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VI

Thermal Conductivity of the Moist Porous Building Material

La conductivité thermique de matériaux de construction poreux et humides

Wärmeleitfähigkeit feuchter poröser Baumaterialien

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SUMMARY

The implication of the thermal conductivity of a moist porous material was investigated by the equations of the simultaneous transfer of heat and moisture. As typical measuring methods, the steady state method and the periodic method were analysed and the thermal conductivities were measured by the periodic method.

RESUME

La conductivité thermique de matériaux de construction poreux et humides a été étudiée à l'aide des équations du transfert simultané de chaleur et d'humidité. Les méthodes habituelles ont été étudiées c-à-d la méthode statique et la méthode périodique. Les conductivités thermiques ont été mesurées à l'aide de la méthode périodique.

ZUSAMMENFASSUNG

Die Wärmeleitfähigkeit feuchter poröser Stoffe wurde mit Hilfe der Gleichungen der gekoppelten Wärme- und Feuchteübertragung untersucht. Als typische Messmethoden wurden die stationären und instationär-periodischen Verfahren analysiert. Die Wärmeleitfähigkeiten wurden mit dem letztgenannten Verfahren gemessen.

1. INTRODUCTION

Up to the present, many theories of heat and moisture transfer in the porous materials have been proposed in the fields of soil science, dry engineering and building engineering. Moreover these theories have been examined on the adequacy of the models by the comparison with the experimental results. But it has been seen that the theory of heat and moisture transfer had never been established completely because of the complexity of transfer mechanism and the difficulty of determination of transfer coefficients and of performance of detail experiments. Especially as the process of condensation and evaporation, the theory of heat and moisture transfer in the wide region of moisture content in which vapour and liquid water transfer existed together have been studied in recent years.

Our purpose in this paper is to establish the theory which can predict the process of condensation. So, the experiments performed under the various conditions were considerably exact, and all the transfer coefficient involved in the theory was determined in detail.

2. THEORY

The theory examined in this paper is that arranged by M. Matsumoto in 1967 [1]. It was assumed in the theory that the porous materials were composed of the parts in which vapour transfered (pore parts), and the other parts in which absorbed and capillarily condensed water transfered (substance parts).

Vapour flux in the pore parts is given in Eq.(1).

$$q_v = -k_v \nabla X \quad (1)$$

Absorbed and capillarily condensed water flux in the substance parts is given in Eq.(2).

$$q_l = -D_{\theta l} \nabla \theta - D_{Tl} \nabla T \quad (2)$$

Heat flux in the material is given in Eq.(3).

$$q_h = -\lambda \nabla T \quad (3)$$

Then, getting the balance of the heat and moisture, the following equations are obtained;

$$\text{for vapour transfer, } C_Y \frac{\partial X}{\partial t} = \nabla \cdot (k_v \nabla X) + \alpha' S (X_i - X) \quad (4)$$

$$\text{for liquid water transfer, } \frac{\partial \theta}{\partial t} = \nabla \cdot (D_{\theta l} \nabla \theta) + \nabla \cdot (D_{Tl} \nabla T) + \alpha_i' S (X - X_i) \quad (5)$$

$$\text{for heat transfer, } C'Y' \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + R \alpha_i' S (X - X_i) \quad (6)$$

Here, considering $\alpha_i' = \infty$ (local equilibrium), the absorption isotherm is

$$X_i = X = g(\theta, T) \quad (7)$$

Therefore from Eq.(4), (5), (7), the basic differential equation for moisture transfer is expressed in Eq.(8).

$$(1 + C_Y \frac{\partial g}{\partial \theta}) \frac{\partial \theta}{\partial t} + (C_Y \frac{\partial g}{\partial T}) \frac{\partial T}{\partial t} = \nabla \cdot (D_{\theta} \nabla \theta) + \nabla \cdot (D_T \nabla T) \quad (8)$$

$$\text{here, } D_{\theta} = D_{\theta v} + D_{\theta l} = k_v \frac{\partial g}{\partial \theta} + D_{\theta l}, \quad D_T = D_{T v} + D_{T l} = k_v \frac{\partial g}{\partial T} + D_{T l} \quad (9)$$

Similarly from Eq.(4), (6), (7), the basic differential equation for heat transfer is expressed in Eq.(10).

$$(C'Y' + RC_Y \frac{\partial g}{\partial T}) \frac{\partial T}{\partial t} + (RC_Y \frac{\partial g}{\partial \theta}) \frac{\partial \theta}{\partial t} = \nabla \cdot (\lambda \nabla T) + R \nabla \cdot (D_{\theta} \nabla \theta + D_T \nabla T) \quad (10)$$

Equation (8), (10) are the basic equations which we will examine in this paper. The above basic equations might reduce to Philip and de Vries's equation if getting $C\gamma = 0$, and correspond with Luikov's equation if getting $C\gamma = 0$ and moreover ε and λ as constant [2,3], here

$$\varepsilon = \frac{D_{gv}\nabla\theta + D_{Tv}\nabla T}{\frac{\partial\theta}{\partial t}} \quad (11)$$

3. EXPERIMENTS

We used the wood fibre board as the experimental material which was 10 cm square and 8.5 mm depth. Vapour barrier was applied to one end the four sides of this material.

As shown in Fig.1, the experimental apparatus is composed with three parts. The first part is the double walled cover, the second is the plate of the experimental material and the third is the copper box in which the regulated water is circulating to keep the copper surface of the box at the required temperature. At each experiment, these parts were set and sealed tightly. The air temperature in the cover was regulated by setting the experimental apparatus in the constant temperature room. Also the humidity of air in this cover was kept constant by the water solution saturated with some salt. Temperature of the material surface applied with vapour barrier was regulated by the copper surface of the box on which the material put closely. Increase of vapour amount absorbed into the material was obtained by the measurement of weight of the salt solution. Moisture distribution in the material was obtained by cutting the material into small pieces and weighting the mass immediately after the end of the experiment. Changing process of the moisture distribution were obtained by varying the times of experiments under the same condition.

First, all the experimental system was set at the same temperature and the material in equilibrium condition. Next, the temperature of circulating water was lowered to the point at which internal condensation could be attained.

The experimental conditions are shown together with the number of experiments in table 1.

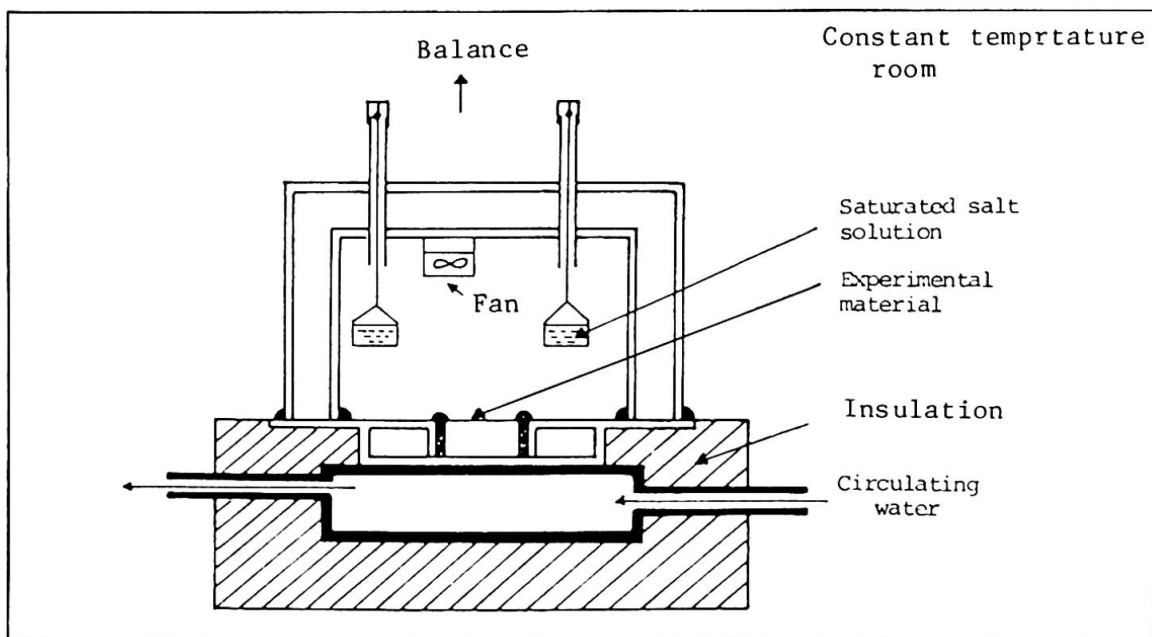


Fig.1. Experimental apparatus

Table 1. Experimental conditions

Experi. condition	Experi. No	Temp. in air	Temp. cold face	Humidity in air		Temp. dew point	Experi. times
		°C	°C	RH %	X (kg/kg)	°C	
A	1	18.6	5.4	54.4	7.37×10^{-3}	9.2	92
	2	18.8	5.0	54.4	7.49×10^{-3}	9.5	296
B	3	20.8	9.6	75.5	11.78	16.4	28
	4	20.5	9.6	75.5	11.54	16.1	48
	5	20.5	9.6	75.5	11.54	16.1	100
	6	20.3	9.6	75.5	11.40	15.9	165
	7 *	20.8	9.8	75.5	11.78	16.4	165
C	8	28.5	5.2	47.9	11.98	16.7	68

* Measurement of the temperature distribution in the material

4. DETERMINATION OF THE TRANSFER COEFFICIENTS INVOLVED IN THE EQUATION

Transfer coefficients in Eq.(8),(10) are moisture conductivity D_θ , thermal moisture conductivity D_T and heat conductivity λ . Moreover, it is necessary to separate moisture conductivities D_θ , D_T into vapour and liquid components $D_{\theta v}$, $D_{\theta l}$; D_{Tv} , D_{Tl} respectively. We obtained all the transfer coefficients of our experimental material as following.

4.1 Isothermal Moisture Conductivity D_θ related to Moisture Gradients

Various methods of measuring D_θ have been proposed. In our study, D_θ was measured by the steady state method.

One dimensional moisture flow in the assumed local equilibrium is

$$q_w = q_v + q_l = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x} \quad (12)$$

Here, under the isothermal state, Eq.(12) becomes

$$q_w = -D_\theta \frac{\partial \theta}{\partial x} \quad (13)$$

Therefore, D_θ is obtained by measurement of moisture flux q_w and moisture gradient $\partial \theta / \partial x$ at steady state. Measurements were performed under four conditions as shown in Table 2. The measuring results is shown in Fig.2.

The figure shows that by No 1,2,3, D_θ curve is obtained in the region from 5 to 150% mass moisture contents and that there is distinct difference on D_θ curve of 9°C and 20°C in the region from 10 to 60% mass moisture contents.

4.2 Separation of D_θ into vapour and liquid components $D_{\theta v}$, $D_{\theta l}$

Separation of D_θ into vapour and

Table 2. Measuring condition of D_θ

No	Suction	Surrounding air		Moisture flux
	cm	°C	RH %	$10^{-3} (g/cm^2 h)$
1	122	22.5	40.0	0.53
2	48	20.0	40.0	17.28
3	85	20.0	40.0	9.82
4	52	9.0	53.0	0.80

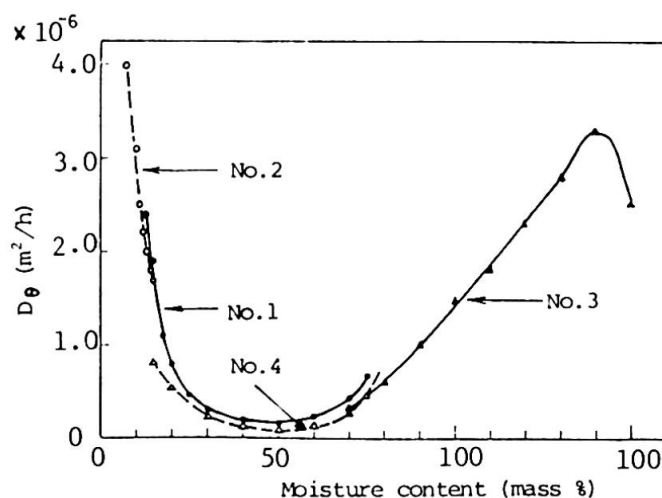


Fig.2. Isothermal moisture conductivity D_θ of wood fibre board

liquid components is very important and necessary in the problem of the simultaneous heat and moisture transfer. So far, some methods of the separation have been tried, but we think that these methods are incomplete. So, in our study, new method of the separation is considered.

That is, assuming that vapour and liquid transfer respectively in accordance with Stephan's law and Darcy's law which is extended in unsaturated flow, the equations for vapour flow

$$q_v = -D_{av} \frac{P}{P - p_v} \beta \nabla p_v \quad (14)$$

for liquid flow

$$q_l = -f_w K \nabla \psi \quad (15)$$

can be obtained.

Here, the following relations exist.

$$p_v = p_{v0} \exp\left[\frac{\psi g}{RT}\right] = f_{v0} h \quad (16)$$

$$\psi = \frac{2\sigma}{r} \frac{1}{f_w g} \quad (17)$$

$$K = \xi k \frac{f_w g}{\eta} \quad (18)$$

Changing these transfer equations into the transfer equations due to temperature and moisture gradients, as it may be considered that f_{v0} only depends on temperature, and h only depends on moisture contents, Eq.(14) becomes

$$q_v = -D_{av} \frac{P}{P - p_v} \beta \frac{h}{RT} \frac{2\sigma}{f_w} \frac{d}{d\theta} \left(\frac{1}{r}\right) \nabla \theta - D_{av} \frac{P}{P - p_v} \beta \frac{df_{v0}}{dT} h \nabla T \quad (19)$$

and Eq.(15)

$$q_l = -\xi k \frac{f_w}{\eta} 2\sigma \frac{d}{d\theta} \left(\frac{1}{r}\right) \nabla \theta - \xi k \frac{2f_w^2}{\eta r} \left[\frac{1}{f_w} \frac{d\sigma}{dT} + \sigma \frac{d}{dT} \left(\frac{1}{f_w}\right) \right] \nabla T \quad (20)$$

each coefficient in the reduced equations respectively correspond to $D_{\theta v}$, D_{Tv} , $D_{\theta l}$ and D_{Tl} in Eq.(9). Some elements involved in these coefficients depend only on temperature, and the other elements depend only on moisture contents. Then, D_{θ} and D_T are expressed in the next forms.

$$D_{\theta} = D_{\theta v} + D_{\theta l} = D_{\theta v}^{\circ} f_1(T) + D_{\theta l}^{\circ} f_2(T) \quad (21)$$

$$D_T = D_{Tv} + D_{Tl} = D_{Tv}^{\circ} f_3(T) + D_{Tl}^{\circ} f_4(T) \quad (22)$$

where f_1, f_2, f_3 and f_4 are the factors which change with temperature and $D_{\theta v}^{\circ}$, $D_{\theta l}^{\circ}$, D_{Tv}° and D_{Tl}° are the factors which change with moisture contents. The changing rates due to temperature in $f_1 - f_4$ are calculated and shown in Table 3. Comparing these changing rates with the values of D_{θ} obtained in the measurements No.1 (22.5°C), No.4 (9.0°C), it was supposed that vapour transfer was dominant in the region less than 45% mass moisture content and liquid transfer was dominant in the region larger than 80% mass moisture contents. Then, it was indicated that vapour and liquid flow existed together in the region from 45 to 80% mass moisture contents. So, the separation of D_{θ} into $D_{\theta v}$ and $D_{\theta l}$ in this region was obtained by means of interpolation with smooth curve. The results of the separation is given in Fig.3.

Table 3. Changing ratio due to temperature

Factor	Temperature (°C)				
	9.0	15.0	20.0	23.0	30.0
$f_1(T)$	1.94	2.94	4.11	4.99	7.78
$f_2(T)$	1.31	1.52	1.71	1.82	2.11
$f_3(T)$	1.91	2.90	4.05	4.94	7.80
$f_4(T)$	1.33	1.57	1.78	1.91	2.24

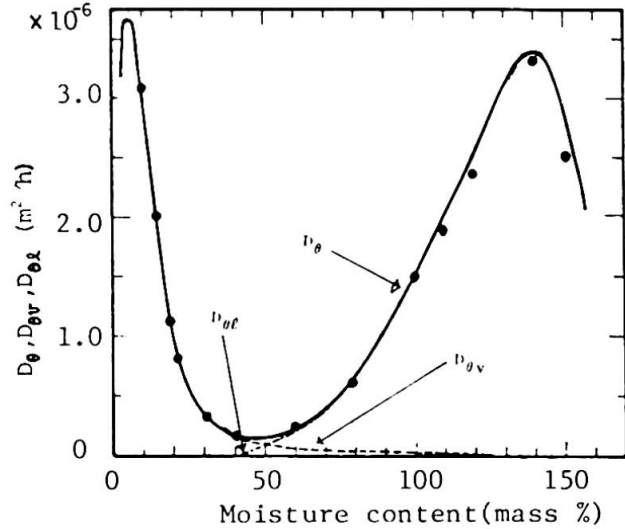


Fig.3. Isothermal moisture conductivity D_{θ} , $D_{\theta v}$, $D_{\theta l}$ of wood fibre board (20°C)

4.3 Thermal Moisture Conductivity D_T related to Temperature Gradients

As thermal moisture conductivity D_T cannot be measured directly, the following method is used. When q_w is zero, Eq.(12) becomes

$$-D_\theta \nabla \theta - D_T \nabla T = 0 \quad (23)$$

also

$$\epsilon = \frac{D_T}{D_\theta} = - \frac{\nabla \theta}{\nabla T} \quad (24)$$

where we will call ϵ as the coefficient of temperature gradient. From Eq.(24),

$$D_T = \epsilon D_\theta \quad (25)$$

Therefore, D_T is obtained by knowing D_θ which can be measured independently and ϵ which can be calculated from the measured values of the temperature and moisture gradients in the equilibrium state ($q_w = 0$).

Measurement of ϵ have been done under the condition provided with a vapour barrier all along the material surfaces [4,5]. But it was pointed out in some papers [5,6] that theoretical results was not agree with the experimental results in the occasion of using ϵ which was obtained in this method.

So, in our study, we used the result of the experiment under the condition of condensation occuring in the material of which the vapour barrier was appried on one end. In such condition, moisture transfer becomes finally to zero, and the moisture profile is shown in Fig.8. Temperature profile in the equilibrium state was calculated using the temperatures of both surfaces and thermal conductivity obtained later (see 4.5). Result of ϵ is given in Fig.4., and D_θ curve calculated from Eq.(25) is given in Fig.5.

4.4 Separation of D_T into vapour and liquid components D_{Tv} , D_{Tl}

From Eq.(9), D_{Tv} is obtained in Eq.(26)

$$D_{Tv} = D_{\theta v} \frac{\frac{\partial g}{\partial T}}{\frac{\partial g}{\partial \theta}} \quad (26)$$

Therefore, D_{Tv} is determined by $D_{\theta v}$ and absorption isotherm. By obtaining D_{Tv} , D_{Tl} can be calculated in Eq.(27)

$$D_{Tl} = D_T - D_{Tv} \quad (27)$$

Result of separation is given in Fig.5.

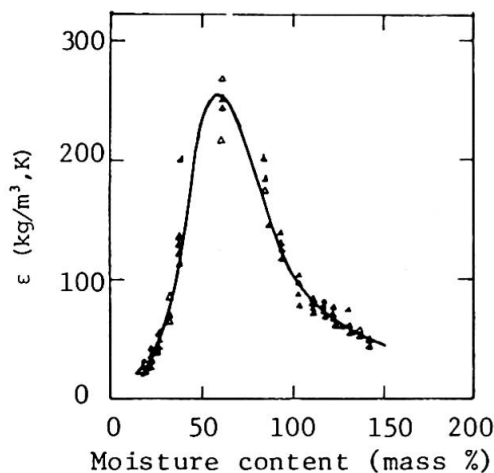


Fig.4. Coefficient of temperature gradient ϵ obtained by experiment of condensation

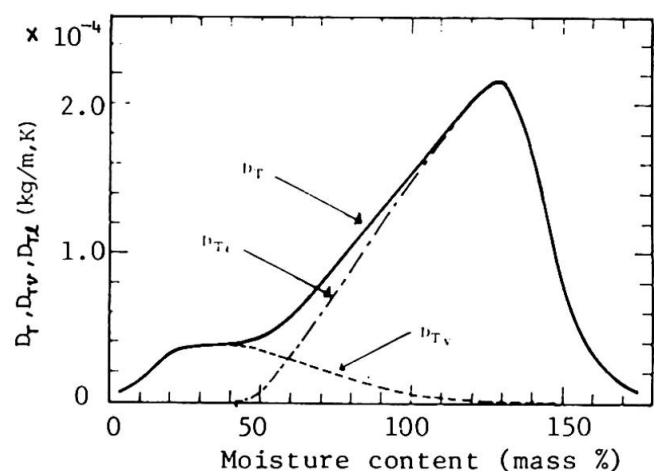


Fig.5. Thermal moisture conductivity D_T , D_{Tv} , D_{Tl} of wood fibre board (20°C)

4.5 Thermal Conductivity λ

It is well known that thermal conductivity λ would change largely with moisture content. There have been many proposed methods of measuring the thermal conductivity. But these methods have not been analyzed on the base of heat and moisture transfer equations, because these equations have not been completely established up to date.

We have developed the measuring methods of thermal conductivity depending on moisture contents. The detail is given in another paper [7]. In this paper, we used the results obtained by the above methods which can be seen in Fig.6.

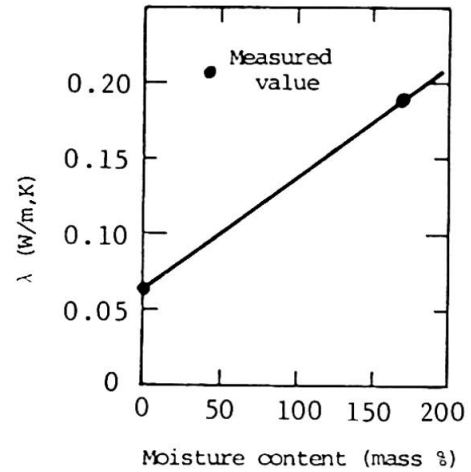


Fig.6. Thermal conductivity λ of wood fibre board

5. RESULT AND DISCUSSION

Experimental results are given in Fig.7,8,9,10,11. The Fig.7 shows that under the experimental condition A, the absorption finally stops and the moisture content approaches the constant value which is less than that of the pores filled completely with water. In the absorption processes of A,B,C, the amount of absorbed moisture increase with the straight line in the early time. The reason seems to be the influence due to the increase of thermal conductivity. The theoretical results are also given in Fig.7,8,9,10,11. The basic equation of heat and moisture transfer was differentiated with Clank-Nicholson method and calculated with electronic computer.

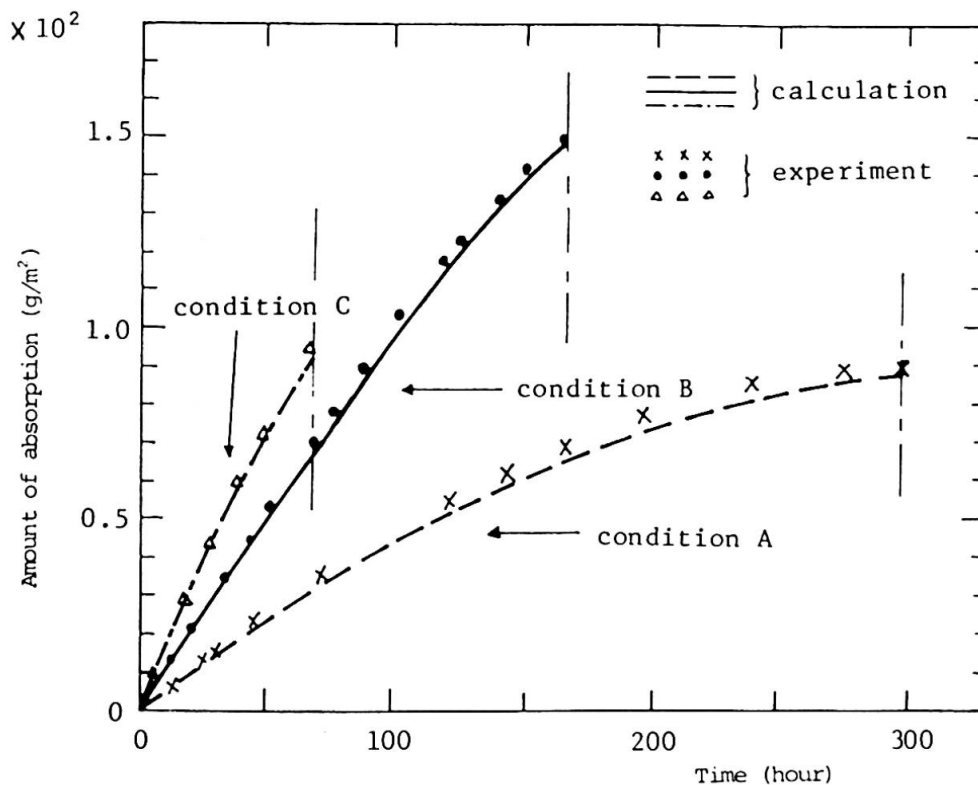


Fig.7. Experimental and theoretical results of amount of absorption under internal condensation (A,B,C)

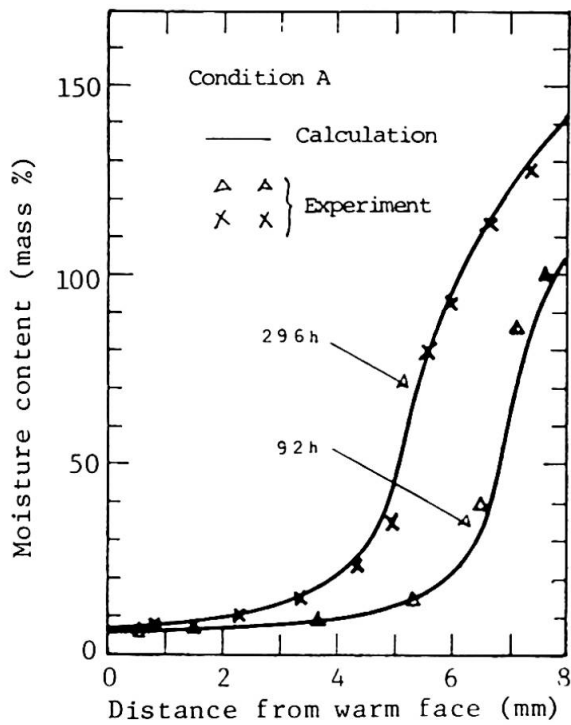


Fig.8. Experimental and theoretical results of moisture content distribution (condition A)

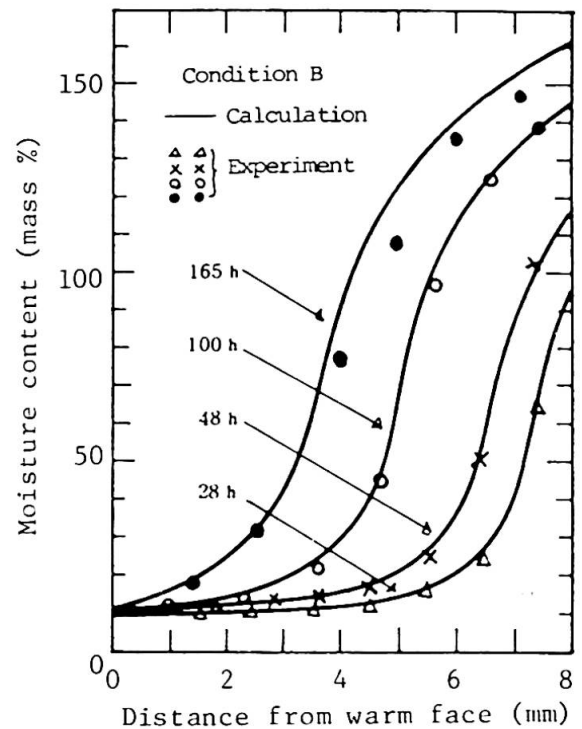


Fig.9. Experimental and theoretical results of moisture content distribution (condition B)

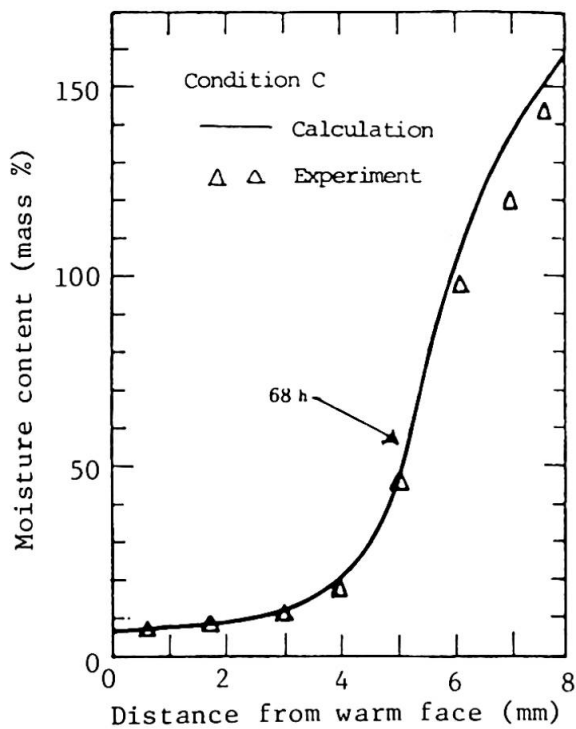


Fig.10. Experimental and theoretical results of moisture content distribution (condition C)

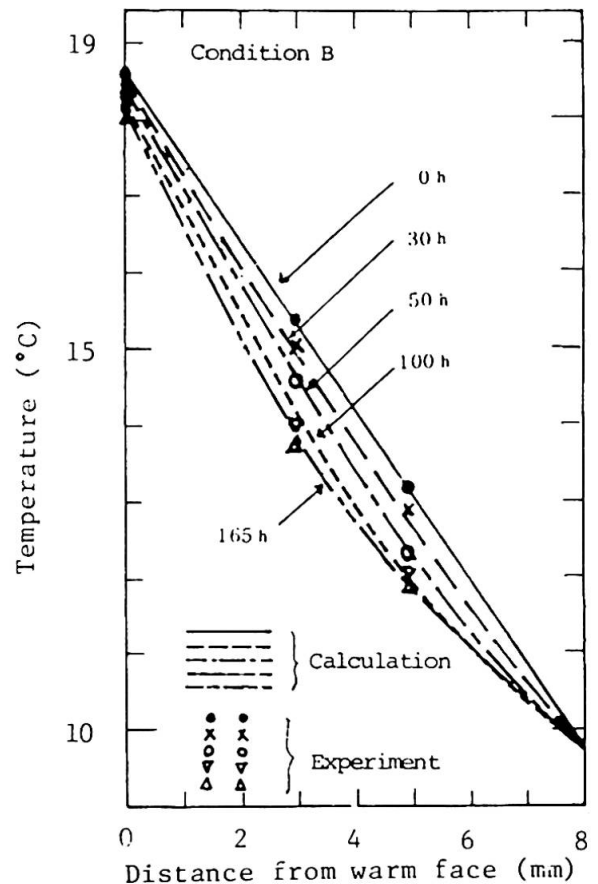
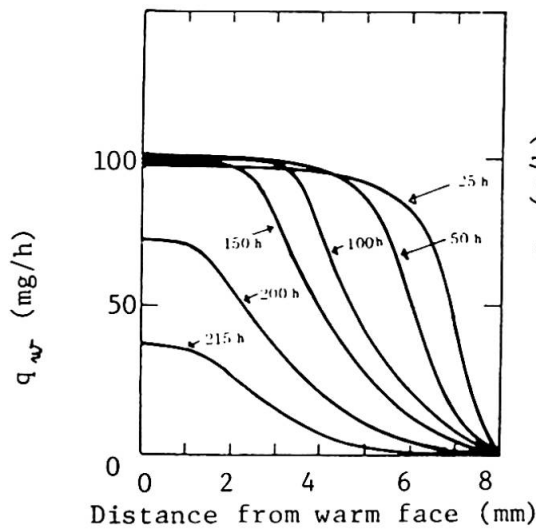


Fig.11. Experimental and theoretical results of temperature distribution (condition B)

Fig.12. Moisture flux q_w

Figures show the good agreement of the theoretical results with the experimental results. Namely, our theory can sufficiently estimate the process of condensation in the region over 0°C .

Next, we will analyze in detail the mechanism of heat and moisture transfer in the material on the basis of the theory. The condition of calculation is that of the experiment B. Theoretical results are given in Fig. 12,13,14,15,16.

As shown in Fig.12. the distribution of the moisture flux q_w in the material are made up of two parts; one part in which q_w is constant value, and the other part in which q_w decrease rapidly from constant value to zero. The former is hygroscopic region in which vapour transfer is dominant, and this region decrease with time. In the latter part, vapour and liquid water transfer exist together, and as approaching the cold face, liquid water transfer becomes dominant. These are understood from the figure 13 - 16. As shown in these figures, the liquid water fluxes $q_{\theta l}$, $q_{\tau l}$ are higher than the vapour fluxes $q_{\theta v}$, $q_{\tau v}$. Moreover, $q_{\theta l}$ and $q_{\tau l}$ are almost the same order. But, $q_{\theta l}$ and $q_{\tau l}$ are cancelled each other because the direction of the temperature gradient and moisture content gradient are opposite in the process of condensation. Therefore the moisture transfer in the material under the condition of condensation depends largely on vapour transfer.

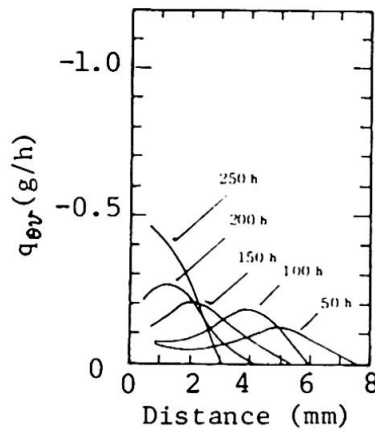


Fig.13. Vapour flux due to moisture content gradient

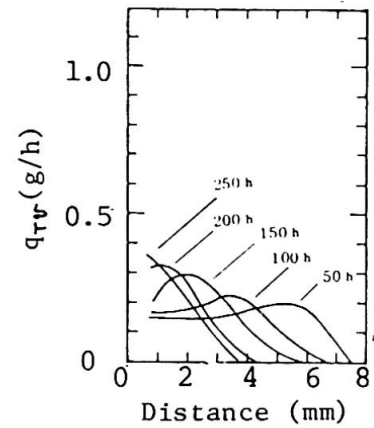


Fig.14. Vapour flux due to temperature gradient

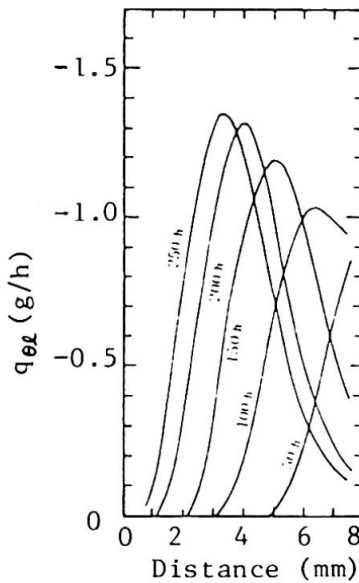


Fig.15. Liquid water flux due to moisture content gradient

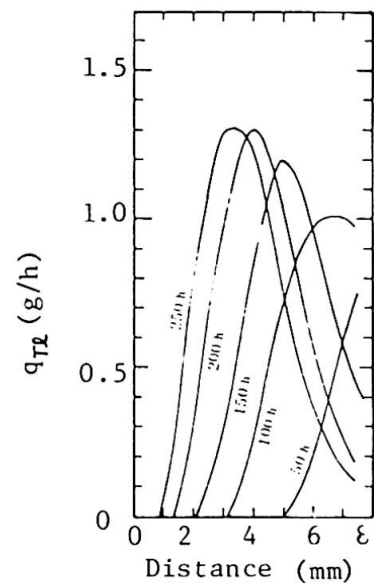


Fig.16. Liquid water flux due to temperature gradient



NOTATION

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),	X_i	equilibrium specific humidity with liquid or capillary water at the interface in the material (kg/kg'),
k_v	vapour diffusivity (kg/m,s,kg/kg'),	$D_{\theta l}$	liquid water conductivity related to moisture content gradient (m ² /s)
C	specific heat of the material (J/kg,K),	D_{Tx}	liquid water conductivity related to temperature gradient (kg/m,s,K)
γ'	density of the material (kg/m ³),	$D_{\theta}, D_T, D_{\theta v}, D_{Tv}$	conductivities defined by Eq.(9),
R	latent heat of vaporization (J/kg),	θ	moisture content of material (kg/m ³)
q_v	vapour flux (kg/m ² ,s)	T	temperature (K)
q_l	liquid water flux (kg/m ² ,s)	t	time (s)
q_A	heat flux (W/m ²)	x	coordinate (m)
$q_{\theta v}$	vapour flux due to moisture content gradient (kg/m ² ,s),	λ	thermal conductivity without moisture movement (W/m,K)
$q_{\theta l}$	liquid water flux due to moisture content gradient (kg/m ² ,s)	Ψ	capillary potential (m)
q_{Tv}	vapour flux due to temperature gradient (kg/m ² ,s)	g	acceleration due to gravity (m/s ²)
q_{Tl}	liquid water flux due to temperature gradient (kg/m ² ,s),	R	gas constant of vapour (N/kg,K)
q_w	moisture flux (kg/m ² ,s)	σ	surface tension (N/m)
D_{vm}	vapour diffusivity in air (m ² /s)	η	viscosity (kg/m,s)
P	total pressure (kg/m ²)	ξ	coefficient depends on moisture content (-)
p_v	partial pressure of vapour (kg/m ²)	ρ_{v0}	density of saturated water vapour (kg/m ³)
β	tortuosity (-)		
K	unsaturated hydraulic conductivity (m/s)		
h	relative humidity (-)		
r	radius of capillary (m)		
k	specific permeability (m ²)		
ρ	density (kg/m ³)		

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