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MOISTURE TRANSFER IN MATERIAL

M.Mizuhata, T.Terashima, S.Nishiwaki
Faculty of Engineering, Mie University
Tsu 514, Japan

ABSTRACT

Calcium silicate board has recently been extensively used as an interior finish material for Japanese houses, in which the humidity needs to be controlled. The dependence of moisture diffusivity, due to both a moisture content gradient and a temperature gradient, and the thermal conductivity on the moisture content and the properties of the equilibrium moisture content curve in such calcium silicate board, were measured. Analysis showed that results were largely dependent upon levels of moisture content. The experiment on the condensation and re-evaporation process in interior finish materials, which are dampproofed on the vapor-barrier side, was carried out and the change of moisture content in materials over a period of time was measured. The results were compared with the analyzed value by simultaneous heat and moisture transfer equation. It was found that the equilibrium moisture content curve had a significant influence on the calculated value. It is proposed that the heat and moisture transfer equation is applicable in the case of the condensation and re-evaporation process.

1 INTRODUCTION

The analysis of moisture movement is very difficult and complex because vapor diffusion and liquid water movement, which occur at the same time, have an influence on each other, and the properties of the material change considerably depending on the moisture content and temperature of the given material. Studies dealing with quantitative analysis of the results of experiments on the condensation and re-evaporation process have been made by Kooi1), Matsumoto et al2), Mizuhata3)(using cellular concrete),and Ikeda et al4)(using soft fiber board). These studies suggest the validity of analysis of the condensation and re-evaporation by heat and moisture transfer equation. However, quantitative analyses of as many materials as possible are deemed necessary, since the thermal and moisture properties of building materials vary widely, even when they are of the same kind.

The purpose of this study is to obtain fundamental data on the design of condensation prevention methods, through theoretical analysis of and experiments on the moisture movement in the calcium silicate board, and through discussion of the validity of analysis using the simultaneous heat and moisture transfer equation.

2 THEORY AND CALCULATION

When the moisture content in materials is relatively low, then moisture diffusion depends almost entirely on the differences in moisture content, but when the moisture content is greater, moisture diffusion depends on differences not only in moisture content but also in temperature. Therefore in materials in which condensation occurs, moisture moves principally because of moisture content gradient and temperature gradient. Where there is no difference of pressure in a material and the influence of gravitation is negligible, then, for a one-dimensional flow the heat and moisture transfer equation can be expressed as; 5)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} D_\theta \frac{\partial \theta}{\partial x} + \frac{\partial}{\partial x} D_T \frac{\partial T}{\partial x} \tag{1}$$

$$c\gamma \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \lambda_\theta \frac{\partial T}{\partial x} + R \frac{\partial}{\partial x}\left(D_{\theta v} \frac{\partial \theta}{\partial x} + D_{Tv} \frac{\partial T}{\partial x}\right). \tag{2}$$

On the interior surfaces the boundary condition can be expressed as ;

$$\alpha'(p_i - p_s) = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x}, \quad \alpha(T_i - T_s) = -\lambda_\theta \frac{\partial T}{\partial x}$$

in which the influence of adsorption heat on heat transfer is negligible.
On dampproofed surfaces the following equations apply ;

$$-D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x} = 0, \quad T = T_d(t)$$

Numerical calculation is carried out using the Crank-Nicolson type explicit finite difference method. In numerical calculation time interval Δt is 1/10 hour and division interval Δx is 0.003 m (number of division 10). Stability of solution of this calculation has already been confirmed.

3 MEASUREMENTS OF MATERIAL PROPERTIES AND ITS RESULTS

3.1 Total moisture diffusivity due to moisture gradient$^{6)}$

Method of measurement and measuring equipment used For a one-dimensional flow, the Eq.(3) can be written thus for material that is isothermal and when the flow is in steady state ;

$$\frac{q_w}{\gamma} = -D_\theta \frac{\partial \theta}{\partial x}. \tag{3}$$

If moisture is provided at one end of the specimen and evaporates at the other end the moisture flow eventually becomes steady. After this the quantity of moisture flow q_w, and distribution of moisture content by dividing specimen and moisture content gradient $\partial\theta/\partial x$, are measured and D_θ is determined by Eq.(3).

The measuring equipment is shown in Fig.1. The specimen dimension is 3.0cm(l)×3.0cm(w)×4 cm(h). The specimen is thoroughly dried in an ovendryer at 105 ± 2 ℃ ,and its dry weight is measured. The side surface of the specimen is covered with aluminum tape to dampproof it, and the suction end of the specimen is covered with a cellophane semipermeable membrane. The membrane is installed to shield the air flow into the tank from the specimen, which is under constant suction pressure. Through control of the resistance of permeability of semipermeable membrane and control of the pressure by changing the vertical height of the tank from the mes-pipet to the top of the water tank, the evaporation and the average moisture content are controlled. As an acrylic acid resin vessel containing an NaCl-saturated water solution is mounted on the side on which evaporation occurs the humidity of the chamber is kept constant.

Measurement and the results All the equipment was laid horizontally on the table in the room. The temperature of room air was kept at 20±0.5 ℃, and that of the chamber was kept at 20± 0.2 ℃. The inflow into the specimen was measured according to the distance moved by the meniscus of the water in the mes-pipet. Measuring was carried out daily, ensuring that there was always water in the mes-pipet. The experiment was continued until the change of the inflow became constant. Then, the specimen was removed from the equipment and the aluminum tape was removed. After measuring the weight of the specimen the width was cut with a multiband saw at approximately 5mm intervals. Using the same method as described previously all the pieces were then thoroughly dried and the dry weight and thickness of the pieces was measured. The achieved moisture content of each piece was regarded as the moisture content at the center of each piece. Measurement of 8 specimens was carried out. The moisture diffusivity D_θ which was obtained from stationary inflow and moisture content gradient of the specimen is shown in Fig.2.

3.2 Total moisture diffusivity due to temperature gradient$^{6)}$

The method of measurement and measuring equipment When there is no inflow the following equation can be written for a one-dimensional flow in a steady state ;

$$0 = -D_\theta \frac{\partial \theta}{\partial x} - D_T \frac{\partial T}{\partial x}. \tag{4}$$

Therefore, it follows that ;

$$\frac{D_T}{D_\theta} = -\frac{\nabla\theta}{\nabla T} \equiv \varepsilon. \tag{5}$$

where ε is the temperature gradient factor. Therefore, if the specimen is dampproofed on all surfaces, and a difference of temperature is maintained between both ends then a steady state will be achieved after a long while. Factor ε is determined by moisture content and temperature gradient at that time. Therefore, if ε and D_θ are known, the diffusivity due to temperature gradient D_T can be obtained thus ;

$$D_T = \varepsilon D_\theta. \tag{6}$$

The size of each specimen used was 45mm(l) × 45mm(w)× 30mm(h).To examine the dependence of temperature gradient coefficient on the average moisture content four kinds of specimens, of which the initial weight moisture contents was 9,20,30 and 40 % respectively, were used. For each kind of specimen, one for measurement of temperature distribution and seven for measurement of moisture content distribution, 32 specimens in all were used. As to the equipment of the experiment, the specimens, dampproofed on all surfaces with aluminum foil, were all put on copper plate on the same level and their side surfaces were insulated with foamed styrene so that heat flow might be one-dimensional as shown in Fig.3. Their upper surface was covered with a flat heating device, which was insulated with foamed styrene ,and on this a copper plate was placed so as to attach the heater and specimens. The entire equipment was put in the climate room.

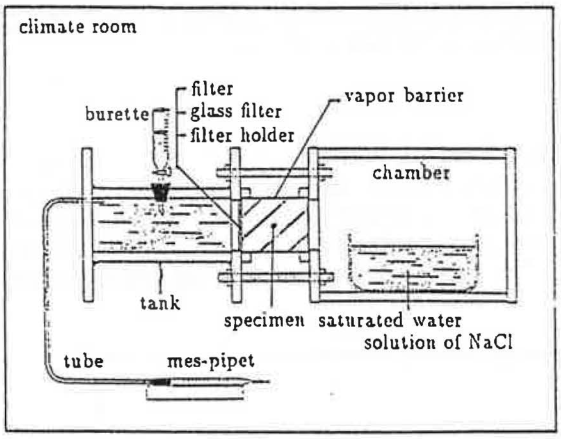

Fig.1 Experimental equipment
on diffusivity due to moisture gradient

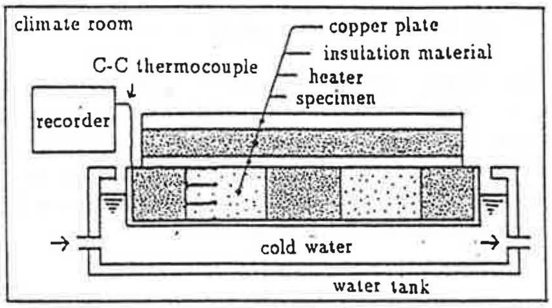

Fig.3 Experimental equipment
on diffusivity due to temperature gradient

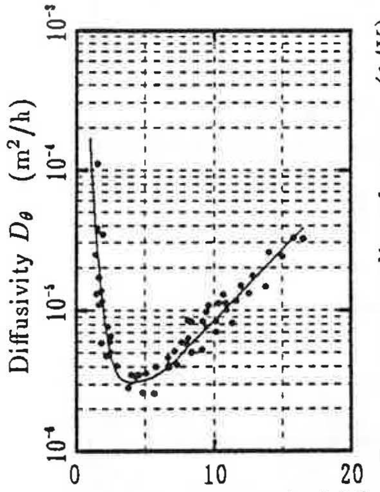

Fig.2 Diffusivity due to
moisture content gradient

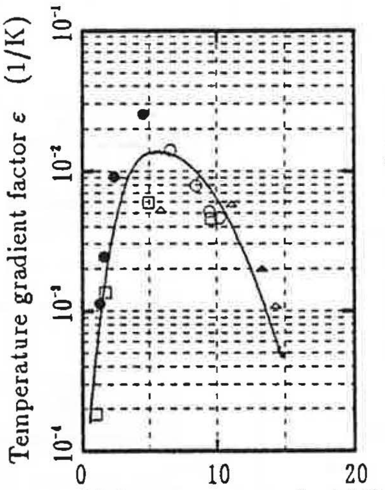

Fig.4 Temperature
gradient factor

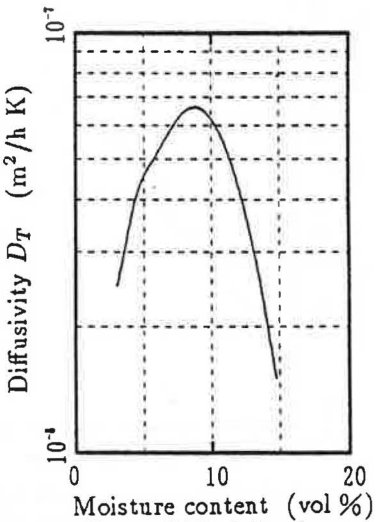

Fig.5 Diffusivity due to
temperature gradient

Measurement and the results After water was absorbed gradually to saturation from the end of the 4 kinds of specimens they were left in the climate room and dried until their moisture content achieved the specified level. Following this the initial average moisture content of each specimen was determined. Immediately after this the surface of each specimen was bound with aluminum foil three times and then fixed with cellophane tape in order to dampproof it. The specimens were left like this for about 2 weeks in the climate room, in which the constant temperature was 20±0.5 ℃.

The specimens were placed on the testing equipment, of which the tank water temperature was previously set at 10 ℃ and the temperature of the bottom surface of the flat heater was previously set at 70 ℃. After beginning the experiment each specimen was removed at an appropriate time, and divided into 5 pieces with a multiband saw at an average of 6 mm intervals. After the weight of each piece was measured it was then dried completely and its moisture content distribution was determined. The temperature gradient factor ε was obtained by calculation from the temperature gradient and the moisture content gradient as before. The calculated temperature gradient factor ε of 4 kinds of the specimens is shown in Fig.4. Fig.5 shows the diffusivity D_T obtained from D_θ in Fig.2 and ε in Fig.4.

3.3 Thermal conductivity

It is known that the thermal conductivity of humid material increases with the rise of moisture content. Measurement by the steady method is not suitable for long-term measuring or for measuring humid material because the moisture content changes while measurement is being carried out. Here, the measurement of humid calcium silicate board is carried out by the non-steady method which takes only about 5 minutes and is determined by the rate of the increase in temperature of the probe. The results are shown in Fig.6.

3.4 The equilibrium moisture content

In the glass vessels containing five kinds of saturated water solution of salts, such as LiCl, $MgCl_2 \cdot 6H_2O$, $Mg(NO_3)_2 \cdot 6H_2O$, NaCl, KNO_3, several small specimen pieces of calcium silicate board were set up for a long period, and when the weight change of each specimen became negligible, the equilibrium moisture content was calculated from that weight and the original dry weight. The results are shown in Fig.7. In the glass vessels the air temperature was maintained at 20 ℃.

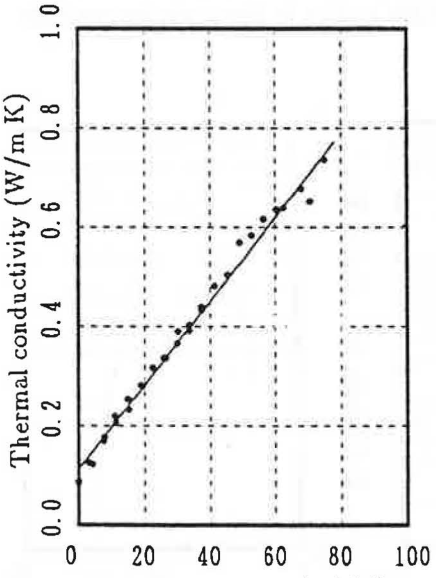

Fig.6 Thermal conductivity

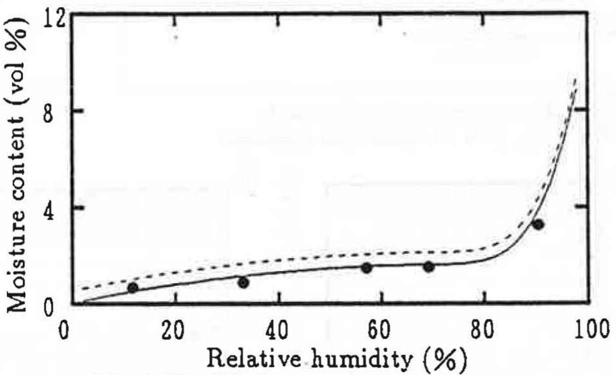

Fig.7 Equilibrium moisture content curve

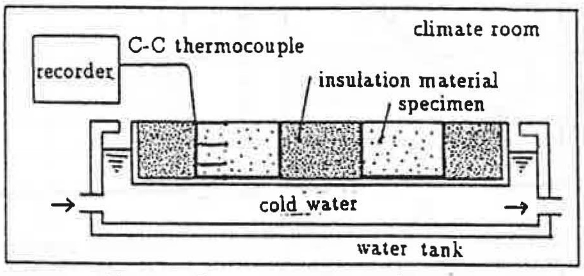

Fig.8 Experimental equipment on the condensation and re-evaporation process

4 EXPERIMENT ON AND ANALYSIS OF CONDENSATION AND RE-EVAPORATION

4.1 Summary of the experiment

As shown in Fig.8 the specimens made of calcium silicate board were put on a copper plate which was set up in the climate room. The bottom of the specimen was water-cooled and moisture was absorbed from the room air into the specimen. One specimen was used for measuring the distribution of temperature from top to bottom and three specimens used for measuring the average moisture content. All specimens measured 10 cm × 10 cm × 3 cm. The side and bottom of the specimens were dampproofed by covering them with aluminum tape and their sides were insulated from heat with foamed styrene so that heat and moisture flow would be in one direction. The room temperature and humidity were kept at 25 ℃, 68 % (21.5×10^2 Pa) during the condensation process, and the temperature of the bottom surface of the specimen was kept at 14 ℃ during the entire process. The weight of the specimens was measured for average moisture content every two days and then they were replaced on the copper plate. Once the weight change during the condensation process ceased, the room temperature and humidity were set at 25 ℃, 54 % (17.1×10^2 Pa), and the weight of the specimens was measured at irregular intervals.

4.2 Results and analysis of the experiment

The changes of the moisture content of the specimens, the temperature and humidity in the room and the temperature of the bottom surface of the specimen over a period of time are shown in Fig.9a and b. The condensation process is shown in Fig.9a and the re-evaporation process is shown in Fig.9b. In both figures the changes of measured moisture content in respect of the average values of three specimens are shown. In both cases the change of the moisture content is shown to be nearly steady after 50 days and the differences of their moisture content during the condensation process is approximately 1 vol %. In the re-evaporation process, however, no differences were noted. The value of properties used for calculation of moisture content are the measured value in §3 ,$\alpha = 7.8\mathrm{W/(m^2{\cdot}K)}$ and $\alpha' = 0.18 \times 10^{-3}\mathrm{kg/(m^2{\cdot}h{\cdot}Pa)}$. The vapor pressure on the inside surface p_s is determined according to the temperature at the surface of the specimen T_s and the relative humidity, which corresponds to the moisture content of the specimen θ_s in the curve of equilibrium moisture content1). The curve changes over time, of calculated moisture content, are plotted in calculation value 1 in the figures. The calculated value agrees with the measured values in the condensation process ,but the former is smaller than the latter in the re-evaporation process.

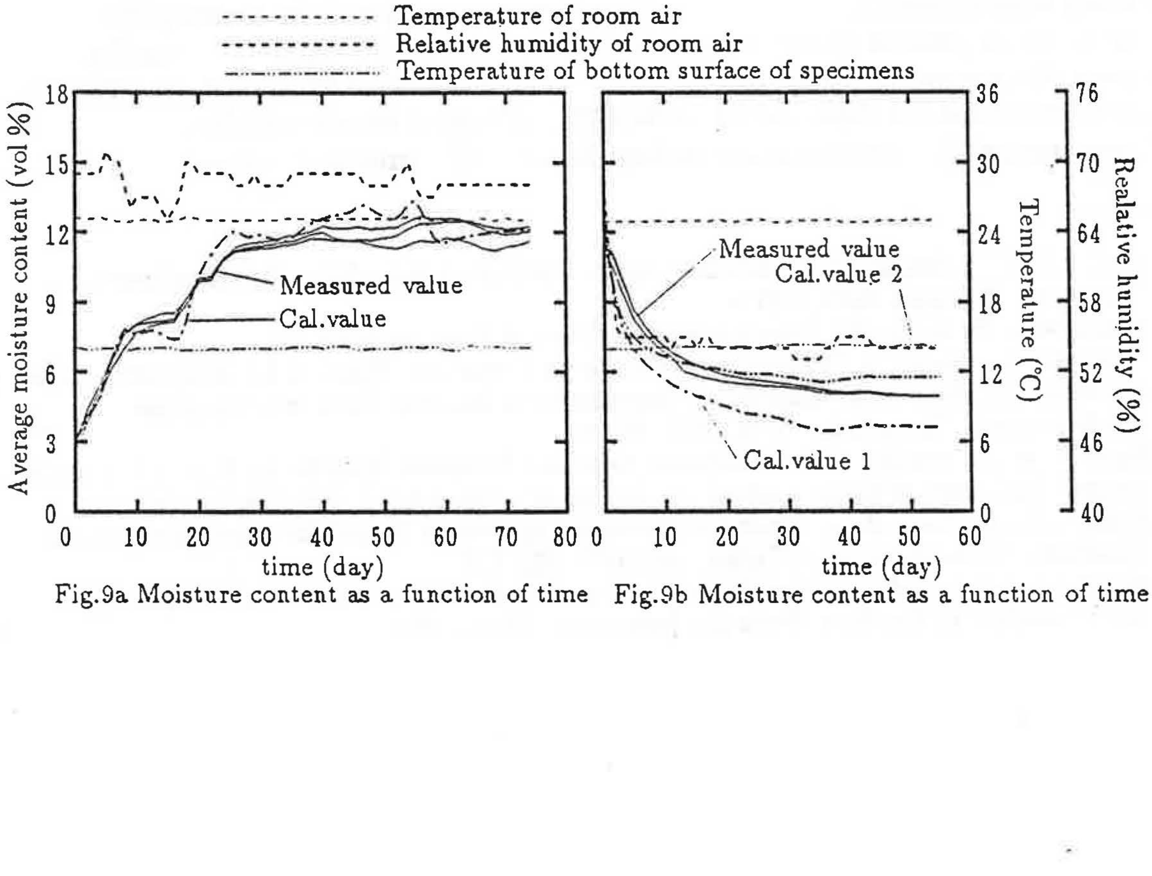

Fig.9a Moisture content as a function of time

Fig.9b Moisture content as a function of time

It is thought that one of the causes of this is the difference of the applied value of the α, α',equilibrium moisture content curve and so on, used for calculating in both processes. Therefore another calculated value was established using the estimated values of the higher equilibrium moisture content curve of 0.5 % more than that of the absorption process in a solid line, as shown in Fig.7. The results are depicted as calculation value 2 in Fig.9b. Calculation value 2 is similar to the measured values compared with calculation value 1, but the values during the steady state are very different from those of calculation value 1. Results show that even a small difference of the equilibrium moisture content curve has a quite significant influence on the calculated values. This appears to be the reason why the moisture content increases so little while the relative humidity increases significantly, as seen in the equilibrium moisture content curve. In the future the influence of hysteresis will have to be examined.

5 CONCLUSION

The dependence of moisture diffusivity, due to both a moisture content gradient and a temperature gradient, and the thermal conductivity on the moisture content and the properties of the equilibrium moisture content curve in calcium silicate board, were measured. Analysis showed that results were largely dependent upon levels of moisture content. The experiment on the condensation and re-evaporation process was carried out using materials which were dampproofed on one side, and the change of moisture content in the materials over time was measured. The results were compared with the analyzed value by simultaneous heat and moisture transfer equation.

Results show that the calculated values are shown to correspond with the measured values during the condensation process, but do not correspond during the re-evaporation process. It is clear that the equilibrium moisture content curve has a great influence on the calculated value. Further examination of the influence of the hysteresis is left as a future problem. The validity of the application of the heat and moisture transfer equation to the case of the condensation and re-evaporation process is proposed.

Nomenclature

D_θ:total moisture diffusivity due to moisture gradient[m^2/h],
D_T:total moisture diffusivity due to temperature gradient[$m^2/(h \cdot K)$],
θ:volume moisture content[vol %], c:specific heat of material[$J/(kg \cdot K)$],
γ:specific weight of material[kg/m^3], λ_θ:thermal conductivity of material[$W/(m \cdot K)$],
α:heat transfer coefficient[$W/(m^2 \cdot K)$], α':moisture transfer coefficient[$kg/(m^2 \cdot h \cdot Pa)$],
T_i:room temperature[℃], T_s:surface temperature of the specimen[℃],
p_s:water vapor pressure at the surface of the specimen[Pa], x:length[m], t:time[h],
p_i:room water vapor pressure[Pa], q_w:quantity of moisture flow[$kg/(m^2 \cdot h)$],
T_d:temperature at the vapor barrier surface[℃], R:heat of adsorption[J/kg],
T:temperature[℃], ε:temperature gradient factor[1/K], subscript v:vapor

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