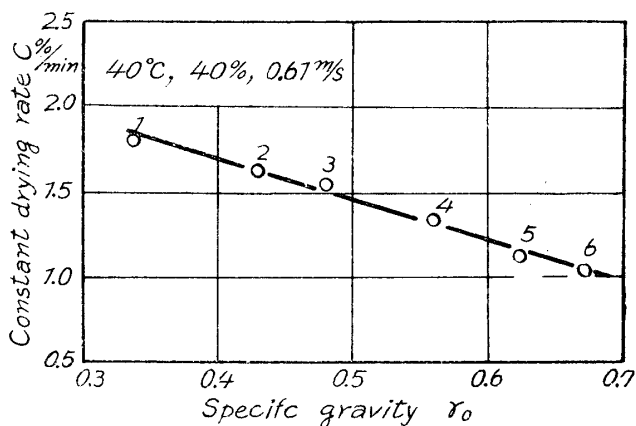(*Shorea*, lauaan, 1.24 mm thick veneer)

Fig. 32   Relation of constant drying rate to the specific
gravity of wood (for 1 mm thick)

1	*Chamaecyparis*	(HINOKI)
2	*Tilia*	(SINA)
3	*Shorea*	(lauaan)
4	*Fagus*	(BUNA)
5	*Betula*	(KABA)
6	//	(//)

from various wood species and converted to veneer of 1 mm thick under the assumption that in the thin plate such as veneer drying period is proportional to the thickness, that is, drying velocity is inversely proportional to the thickness.   As obvious from the figure, the constant drying rate decreases linearly with increasing of the specific gravity.

232.   Drying in hygroscopic range

232,1   Relation of K and α to the drying conditions

The drying process of veneer in hygroscopic range gave a good agreement with the differential equation, that is, similarly as in 222,13 calculating V_{av} for $U_m = 0.3$ by equation (18) and determing the time by means of this V_{av}, from the drying data in 231

the author obtained a linear relation of $v_{av}/V_{av} - \theta/a^2$ diagram.

Then, as similar as in 222, 11, the most probable value of ha was determined as about 0.5 from minimum coefficient of variation of K. ha was independent on the drying conditions and had a good agreement with one calculated by $h = 6.67$ which is determined by $ha = 10$ (i. e. $h = 6.67$) of *Fraxinus* and *Prunus* of 3 cm thick (for *Fagus* veneer $a = 0.075$ cm ; $ha = 6.67 \times 0.075 = 0.51$). Therefore, putting $ha = 0.5$, the relation between drying diffusion constant K and the drying conditions was obtained in Fig. 33. From the figure, K increases with increasing of the absolute temperature and decreases in inverse proportion to the relative humidity as similarly as the diffusion coefficient. That is

$$K = n\left(\frac{273+t}{273}\right)^{m}\left(\frac{1}{H}\right) \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(38)$$
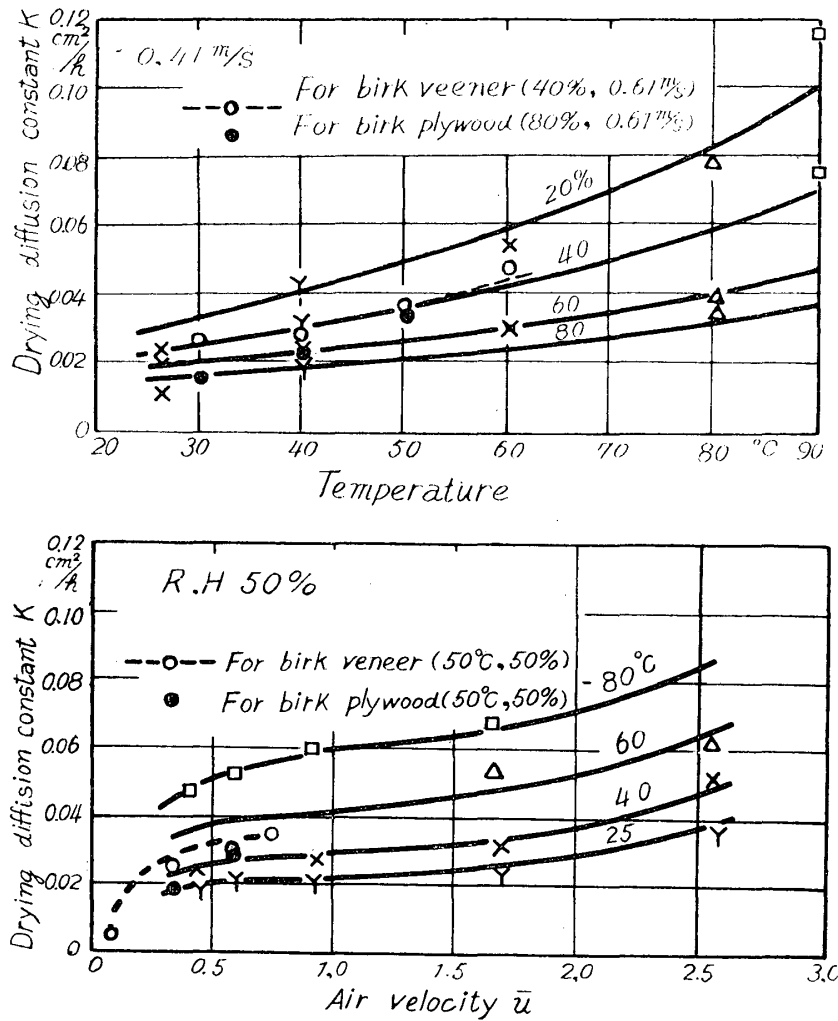

Fig. 33 Relation of transverse drying diffusion constant to the drying conditions (*Fagus*, for veneer of 1.5 mm thick)

where n, m are the experimental constant, and in the experimented range $n = 0.35\text{-}0.8$, $m = 4.5\text{-}6.1$.

As for the relation of the drying diffusion constant to the air velocity, K increases quickly in the range of $\bar{u} = 0\text{-}0.5$ m/s, gradually in the range of $0.5\text{-}2.0$ m/s i. e. in proportional to $\bar{u}^{0.3-0.5}$ and in over 2 m/s seems to increase again. Fig. 34 shows the relation between the coeffcient of surface evaporation α and the drying conditions, as same as K, the following formula is given for α

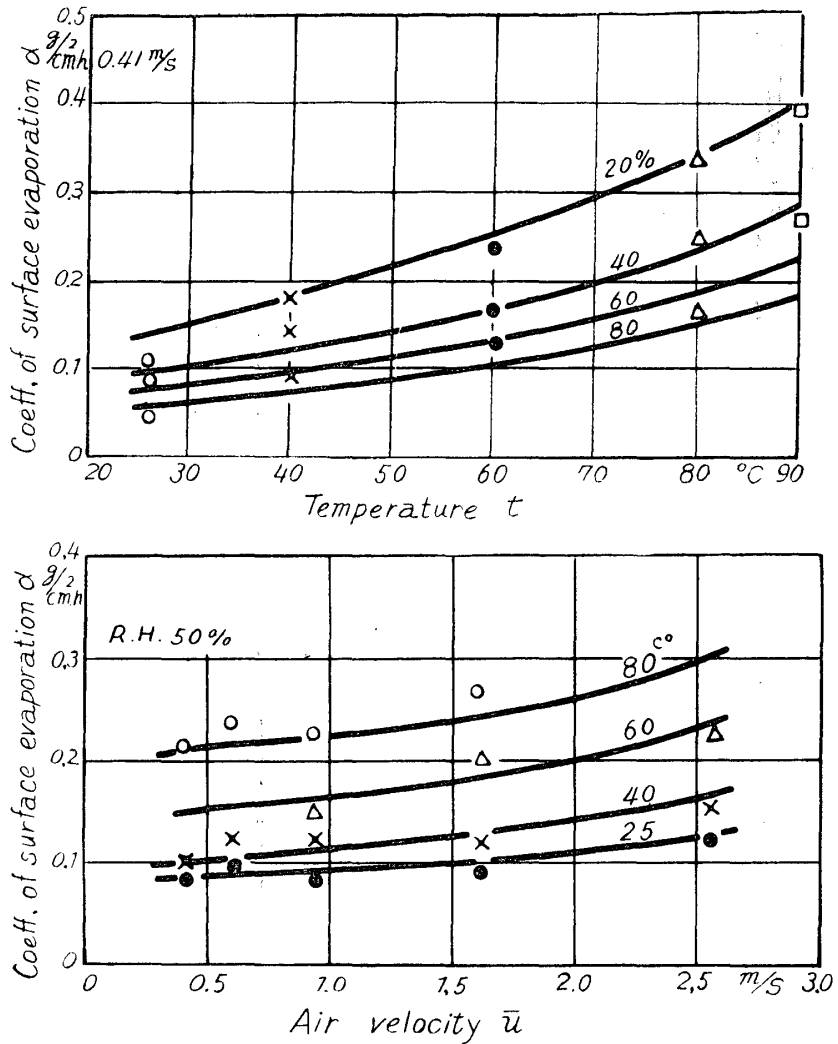$$\alpha = n'\left(\frac{273+t}{273}\right)^{m'}\left(\frac{1}{H}\right) \quad\quad\quad (39)$$

Fig. 34 Relation of transverse coefficient of surface evaporation to the drying conditions (Fagus, for veneer of 1.5 mm thick)

where $n' = 1.7\text{-}2.7$, $m' = 5.4\text{-}5.9$.

Fig. 21 and 22 show the values converted from Fig. 33 and 34 by equation (28) and

(29). Fig. 35 shows the measured values of the moisture evaporated after the moisture content of mid-plane reached the fiber saturation point (hatched point on curve in Fig. 31) and the values calculated by equation (18) and K which was obtained by the above mentioned method.
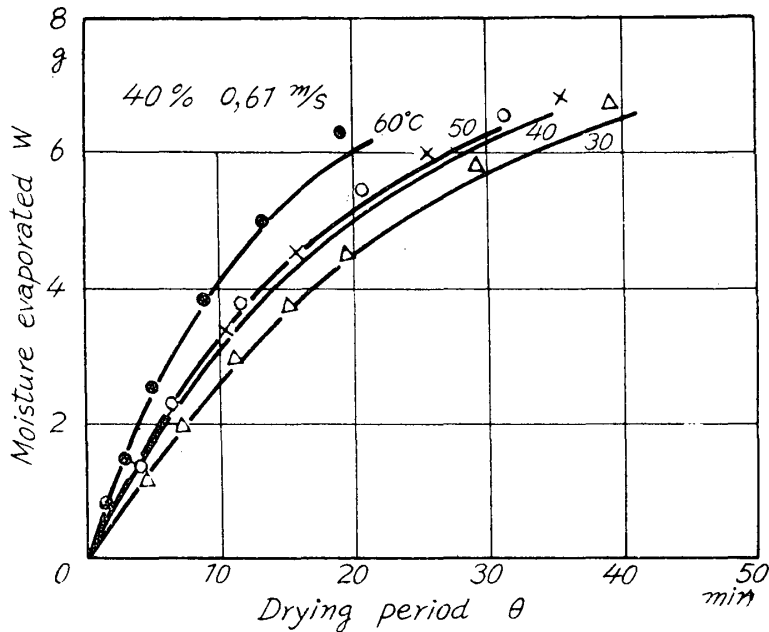

Fig. 35 Evaporated moisture in hygroscopic range
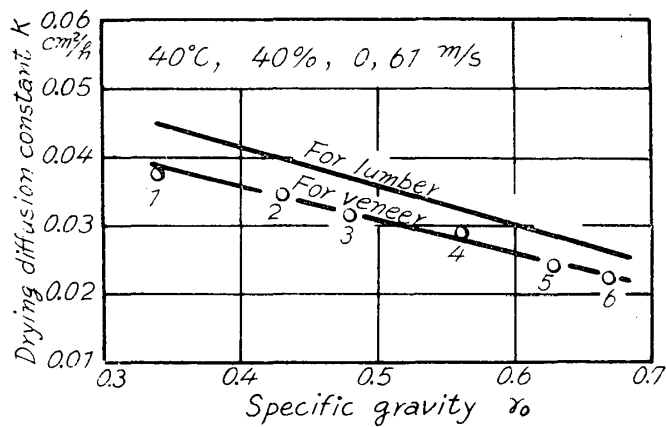(*Shorea*, lauaan, 1.24 mm thick veneer)

Fig. 36 Relation of the drying diffusion constant
to the specific gravity

1	*Chamaecyparis* (HINOKI)
2	*Tilia*	(SINA)
3	*Shorea*	(lauaan)
4	*Fagus*	(BUNA)
5	*Betula*	(KABA)
6	//

232, 2　Relation of K to the specific gravity

According to the data of Fig. 32 the relation between the specific gravity and K are shown in Fig. 36. K decreases linearly with increase of the specific gravity.　The relation between both for timber of over 1 cm thick are calculated by equation (28) and shown in Fig. 36 together.

24.　Drying of plywood [14]

Urea resin bonded, 3 ply, *Betula* (Birk) and *Shorea* (Lauaan) plywood (thickness 3.2 and 4.6 mm respectively ; initial moisture content 23-24%) were dried under the various drying conditions.

As same as in timber or veneer, $v_{av}/V_0 - \theta/a^2$ diagram shows a straight line and ha obtained from minimum value of coefficient of variation of K_0 are given as follows

Table 5　Values of ha

Wood species	Thickness 2a	Spec. gravity r_0	ha at C.V. min.	h	ha calculated by h	Drying air conditions
Chamaecyparis SAWARA	cm 3.0	0.4	2~3	1.3~2		55°, 40%, 0.4~0.5m/s
" HINOKI	*"*	0.41	6	4		*"*
Fraxinus TAMO	*"*	0.56	10 ⎫			*"*
Prunus SAKURA 〉Timber	*"*	0.63	10 ⎭ 6.67			*"*
Thujopsis HIBA	*"*	0.43	6	4		*"*
"	1.0	*"*	2~3		2 $h=4$	*"*
"	0.5	*"*	1		1 *"*	*"*
"	0.2	*"*	0.5~1		0.4 *"*	*"*
Chamaecyparis HINOKI	0.16	0.34	0.2		$h=4$ 0.32	40°, 40%, 0.6m/s
Tilia SINA	0.14	0.43	0.5		$h=6.67$ 0.46	*"*
Shorea Lauaan 〉Veneer	0.124	0.48	0.5~1		*"* 0.41	30~60°C, 25~72% 0.1~0.75m/s
Fagus BUNA	0.154	0.56	0.5		*"* 0.52	26~90°C, 20%~80% 0.4~2.5m/s
Betula KABA	0.14	0.63	0.5		*"* 0.47	30~60°C, 25~72% 0.1~0.75m/s
"	0.133	0.67	1		*"* 0.45	*"*
Shorea Lauaan 〉Plywood	0.46		1~2		$h=6.67$ 1.5	30~50°, 20~40% 0.1~0.6m/s
Betula KABA	0.32		0.5~1		1.1	*"*

for lauaan plywood ha = 1-2

for birk plywood ha = 0.5-2

and the value of ha calculated from h = 6.67 are

for lauaan plywood ha = 6.67×0.23 = 1.53

for birk plywood ha = 6.67×0.16 = 1.07

Undoubtly, the values of ha of both cases have a good agreement.

Table 5 shows summarily the values of ha on timber, veneer, and plywood. As obvious from the table, ha obtained from the minimum value of coefficient of variation
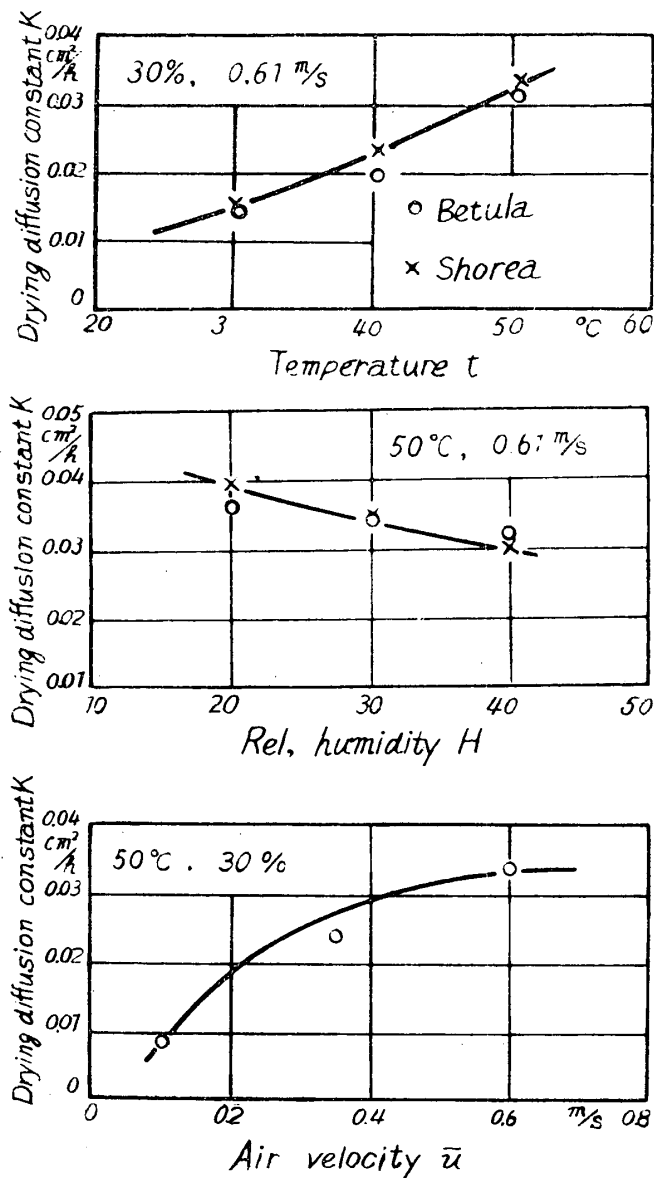

Fig. 37   Relation of the drying diffusion constant to the drying conditions (*Betula-*, *Shorea*-plywood)

of K_0, *ha* obtained from the moisture gradient and *ha* of veneer and plywood which calculated from *h* of timber coincide well each other. From this fact it seems that in hygroscopic range the value of *h* varies somewhat with wood species (*ha* is smaller in light wood and larger in heavy one, so the moisture gradient becomes gentler in former and steeper in latter) but does not vary with the thickness of wood and the drying conditions in the extent of experiment, and even in plywood which has a few glue lines *h* does not vary with above factors.

Fig. 37 shows the relation between K calculated from the above value of *ha* and the drying condition and in Fig. 33 the values converted for thickness are shown, namely the influence of the drying conditions on the drying diffusion constant in plywood is similar to that in timber and veneer, but it seems that the absolute value of K is somewhat smaller in plywood than in timber or veneer by the presence of glue lines.

Summary

In drying of wood the differential equation similar to the heat conduction equation is not always adaptable to explain the moisture movement through wood, however, it is often used for the convenience that (1) it represents directly the moisture content (2) the other equations can not be connected directly with the relative humidity and the velocity of drying air, but it can be easily connected with them (3) at least from 30 - 10 % moisture content it coincides well with the drying process (4) it is convenient for the calculation of the drying time and the moisture gradient.

At the above mentioned standpoint, the present author treated of the differential equation and obtained the relations of the drying constant to the drying conditions.

1. Under the assumption that the coefficient of the differential equation i. e. drying diffusion constant K is constant, the solutions were obtained in steady drying condition and in confined unsteady drying condition.

2. In high moisture range, the differential equation can not be used generally, however, in hygroscopic range it coincides well with the drying process.

3. According to the drying process and the moisture gradient in hygroscopic range, drying diffusion constant K and the coefficient of surface evaporation a are independent upon the moisture content of wood both in the transverse direction and in the longitudinal direction, and the moisture content at the wood surface is always higher a little than the equilibrium moisture content of the drying air, and the drying proceeds under the

correlation between the surface evaporation by this moisture difference and the internal diffusion.

4. In the transverse direction the value of K and a decrease somewhat with decreasing of thickness of wood in the extent below 1 cm thick and in the longitudinal direction they decrease similary in the extent below 4 cm thick. It may be caused by the existence of the thin anomalous layer at the wood surface, but the value of the coefficient becomes constant over the above mentioned thickness because the thin layer does not influence in practice.

5. The relation of the drying air conditions to drying coefficent K and a was searched by the drying data of veneer and this was converted to the value of timber. The value of K and a increase as a exponential function of absolute temperature and decreases inverse proportionally with increase of the relative humidity as similar as the general diffusion coefficient. The influence of the air velocity u on K and a is quite slight in the extent of $u = 0.5$-2.0 m/s and K and a are nearly proportional to $\overline{u}^{0.3-0.5}$.

The value of K thus obtained are larger a little than the value determined by the assumption that the surface moisture content of wood conforms to the equilibrium moisture content of the drying air in hygroscopic range, but, for reference, they are shown in comparison with the value calculated by STAMM and KRÖLL.

6. In drying of veneer the constant rate of drying takes place until near the fiber saturation point in practice and therefore the relation between the constant drying rate and the drying condition was searched.

7. The drying process of plywood coincides well with the differential equation, but the drying constant is somewhat smaller than that of veneer and timber. It may be caused by the existence of the glue lines.

Literature cited

1) Bateman, E., Hohf, J. P. and Stamm, A. J. : Ind. and Eng. Chem. **31** (1939)

2) Egner, K. : Forsch. Ber. Holz 2 (1934)

3) Hawley, L. F. : U. S. Agric. Bull. 248 (1931)

4) KAMEI, S. : J. Soc. Chem. Ind., Japan **40**, 7 (1937)

5) —— 〃 **40**, 9 (〃)

6) Keylwerth, R. : Holz als Roh- u. Werkstoff **10**, 3 (1952)

7) —— 〃 **11**, 1 (1953)

8) Kollmann, F. : "Technologie des Holzes" (1936)

9) —— : "Technologie des Holzes und der Holzwerkstoffe" Bd. 1 (1951)

10) Kröll, K. : Holz als Roh- u. Werkstoff **9** ; 5, 6 (1951)

11) Ludwig, K. : Forsch. Ber. Holz., 1 (1933)

12) MAKU, T : "Wood Research" **6** (1951)

13) ———— : Trans. 2nd Meet. KANSAI Branch Jap. For. Soc. (1953)

14) ———— : Trans. 62th Meet. Jap. For. Soc (1953)

15) ———— : Trans. 63th Meet. Jap. For Soc. (1954)

16) ———— : This Bulletin, this Number.

17) Martley, J. F. : For. Prod. Res. Techn. Paper **2** (1926)

18) Newmann, A. B. : Trans. Am. Inst. Chem. Eng. **27** (1931)

19) Peck, R. E., R. T. Griffith u. Nagaraja Rao. K. : Ind. Eng. Chem. **44**, 3 (1952)

20) Schlüter, R. u. F. Eessel : Holz als Roh- u. Werkstoff **2**, 5 (1939)

21) Sherwood, T. K. : Ind. Eng. Chem. **21** (1929)

22) ———— :   〃   **24, 25** (1932-33)

23) Stamm, A. J. : U. S. Agric. Techn. Bull. 929 (1946)

24) Tuttle, T : J. Franklin Inst. 200 (1925)

25) UTIDA, S., S. KAMEI and S. HATTA : "KAGAKU KOGAKU" (1951)

26) W. H. Walker, W. K. Lewis a. W. H. Mcadams : "Principles of chemical Engineering" (1929)

27) Voigt, H., O. Krischer u. H. Schauss : Holz als Roh- und Werkstoff **3**, 10 (1940)