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Heat and Moisture Transfer in Porous Building Material under Condensation

Le transfert thermique et humide dans des matériaux poreux dans un état de condensation

Wärme- und Feuchtetransport in porösen Baumaterialien unter Kondensation

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SUMMARY
Theory of heat and moisture transfer which could predict the condensation processes was investigated by comparison with experimental results. Transfer coefficients in the theory which largely changed with moisture content and temperature were measured and determined in detail. It was shown that the theoretical calculation agree well with the experimental results.

RESUME
La théorie du transfert thermique et humide permettant de prévoir le développement de la condensation a été comparée avec les résultats expérimentaux. Les coefficients de transfert dépendant largement du degré d'humidité et de la température ont été mesurés et déterminés en détail. La concordance est bonne entre le calcul théorique et les résultats empérimentaux.

ZUSAMMENFASSUNG
Die Theorie der Wärme- und Feuchteübertragung, welche Kondensationsprobleme vorherzusagen gestattet, wurde durch Vergleich mit experimentellen Ergebnissen untersucht. Die theoretischen Transportkoeffizienten, welche mit dem Feuchtegehalt und der Temperatur stark schwanken, werden gemessen und im Detail bestimmt. Es zeigt sich, dass die theoretischen Rechnungen gut mit den experimentellen Ergebnissen übereinstimmen.

1. Introduction

Up to now, although the thermal conductivity measurements of a moist material have been done in so many fields, such as soil science[1], drying engineering[2], mechanical engineering[3], etc., it seems that they use the measured thermal conductivity without knowing precisely what it means. So far, the major reason might depend on the fact that the mechanism of the heat and mass transfering simultaneously in the porous material has not been known enough. Recently, investigations about the mechanism have been developed[4][5][6] and the measurements of the transfer coefficients have been made[7].

The objectives of this study are as follows,
i) to investigate the implication of the thermal conductivity of a moist porous material
ii) to investigate the influences of the moisture movement on the measured values and to propose the formula which gives the measurement error.

The steady state method and the periodic method are considered as typical measuring methods, and the implication of the thermal conductivities measured by them is analysed. The formula which gives the errors induced by moisture movement is proposed for the periodic method. Based on this formula, temperature conductivities of wood fibre board are measured for several different temperatures and water contents.

2. The implication of the thermal conductivity of a moist porous material

2.1 Fundamental equations

Equations that describe the simultaneous flow of heat and moisture in a moist material are as follows[4].

(vapour balance) $$c\gamma\frac{\partial X}{\partial t} = \frac{\partial}{\partial x}[k_v\frac{\partial X}{\partial x}] + \alpha_i'S(X_i - X) \quad (1)$$

(liquid water balance) $$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}[D_{\theta\ell}\frac{\partial \theta}{\partial x}] + \frac{\partial}{\partial x}[D_{T\ell}\frac{\partial T}{\partial x}] + \alpha_i'S(X - X_i) \quad (2)$$

(heat balance) $$c'\gamma'\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[\lambda\frac{\partial T}{\partial x}] + R\alpha_i'S(X - X_i) \quad (3)$$

(absorption isotherm) $$X_i = g(\theta, T) \quad (4)$$

where, the sensible heat transported by vapour and liquid is neglected.

Assuming $\alpha_i' = \infty$ (local equilibrium), using eq.(4), eqs.(1)-(3) are transformed as follows.

(mass balance) $$(1+c\gamma\frac{\partial g}{\partial \theta})\frac{\partial \theta}{\partial t} + (c\gamma\frac{\partial g}{\partial T})\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[D_\theta\frac{\partial \theta}{\partial x}] + \frac{\partial}{\partial x}[D_T\frac{\partial T}{\partial x}] \quad (5)$$

(heat balance) $$(Rc\gamma\frac{\partial g}{\partial \theta})\frac{\partial \theta}{\partial t} + (Rc\gamma\frac{\partial g}{\partial T} + c'\gamma')\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}[(\lambda + RD_{Tv})\frac{\partial T}{\partial x}] + R\frac{\partial}{\partial x}[D_{\theta v}\frac{\partial \theta}{\partial x}] \quad (6)$$

where, $$D_\theta = D_{\theta v} + D_{\theta\ell} = k_v\frac{\partial g}{\partial \theta} + D_{\theta\ell}\, , \quad D_T = D_{Tv} + D_{T\ell} = k_v\frac{\partial g}{\partial T} + D_{T\ell} \quad (7)$$

2.2 Thermal conductivities, λ and λ^*

In eq.(3), λ represents the thermal conductivity which is mainly determined by conduction through the constituents(solid skeleton, water, air) in case of no moisture movement, and of course it varies with the water contents. On the other hand, as it is seen in eq.(6), λ and $RD_{T\upsilon}$ appear always in the conjunct form $\lambda^*=\lambda+RD_{T\upsilon}$, and λ^* exists as a coefficient to the temperature gradient.

As mentioned above, λ and $RD_{T\upsilon}$ never appear separately in the fundamental equations (5) and (6) and also in the boundary conditions. Consequently, D_θ, D_T, $\lambda^*=\lambda+RD_{T\upsilon}$, $D_{\theta\upsilon}$ are necessary to calculate the heat and mass transfer, and the respective values of λ and $D_{T\upsilon}$ are not necessary. Because of these properties of the fundamental equations, only λ^*(not λ) is given by any measuring method of thermal conductivity. Thus the methods which minimize the effects of moisture movement could minimize mainly the effect of the term $R\frac{\partial}{\partial x}[D\frac{\partial\theta}{\partial x}]$ and measure λ^* more correctly. This situation is the same as, for example, that of periodic method, which can be made clear in §4. It is concluded from the above mentioned that in order to solve the equations of heat and mass transfer, one must measure and use the value of λ^* not λ.

On the other hand, as λ is defined under the assumption that there is no moisture movement under the temperature gradient, it is a hypothetical one. But it may offer informations about the way of the connection of the constituents and about moisture distribution. $D_{T\upsilon}$ represents the vapour transfer coefficient as the part of D_T. Both λ and $D_{T\upsilon}$ are of importance to know the mechanism of heat and mass transfer in the material. As mentioned above, only λ^* can be measured in this system, so λ can not be measured except the special case, but may be estimated by assuming an appropriate model.

3. Steady state method

Up to now, it has been believed that λ(or λ^*) could be measured accurately by reducing the temperature gradient over the sample material in the steady state method. First, we investigated the case of which the temperature difference over the sample was very small. Next, we examined the case of the temperature difference was larger. We found that there might be a possibility to measure λ rather in the latter case.

3.1 Fundamental equations

In the steady state method, boundary temperatures of the sample T_A, T_B, and heat flux Q are measured, and the thermal conductivity measured by this method λ' is given by

$$\lambda' = \frac{\ell Q}{T_A - T_B} \tag{8}$$

Assuming steady state in eqs.(5)(6),

$$\frac{\partial}{\partial x}[D_\theta\frac{\partial\theta}{\partial x}] + \frac{\partial}{\partial x}[D_T\frac{\partial T}{\partial x}] = 0 \tag{9}$$

$$\frac{\partial}{\partial x}[(\lambda+RD_{T\upsilon})\frac{\partial T}{\partial x}] + R\frac{\partial}{\partial x}[D_{\theta\upsilon}\frac{\partial\theta}{\partial x}] = 0 \tag{10}$$

Boundary conditions

$$[-D_\theta\frac{\partial\theta}{\partial x} - D_T\frac{\partial T}{\partial x}]_{S_1, S_2} = 0 \tag{11}$$

$$T|_{S_1} = T_A, \quad T|_{S_2} = T_B \tag{12}$$

and the mean water content is given

$$\theta_m = \frac{1}{\ell}\int_0^\ell \theta dx \tag{13}$$

3.2 The case of the very small temperature difference

In this case, the difference of water content occuring in the sample is small too, so it is possible to treat the transfer coefficients to be constant. Then eqs.(9) and (10) become linear equations and the solutions of these equations subjected to the conditions (11)-(13) are linear functions of x. λ' is given as

$$\lambda' = (\lambda+RD_{Tv})-D_T RD_{\theta v}/D_\theta \tag{14}$$

It is concluded from the eq.(14) that,
i) generally speaking, λ' doesn't equal λ nor $\lambda^*(=\lambda+RD_{Tv})$,
ii) in the liquid dominant region ($D_{\theta v}=0$, $D_{Tv}=0$), $\lambda'=\lambda^*=\lambda$,
iii) in the vapour dominant region ($D_\theta=D_{\theta v}$, $D_T=D_{Tv}$), $\lambda'=\lambda$.

3.3 The case of which the temperature difference is not so small

In this case, the variations of the coefficients with θ and T can not be neglected, and it is difficult to treat the problem analytically. So, we discuss the problem only by numerical method. By solving eqs.(9)-(11), we obtain

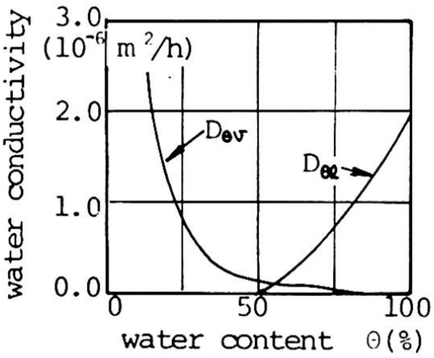
$$\frac{\partial T}{\partial x} = \frac{-QD_\theta}{(\lambda+RD_{Tv})D_\theta-RD_T D_{\theta v}} \tag{15}$$

$$\frac{\partial \theta}{\partial x} = \frac{QD_T}{(\lambda+RD_{Tv})D_\theta-RD_T D_{\theta v}} \tag{16}$$

(Heat flux Q appears as an integral constant in eq.(10).) In calculation, eqs. (15) and (16) are discretized, assuming $\theta=\theta_1$ at x=0(surface s_1) and Q, we calculate θ_i, T_i at the next mesh point. Continuing this procedure, we obtain θ_M, T_M at $x=\ell$(surface s_2). When $T_M=T_B$ is obtained we stop. If not, we assume new value of Q until the above condition is satisfied.

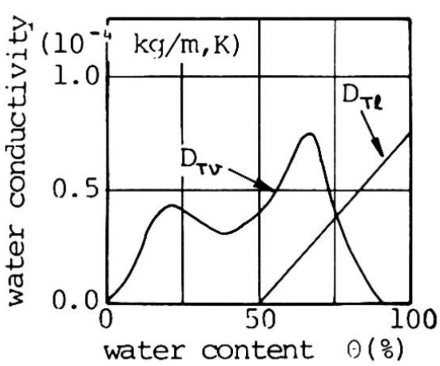
Numerical example
material wood fibre board, 8mm thick
mean temperature = 20 (°C), ΔT = 1.0, 2.0, 3.0 (K) (17)
ΔT = 0.1, 0.2, 0.3 (K) (case §3.2) (18)
transfer coefficients Fig.1($D_{\theta v}$,$D_{\theta \ell}$), Fig.2(D_{Tv},$D_{T\ell}$), Fig.3(λ,λ^*) [6]

The results of water content distribution are shown in Figs.4,5 and λ' is in Fig.3. (in these figures, $\Theta = 100\cdot\theta/\gamma'$%)



Water conductivities related to water content gradient (wood fibre board)

Fig. 1



Water conductivities related to temperature gradient (wood fibre board)

Fig. 2

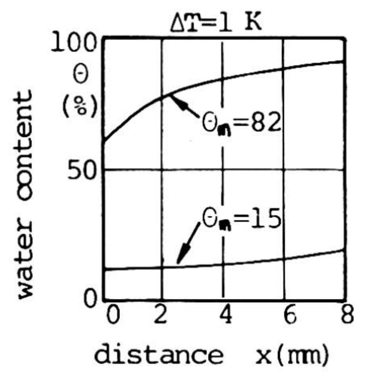


Fig. 4

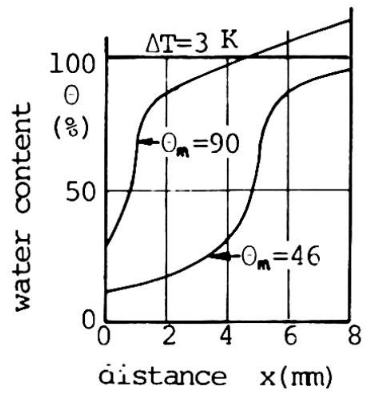
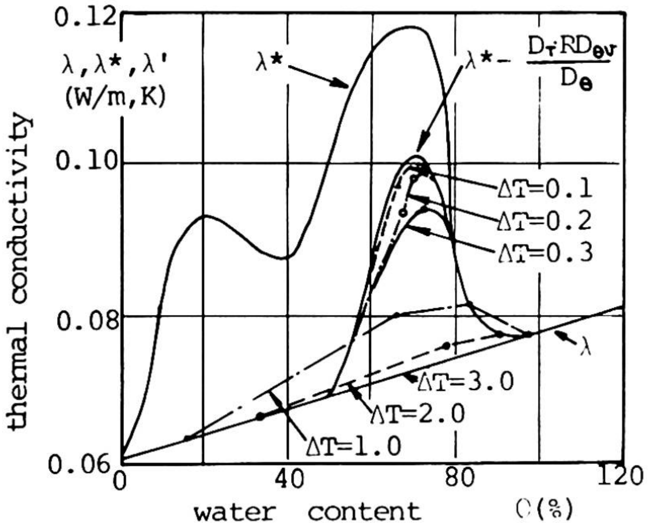


Fig. 5

Water content distribution in the material at the steady state condition

Θ_m= mean water content of the material

Figs. 4,5



Comparison of the thermal conductivities λ, λ^*, λ' (wood fibre board)

Fig. 3

As the temperature difference ΔT falls from 3K to 1K, water content distribution becomes rather uniform (Figs.4,5), and λ' departs from λ and approach $\lambda^*-D_T RD_{\theta v}/D_\theta$ (Fig.3). On the other hand, in the case of $\Delta T=3$(K), $\Theta_m=46$(%), although water content distribution varies rather sharply (Fig.5), λ' is almost equal to λ which corresponds to the mean water content θ_m (Fig.3). From the above results, it is seen that if we choose an appropriate temperature difference in the steady state method, the measured λ' can be almost equal to λ. Fig.3 also shows $\lambda^*-D_T RD_{\theta v}/D_\theta$ values with λ, λ^* and λ' for ΔT=0.1, 0.2, 0.3 (K). It shows that the range of ΔT where the result in §3.2 holds approximately is rather small and there is a wide range of water content in this material where the values of λ, λ^*, $\lambda^*-D_T RD_{\theta v}/D_\theta$ are considerably different.

4. Measurement of temperature conductivity by periodic method

4.1 Objective

It is estimated from the result of §2 that the temperature conductivity corresponding to λ^* can be measured in a non-steady state method minimizing the moisture movement. We consider here the periodic method as a representstive of many methods. The objective of the analysis is to estimate quantitatively a measuring error caused by moisture movement and to derive formula to give the error which is composed of material properties and is applicable to any material.

We analyze this problem by perturbation method, that is, we assume that the transfer coefficients are linear functions of water content and temperature and that the solution is power series of the input surface temperature amplitude. The influences of moisture are those caused by
i) the existence of the moisture movement,
ii) variation of the transfer coefficients with water content and temperature.
It may be considered approximately that the first term of the solution represents i) and the second term represents ii).

4.2 Formulation

Consider that the material is semi-infinite and its surface temperature variations are sinusoidal. Basic equations are eqs.(5)and (6) (neglecting smaller order terms in the left hand side)

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\{D_{\theta\ell}[1+\eta_1(\theta-\theta_0)][1+\eta_2(T-T_0)]\frac{\partial\theta}{\partial x} + \frac{\partial}{\partial x}\{D_{\theta v}[1+\zeta_1(\theta-\theta_0)][1+\zeta_2(T-T_0)]\frac{\partial\theta}{\partial x}\}$$
$$+\frac{\partial}{\partial x}\{D_{T\ell}[1+\beta_1(\theta-\theta_0)][1+\beta_2(T-T_0)]\frac{\partial T}{\partial x} + \frac{\partial}{\partial x}\{D_{Tv}[1+\xi_1(\theta-\theta_0)][1+\xi_2(T-T_0)]\frac{\partial T}{\partial x}\} \qquad (19)$$

$$c'\gamma'[1+\kappa_1(\theta-\theta_0)]\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\{\lambda[1+\gamma_1(\theta-\theta_0)][1+\gamma_2(T-T_0)]\frac{\partial T}{\partial x} + RD_{Tv}[1+\xi_1(\theta-\theta_0)]$$
$$\cdot[1+\xi_2(T-T_0)]\frac{\partial T}{\partial x}\} + R\frac{\partial}{\partial x}\{D_{\theta v}[1+\zeta_1(\theta-\theta_0)][1+\zeta_2(T-T_0)]\frac{\partial\theta}{\partial x}\} \qquad (20)$$

(Initial conditions) $\quad T = T_0, \quad \theta = \theta_0 \qquad (21)$

(Boundary conditions)

$$\{D_{\theta\ell}[1+\eta_1(\theta-\theta_0)][1+\eta_2(T-T_0)]+D_{\theta v}[1+\zeta_1(\theta-\theta_0)][1+\zeta_2(T-T_0)]\}\frac{\partial\theta}{\partial x}$$
$$+ \{D_{T\ell}[1+\beta_1(\theta-\theta_0)][1+\beta_2(T-T_0)]+D_{Tv}[1+\xi_1(\theta-\theta_0)][1+\xi_2(T-T_0)]\}\frac{\partial T}{\partial x} = 0 \quad (x=0) \qquad (22)$$

$$\theta = \text{Finite } (x \to +\infty), \quad T = T_0 + I_0\sin\omega t \ (x=0), \quad T = \text{Finite } (x \to +\infty) \qquad (23)(24)(25)$$

Transforming θ, T to θ', T' by the relation,

$$\theta' = \theta - \theta_0, \quad T' = T - T_0 \qquad (26)$$

transformed equations have the same form as eqs.(19)-(25) except that θ_0 and T_0 are 0. Hereafter we rewrite θ', T' by θ, T.

4.3 Solution

We assume power series solution as

$$\theta = I_0\theta_1 + I_0^2\theta_2 + I_0^3\theta_3 + \cdots$$
$$T = I_0T_1 + I_0^2T_2 + I_0^3T_3 + \cdots \qquad (27)$$

Substituting these equations to transformed eqs.(19)-(25) and equating the coefficients of the same order, we obtain the equations for θ_1, T_1, θ_2, T_2, etc.

i) θ_1, T_1 (periodical solution)

$$\theta_1(t,x)=\alpha_1E\cdot\exp(-\sqrt{\omega/2}\alpha_1x)\sin(\omega t-\sqrt{\omega/2}\alpha_1x)-\alpha_2E\cdot\exp(-\sqrt{\omega/2}\alpha_2x)\sin(\omega t-\sqrt{\omega/2}\alpha_2x) \qquad (28)$$

$$T_1(t,x) = \alpha_1 EE_1/B\cdot\exp(-\sqrt{\omega/2}\alpha_1 x)\cdot\sin(\omega t-\sqrt{\omega/2}\alpha_1 x) - \alpha_2 EE_2/B\cdot\exp(-\sqrt{\omega/2}\alpha_2 x)\cdot\sin(\omega t-\sqrt{\omega/2}\alpha_2 x) \quad (29)$$

where,

$$E = \frac{B}{(\alpha_1-\alpha_2)[C-(CA-BD)(\alpha_1^2+\alpha_1\alpha_2+\alpha_2^2)]}$$

$$E_1 = C-(CA-BD)\alpha_1^2,\quad E_2 = C-(CA-BD)\alpha_2^2 \quad (30)$$

α_1, α_2 are positive roots of the quadratic equation ($\alpha_1<\alpha_2$)

$$(AC-BD)\alpha^4 - (A+C)\alpha^2 + 1 = 0 \quad (31)$$

$$A = D_\theta,\quad B = D_T,\quad C = \lambda^*/c'\gamma',\quad D = RD_{\theta v}/c'\gamma' \quad (32)$$

ii) Solution θ_2, T_2 Periodical solutions are

$$\begin{aligned}\theta_2(t,x) = {} & 2U_3\exp(-\alpha_1\sqrt{\omega}x)\cos(2\omega t-\alpha_1\sqrt{\omega}x) + 2U_7\exp(-\alpha_2\sqrt{\omega}x)\cos(2\omega t-\alpha_2\sqrt{\omega}x)\\ & +2Q_1\exp(-2\sqrt{\omega/2}\alpha_1 x)\cos(2\omega t-2\sqrt{\omega/2}\alpha_1 x)+2Q_2\exp(-2\sqrt{\omega/2}\alpha_2 x)\cos(2\omega t-2\sqrt{\omega/2}\alpha_2 x)\\ & +2Q_3\exp[-\sqrt{\omega/2}(\alpha_1+\alpha_2)x]\cos[2\omega t-\sqrt{\omega/2}(\alpha_1+\alpha_2)x] + Q_4\exp(-2\sqrt{\omega/2}\alpha_1 x)\\ & +Q_5\exp(-2\sqrt{\omega/2}\alpha_2 x) + 2Q_6'\exp[-\sqrt{\omega/2}(\alpha_1+\alpha_2)x]\cos[\sqrt{\omega/2}(\alpha_1-\alpha_2)x]\\ & +2Q_6''\exp[-\sqrt{\omega/2}(\alpha_1+\alpha_2)x]\sin[\sqrt{\omega/2}(\alpha_1-\alpha_2)x]\end{aligned} \quad (33)$$

$$\begin{aligned}T_2(t,x) = {} & 2\frac{1-A\alpha_1^2}{B\alpha_1^2}U_3\exp(-\alpha_1\sqrt{\omega}x)\cos(2\omega t-\alpha_1\sqrt{\omega}x) + 2\frac{1-A\alpha_2^2}{B\alpha_2^2}U_7\exp(-\alpha_2\sqrt{\omega}x)\cos(2\omega t-\alpha_2\sqrt{\omega}x)\\ & +2R_1\exp(-2\sqrt{\omega/2}\alpha_1 x)\cos(2\omega t-2\sqrt{\omega/2}\alpha_1 x)+2R_2\exp(-2\sqrt{\omega/2}\alpha_2 x)\cos(2\omega t-2\sqrt{\omega/2}\alpha_2 x)\\ & +2R_3\exp[-\sqrt{\omega/2}(\alpha_1+\alpha_2)x]\cos[2\omega t-\sqrt{\omega/2}(\alpha_1+\alpha_2)x] + R_4\exp(-2\sqrt{\omega/2}\alpha_1 x)\\ & +R_5\exp(-2\sqrt{\omega/2}\alpha_2 x) + 2R_6'\exp[-\sqrt{\omega/2}(\alpha_1+\alpha_2)x]\cos[\sqrt{\omega/2}(\alpha_1-\alpha_2)x]\\ & +2R_6''\exp[-\sqrt{\omega/2}(\alpha_1+\alpha_2)x]\sin[\sqrt{\omega/2}(\alpha_1-\alpha_2)x] + V_{18}\end{aligned} \quad (34)$$

4.4 Approximation of the coefficients appearing in the solution

By assuming $A/C<<1$, $BD/AC<1$, etc.(which were derived from the values shown in Figs.1,2,3 and refer to [2]), the following approximate equations are obtained.

$$\alpha_1 \simeq \frac{1}{\sqrt{C}}(1-\frac{BD}{2C^2}),\quad \alpha_2 \simeq \frac{1}{\sqrt{A}}(1+\frac{BD}{2AC}),\quad E \simeq \frac{B}{\sqrt{C}}(1-\frac{\sqrt{A}}{\sqrt{C}}\cdot\frac{BD}{AC})$$

$$E_1 \simeq C(1-\frac{A}{C}),\quad E_2 \simeq -\frac{BD}{C}(1+\frac{A}{C}-\frac{BD}{C^2}),\quad \alpha_1 E_1\frac{E}{B} \simeq 1-\frac{\sqrt{A}}{\sqrt{C}}\cdot\frac{BD}{AC}$$

$$\alpha_2 E_2\frac{E}{B} \simeq -\frac{\sqrt{A}}{\sqrt{C}}\cdot\frac{BD}{AC}(1+\frac{BD}{2AC}),\quad 2\frac{1-A\alpha_1^2}{B\alpha_1^2}U_3 \simeq -2(R_1+R_3) \quad (35)$$

4.5 Observational error

i) The solution of the heat flow without moisture

$$T(t,x) = I_0\exp(-\sqrt{\omega/2a}x)\cdot\sin(\omega t-\sqrt{\omega/2a}x) \quad (36)$$

is the solution, and, for example, the method using phase difference gives the temperature conductivity 'a' as follows

$$a = \frac{1}{\phi_0^2}(\frac{\omega}{2})(x_1-x_2) \quad (37)$$

where, x_1,x_2 are any two points in the material, and ϕ_0 is a phase difference between temperatures at points x_1 and x_2.

ii) The solution of the heat flow with moisture
By using the fact that generally $\alpha_2(\simeq 1/\sqrt{A})$ is larger than $\alpha_1(\simeq 1/\sqrt{C})$, eq.(35) approximately becomes

$$T_1(t,x) \simeq \alpha_1 EE_1/B\cdot\exp(-\alpha_1\sqrt{\omega/2}x)\cdot\sin(\omega t-\alpha_1\sqrt{\omega/2}x) \tag{38}$$

because of the rapid exponential decay of the second term.

The error of temperature conductivity calculated by using phase difference ϕ measured in this case relative to that of eq.(39) is

$$\frac{\phi_0^2}{\phi^2} - 1 = \frac{1}{C}\cdot\frac{1}{\alpha_1^2} - 1 \simeq \frac{BD}{C^2} \tag{39}$$

where, an approximation $1/\alpha_1^2 \simeq 1/C(1-BD/C^2)$ (eq.(35)), was used. As expected, eq.(39) represents the influence of the term $R\partial/\partial x(D_{\theta v}\partial\theta/\partial x)$. Similary, T_2 may be utilyzed to determine the amplitude of the input temperature.

5. Experiment (measurement of λ^* by periodic method) [8]

5.1 Measuring conditions pre-examined by calculation and apparatus

Amplitude of the input temperature, the time necessary for achieving stationary state, etc., are referred to [8]. A schematic diagram of the apparatus is given in Fig.6.

5.2 Temperature conductivity and thermal conductivity (wood fibre board)

i) The results of the thermal conductivities obtained are shown in Fig.7. In calculating the thermal conductivity, the volumetric heat capacity of the material was calculated with the following equation

$$c\gamma = (c_s + \theta)\cdot\gamma_s \tag{40}$$

where, c_s, γ_s are specific heat and density of the solid skeleton, respectively. The mean temperatures of the sample were 8.0,27.5,40.0 (°C).

ii) In these measurements, the maximum theoretical error of the periodical method calculated by eq.(39) is 0.1(%) (at θ =10%), and is sufficiently small compared with the other errors caused by experimental processes.

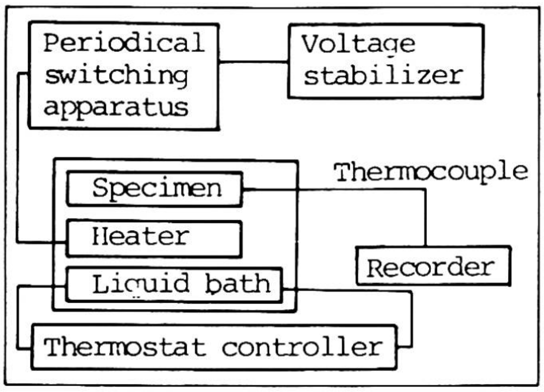
5.3 Discussion

i) The results obtained for a wood fibre board show that thermal conductivity λ^* increases rapidly with water content from 0.06(W/m,K) when air dry, to 0.21 (W/m,K) at 200% of water content (at 25°C). This fact suggests that the variation of the thermal conductivity with water content must be considered.

ii) Thermal conductivity increases with the mean temperature and its change is rather large. This increase is because of the temperature variation of the values of λ and D_{Tv} which are components of λ^*. Making use of this fact, the value of D_{Tv} and λ can be known separately by the results obtained[7].

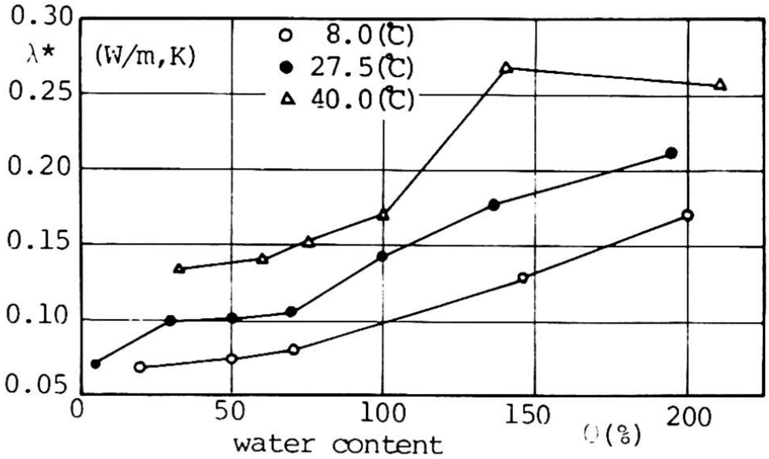
6. Conclusions

i) The implication of the thermal conductivity of a moist porous material was discussed and it was shown that $\lambda^*=\lambda+RD_{Tv}$ was sufficient to solve the simultaneous flow of heat and moisture and that λ was necessary for the elucidation of the mechanism of heat and mass transfer in the material.



Block diagram of measuring equipment for thermal conductivity λ^*

Fig. 6



Thermal conductivity λ^* of wood fibre board
mean temperature 8.0,27.5,40.0(℃)

Fig. 7

ii) In the steady state method, it was shown analytically that when the temperature difference was very small, the measured value did not generally equal λ nor λ^*, and that the care must be paid to interpret the measured value. Further it was shown numerically that when ΔT was larger, there was a possibility that the measured value almost coincided with λ.

iii) In the periodic method, we obtained the formula which gives the measurement errors in terms of the material properties.

iv) Based on the above analysis, λ^* of the wood fibre board at the mean temperatures 8.0,27.5,40.0(℃) were measured. It seems that the good results were obtained.

Nomenclature

X=specific humidity in the pore (kg/kg'), γ=specific weight of dry air (kg/m^3),
α_i'=effective vapour transfer coefficient at the interface (kg/m,s,kg/kg'),
S=specific surface area inside the material, i.e., ratio of surface area to the pore volume (m^2/m^3), c=porosity (m^3/m^3), k_v=vapour diffusivity (kg/m,s,kg/kg'),
X_i=equilibrium specific humidity with liquid or capillary water at the interface in the material (kg/kg'), C'=specific heat of the material (J/kg,K),
γ'=density of the material (kg/m^3), R=latent heat of vaporization (J/kg),
$D_{\theta\ell}$=liquid water conductivity related to water content gradient (m^2/s),
$D_{T\ell}$=liquid water conductivity related to temperature gradient (kg/m,s,K),
θ=water content of material (kg/m^3), θ_0=initial water content (kg/m^3),
T=temperature (℃), T_0=initial temperature (℃), t=time (s), x=coordinate (m),
ω=angular velocity of the input surface temperature (rad/s),
λ=thermal conductivity without moisture movement (W/m,K),
λ^*=thermal conductivity defined as $\lambda^*=\lambda+R\cdot D_{Tv}$ (W/m,K),
λ'=thermal conductivity measured by steady state method (W/m,K),
ℓ=thickness of the sample material (m), A,B,C,D=defined in eq.(32),
$D_{\theta v}, D_{Tv}, D_\theta, D_T$=conductivities defined by eq.(7),
T_A, T_B=boundary temperatures of the sample in the steady state method (℃),
θ_m=the mean water content of the material in the steady state method (kg/m^3),

Q=heat flux in the steady state method (W/m^2), $\Delta T=T_A-T_B$ (K),
$\eta_1,\zeta_1,\beta_1,\xi_1,\kappa_1,\gamma_1$=water content coefficients of $D_{\theta l},D_{\theta v},D_{Tl},D_{Tv},c'\gamma',\lambda$ (m^3/kg),
$\eta_2,\zeta_2,\beta_2,\xi_2,\gamma_2$=temperature coefficients of $D_{\theta l},D_{\theta v},D_{Tl},D_{Tv},\lambda$ (1/K),
$T_1,\theta_1,T_2,\theta_2$=the first and second terms of the perturbation solution of the temperature and water content, respectively,
I_0=amplitude of the input surface temperature (K),
α_1,α_2=defined in eq.(31), E,E_1,E_2=defined in eq.(30),
$U_3,U_7,Q_1,Q_2,Q_3,Q_4,Q_5,Q_6',Q_6'',R_1,R_2,R_3,R_4,R_5,R_6',R_6'',V_{18}$=coefficients in θ_2,T_2,
ϕ_1,ψ_1=water content coefficients of D_θ,D_T, respectively (m^3/kg),
ϕ_2,ψ_2=temperature coefficients of D_θ,D_T, respectively (1/K)

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