Clima p18

NUMERICAL ANALYSIS OF MOISTURE CONDENSATION PROCESS IN A BUILDING ENVELOPE INSULATED BY FIBERGLASS (EFFECTS OF MOISTURE ADSORPTION WITH NATURAL CONVECTION)

MANAMI SATO MAMORU MATSUMOTO***
** Dept. of Architecture, Osaka Institute of Technology., Dr. Eng.*
***Dept. of Environmental Design, Osaka Sangyo Univ., Dr. Eng.*

1. INTRODUCTION

The increase in moisture content caused by internal moisture condensation in the building envelope decreases the thermal resistance of the wall. Therefore, the internal moisture condensation should be considered in energy conservation analysis. The decrease in durability caused by the accumulation of moisture content in a building envelope should be avoided.

The building envelope is often damaged by internal moisture condensation even in a mild climate such as in Japan, because of the increased insulation efficiency of the building envelope and decreased natural ventilation, techniques which are employed to enhance energy conservation [1].

It has been known that natural convection can be caused by slight temperature differences in the fiberglass. When the thermal resistance of the building envelope decreases, it is recognized empirically that moisture condensation damage is accelerated by natural convection and air infiltration through the fiberglass. To enhance thermal resistance efficiency, fiberglass has been used as an inexpensive insulation material. For the building industry, the effects that natural convection and air infiltration in the fiberglass have on the thermal and moisture behavior have been of practical interest.

In various branches of engineering, research dealing only with heat transfer by natural convection has been reported by many. In order to evaluate the thermal property of a building envelope, the effects of air infiltration and natural convection in a vertical insulation-filled enclosure have been reported [2]. And for multi-layer porous materials, the effects of natural convection have been reported ([3] etc.). Air currents caused by natural convection as well as infiltrating air carry not only heat energy but also water vapor. Simultaneously, phase changes occur and moisture is absorbed by the fiberglass. The numerical analyses dealing with the phase change of water have been reported [4] [5]. Analytical studies [5] [6] also indicated that local moisture content in the fibrous insulation material was accumulated as air infiltrated the material. In order to calculate the moisture content, the characteristic property of the material, i.e. moisture adsorption, has been scarcely considered. To obtain a reasonable explanation of the moisture condensation process with natural convection and air infiltration, the equilibrium relationship of the moisture content of the fiberglass and the relative humidity should be considered. Little research dealing with the adsorptive effects has been reported.

In this paper, governing equations of simultaneous heat and moisture transfer are formulated in consideration of moisture adsorption in the fiberglass. First, the thermal and moisture behavior in a vertical fiberglass wall under natural convection is shown. Next, the effects of moisture adsorption on thermal and moisture behavior in the wall are evaluated.

2. GOVERNING EQUATIONS [1] AND CALCULATION METHODS

The conservation equations for a porous material which consists of a solid, water in a liquid state, water vapor and humid air are as follows.

[moisture (liquid & vapor)]

$$\frac{\partial \phi \rho_w}{\partial t} + \frac{\partial \Phi \rho_v}{\partial t} = -\nabla(\phi \rho_w V_w) - \nabla(\Phi \rho_v V_v) \quad (1)$$

[humid air]

$$\frac{\partial \Phi \rho_{av}}{\partial t} + \nabla(\Phi \rho_{av} V_{av}) = W \quad (2)$$

Energy conservation is formulated using enthalpy as follows.

$$\frac{\partial \Phi \rho_{av} H_{av}}{\partial t} + \frac{\partial \phi \rho_w H_w}{\partial t} + \frac{\partial \rho_s H_s}{\partial t}$$
$$+ \nabla(\Phi \rho_{av} V_{av} H_{av}) + +\nabla(\phi \rho_w V_w H_w) = \nabla(\lambda \nabla T)$$

In this equation, enthalpy H is defined as cpdT, wherein cp is the specific heat at a constant pressure.

[energy]

$$c\rho \frac{\partial T}{\partial t} + \Phi \rho_{av} cp_{sv} \nabla(TV_{av}) + \phi \rho_w cp_w \nabla(TV_w) = \nabla(\lambda \nabla T) - rW \quad (3)$$

$$c\rho = \Phi \rho_{av} cp_{av} + \phi \rho_w cp_w + \rho_s cp_s$$
$$r = H_{av} - H_w$$

The natural convection velocity of humid air in a porous material is formulated using the Darcy - Boussinesq approximation.

[momentum equation]

$$V_{av} = -\frac{K}{\Phi \mu}(\nabla P_{av} + \rho_{av} g) \quad (4)$$

[thermodynamic relation] wherein

$$\rho_v = \frac{P_v}{R_v T}, \quad \rho_{av} = \frac{P_{av}}{R_{av} T}, \quad \rho_w : constant \quad (5)$$

In order to evaluate the thermal and moisture behavior in various porous materials, the aforementioned equations can be modified individually.

We propose appropriate equations which describe simultaneous heat and moisture diffusion with convection in the fiberglass layer.

Even if the fiberglass layer is equilibrated by the saturated surrounding air, it can be assumed that the liquid phase volume fraction in the fiberglass exists independently and is stationary. The certainty of this assumption should be confirmed experimentally, though this assumption can be accepted empirically. It is fair to assume that the liquid phase diffusion and convection in the fiberglass can be disregarded. Hence, moisture transfer in the fiberglass is described by diffusion and convection of the water vapor.

Equations (1)(4) can be rewritten on the aforementioned assumption with consideration given to a two-dimensional fiberglass-filled enclosure (Fig. 1).

[moisture] $$\left(\frac{\Phi}{R_v T}+\kappa\right)\frac{\partial P_v}{\partial t}+\left(\Phi\frac{\partial \rho_v}{\partial T}+\nu\right)\frac{\partial T}{\partial t}$$

$$=-\frac{\Phi}{R_v T}\frac{\partial}{\partial x}(P_v V_{avx})-\frac{\Phi}{R_v T}\frac{\partial}{\partial y}(P_v V_{avy})+\frac{\partial}{\partial x}\left(\lambda_{pv}\frac{\partial P_v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{pv}\frac{\partial P_v}{\partial y}\right) \quad (6)$$

$$\kappa=\rho_w\frac{\partial \phi}{\partial P_v} \quad , \quad \nu=\rho_w\frac{\partial \phi}{\partial T}$$

In this moisture balance equation, moisture diffusive flow caused by the temperature gradient of the material is almost negligibly. is an adsorptive coefficient corresponding to the variation in water vapor pressure in the material. is an adsorptive coefficient corresponding to the variation in temperature.

[humid air] $$\frac{1}{R_{av}T}\frac{\partial P_{av}}{\partial t}=-\rho_{av}\frac{\partial V_{avx}}{\partial x}-\rho_{av}\frac{\partial V_{avy}}{\partial y}+W \quad (7)$$

[energy] $$(c\rho-r\nu)\frac{\partial T}{\partial t}+(-r\kappa)\frac{\partial P_v}{\partial t}$$

$$=-\Phi\rho_{av}cp_{av}\frac{\partial(TV_{avx})}{\partial x}-\Phi\rho_{av}cp_{av}\frac{\partial(TV_{avy})}{\partial y}+\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) \quad (8)$$

Using pressure based on a hydrostatic and adiabatic reference value , p_{av} , momentum equation (4) is derived as follows.

[momentum] $$V_{avx}=-\frac{K}{\Phi\mu}\frac{\partial p_{av}}{\partial x} \quad , \quad V_{avy}=-\frac{K}{\Phi\mu}\left\{\frac{\partial p_{av}}{\partial y}-\rho_{av}g\beta(T-T_o)\right\} \quad (9)$$

is a thermal expansion coefficient.

The governing equations (6)(9) were analyzed using the finite difference method. The convection terms in the equations have been approximated by first-order upwind difference.

Darcy's law causes the left side term of equation (7) to be zero, though this term is dealt in too small a quantity to easily calculate by computer.

3. THERMAL AND MOISTURE BEHAVIOR IN FIBERGLASS LAYER

In this section, the effects of natural convection on the temperature distribution and vapor pressure distribution in the fiberglass are shown. The distributions are evaluated for the effects borne by the temperature difference between one surface of the enclosure and the opposite side surface, the aspect ratio of the wall (L/D) and the permeability of the fiberglass. At the end of this section, the effect of moisture adsorption is discussed.

Fiberglass density was 24. kg m^{-3}. Thermal conductivity was $4.89 10^{-2}$ w m^{-1} k^{-1}. Moisture conductivity was $1.72 10^{-10}$ kg m^{-1} s^{-1} pa^{-1}. Moisture conductivity was based on the value of dry air.

The length of a distance x (D) of the enclosure (Fig. 1) was 0.05 m. Two lengths (L), 0.5 m and 2.0 m, were considered for distance y.

The effects of permeability were measured times and evaluated. Adopted values were as follows ,1): $4.52 10^{-8}$ m^2 as the standard value, 2): $9.04 10^{-8}$ m^2 as twice the standard value, 3):$4.52 10^{-7}$ m^2 as ten times the standard value. Experimental research [7] has shown that the variable range of permeability is 10^{-10} m^2 <K<10^{-8} m^2 . In order to express the thermal and

moisture behavior clearly, we chose a large value for the standard permeability by referring to experimental results.

Boundary conditions and other conditions of the calculation are shown in Table 1. For the sake of comparison, we analyzed the steady state distributions of temperature and moisture considering only diffusion.

The geometry considered is a two-dimensional fiberglass-filled enclosure (Fig. 1).

Results from numerical analysis in which the effects of moisture adsorption are disregard, are presented first.

Table 1

	Boundary condition				Height	Permeability	A	Ra*	C3
	T_1(k)	P_{v1}(pa)	T_2(k)	P_{v2}(pa)	L(m)	K(m^2)			10^8
Case1	273.16	426.48	293.16	1636.11	2	4.5210^{-9}	40	2.6	1.8
Case2	283.16	856.99	293.16	1636.11	2	4.5210^{-8}	40	2.6	1.8
Case3	273.16	426.48	293.16	1636.11	2	9.0410^{-8}	40	5.2	3.6
Case4	273.16	426.48	293.16	1636.11	2	4.5210^{-7}	40	26.2	18.0
Case5	273.16	426.48	293.16	1636.11	0.5	4.5210^{-8}	10	2.6	1.8
Case6	283.16	856.99	293.16	1636.11	0.5	4.5210^{-8}	10	2.6	1.8
Case7	273.16	426.48	293.16	1636.11	0.5	4.5210^{-7}	10	26.2	18.0

3.1 Effect of boundary condition

Velocity distribution is shown in Figs 2 and 3. The results from Case 1 are shown in Fig. 2. The results from Case 2 are shown in Fig. 3. Natural convection flow can be seen distinctly along the enclosure surface. The increase in the surface temperature difference through the enclosure (between hot surface and cold surface) causes natural convection in the fiberglass to grow. Because the surface temperature difference of Case 1 is twice that of Case 2, the maximum velocity of Case 1, 1.2210^{-4} m s^{-1}, is twice that of Case 2.

The temperature distribution for Case 1 is shown in Fig. 4. The effect of natural convection on temperature distribution is minimal. The maximum variable rate for temperature variation caused by natural convection is 2.5% compared with the diffusion result. Similarly, the maximum variable rate for vapor pressure is 3% (Fig. 5). The variation in relative humidity is less than 2% as shown in Fig. 6. The increase of relative humidity is small unexpectedly.

The dimensionless velocity and Rayleigh number are shown in Fig. 10. The results from Case 1 and Case 2 are plotted on a line of A=40. It can be seen in Fig. 10 that the dimensionless velocity in the fiberglass increases in almost proportion to the Rayleigh number (Ra*). It can be regarded that there is a linear relationship between this surface temperature difference T and the velocity in the fiberglass within a range of these Ra* numbers.

3.2 Effect of aspect ratio

The relative humidity distribution is shown in Fig. 7 (Case 2), Fig. 8 (Case 5) and Fig. 9 (Case 6). In Case 5 and Case 6, we decreased the height of the enclosure (L) from 2 m to 0.5 m. The relative humidity distribution in Case 1 (Fig. 6) corresponds with results from Case 5 (Fig. 8). Similarly the distribution in Case 2 (Fig. 7) corresponds with results from Case 6 (Fig. 9). The effects of aspect ratio on temperature and moisture distribution is small.

3.3 Effect of permeability

It was expected that the effects of permeability on velocity distribution under natural convection would be significant. The velocity distribution from Case 3 wherein twice the standard permeability was considered, is shown in Fig. 11. The velocity distribution from Case 4 is shown in Fig. 12. Where the permeability of the fiberglass was increased from twice to ten times, a linear increase in air flow velocity due to natural convection can be seen in Figs. 11 and 12.

The effects of natural convection on the distribution of temperature and vapor pressure can be clearly seen in Figs. 1318. The maximum relative humidity in the fiberglass was 93.2% at a 1.95 m height of the enclosure, as shown in Fig. 18. The increase in relative humidity is about 10% as compared with 84.5% obtained by calculation in which only diffusion was considered. To avoid moisture condensation damage in a building envelope, we must take note of this increase in relative humidity.

The vertical distribution of a steady state heat flow at the surface of the fiberglass is shown in Fig. 19 (Case 1, 3 and 4) and Fig. 20 (Case 6 and 7). The effects of natural convection on heat flow can be seen particularly near the top and bottom of the enclosure. The average heat flow on the surface in Case 3 (twice the standard permeability) corresponds with the result from calculations in which only diffusion was considered. For Case 4 (ten times the standard permeability), the average heat flow increased 2% compared to the result from calculations in which only diffusion was considered. For Case 7, the average heat flow increased 8%. The increase in average heat flow was caused particularly by the high degree of permeability and the small aspect ratio.

The distribution of steady state moisture flow is shown in Figs. 21 and 22. The increase in average moisture flow for Case 7 is 17% higher than the result obtained by calculation in which only diffusion was considered. For Case 4, the increase was 4%.

Dimensionless average heat flow is shown in Fig. 23. Dimensionless average moisture flow is shown in Fig. 24. The effects of the aspect ratio of the enclosure on the variation in average heat flow and moisture flow can be seen in Figs. 23 and 24.

3.4 Effect of moisture adsorption

Equations (6)(9) were analyzed under the boundary condition of Case 1. We derived the coefficients and from an equilibrium relation between the moisture content of the fiberglass and the relative humidity as shown in Fig. 25 (reference [8]). The coefficients, and , are shown in Fig. 26.

The variation in temperature in the fiberglass, considering the effect of moisture adsorption, is shown in Fig. 27. The variation in vapor pressure is shown in Fig. 28.

The variation in temperature and vapor pressure continues for more than 30 minutes. It can be seen in Fig. 28 that the variation in vapor pressure has not yet reached steady state after one hour. The variation wherein the effect of moisture adsorption is disregarded reached a steady state after 20 minutes, as shown in Figs. 29 and 30. The effect of moisture adsorption is believed to have maintained the variation in temperature and vapor pressure for more than one hour.

The unsteady state distributions for temperature, vapor pressure and relative humidity are shown in Figs. 31 33. Calculated results taken 10 minutes after starting calculations are shown in Figs. 3133. In Fig. 31, it can be seen that the adsorptive heat production raises the

temperature in the wall on the whole, compared with calculated results which consider only diffusion. Contrary to this, the decrease in vapor pressure is caused by moisture adsorption, as shown in Fig. 32. As shown in Fig.33, the maximum relative humidity of the fiberglass is less than the calculated result which considers only diffusion.

The quasi-steady state distributions are shown in Figs. 3436. The effects of natural convection on the distribution of temperature and vapor pressure can be seen clearly, as compared with results from Case 1 which disregards the effect of moisture adsorption. However, relative humidity distribution is similar to that of Case 1.

The effect of moisture adsorption can be noted to evaluate the unsteady state moisture condensation process in the building envelope.

4. RESULTS AND DISCUSSION

In this paper, effects of natural convection on the moisture condensation phenomenon have been investigated in consideration of moisture adsorption.

Numerical results on thermal and moisture behavior caused by natural convection in fiberglass are evaluated as follows.

For the case which disregards the effects of moisture adsorption, thermal and moisture variation was remarkable, as follows.

1) When the temperature difference through the enclosure (between the hot surface of enclosure and the cold surface)is less than 10, the effects of natural convection on the distribution of temperature and vapor pressure is insignificant. In other words, thermal and moisture behavior in the fiberglass can be estimated using a calculation model dominated by diffusion.
2) The results from analysis in which the temperature difference through the enclosure was 20, show the effects of natural convection on the thermal and moisture distribution clearly. The increase in relative humidity is at most 2%.
3) The effects of aspect ratio are not conspicuous between a height of 2 and 0.5 m.

The effect of natural convection on the thermal and moisture behavior in fiberglass is shown
using dimensionless state values.

4) Dimensionless velocity in the fiberglass increases in proportion to the increase in Rayleigh number($2.6<Ra^*<27.0$), whereas thermal behavior is varied linearly in proportion to the increase in Rayleigh number ($2.6<Ra^*<27.0$).
5) The increase in average heat flow was caused by a decrease in aspect ratio. Even if the Rayleigh number is increased from 2.6 to 27.0, the average heat flow increases only slightly. These phenomena can be seen particularly with a variation in average moisture flow. For an aspect ratio of 10, the average heat flow through the fiberglass is increased 8% compared with the result on diffusion. Similarly, average moisture flow through the fiberglass is increased 17%.
6) The relative humidity distribution is proportional to the increase in Rayleigh number. The effects of aspect ratio are minimal. The maximum relative humidity caused by natural convection is 93.2%. To avoid moisture condensation damage, the partial increase in relative humidity should be noted.

The effects of moisture adsorption are evaluated as follows.

7) It is remarkable that temperature and vapor pressure varied continuously for hours because of moisture adsorption. When analyzing the unsteady state moisture condensation process in a building envelope, the adsorptive effect of the fiberglass under the natural convection should be dealt with cautiously.

REFERENCE

1. M. Matsumoto, Humidity, Building Environmental Physics Series of Building Science, No. 10, Shyokokusya, Tokyo, 1984
2. P. J. Burns, L. C. Chow & C. L. Tien, Convection in a vertical slot filled with porous insulation, Vol. 20, Int. J. Heat and mass transfer, 1977 ,pp 919-926
3. F. C. Lai & F. A. Kulacki, Natural convection across a vertical layered porous cavity, Vol. 31, Int. J. Heat and Mass Transfer, 1988, pp 1247-1259
4. K. Vafai & H. C. Tien, A numerical investigation of phase change effects in porous materials, Vol. 32, Int. J. Heat and mass transfer, 1989, pp 1261-1277
5. T. Ojanen & R Kohonen, Convection and moisture driven heat transfer, Proceeding of International CIB W67 Symposium on Energy , Moisture and Climate in Buildings, 1990
6. H. C. Tien & K. Vafai, A synthesis of infiltration effects on an insulation matrix, Vol. 33, Int. J. Heat and mass transfer, 1990, pp 1263-1280
7. D. Fournier & S. Klarsfeld, Some recent experimental data on glass fiber insulating materials and their use for a reliable design of insulation at low temperatures, ASTM STP 544,1974, pp 223-243
8. C. Johansson & G. Persson, Byggmastaren 17 Hoft 311, 1946

NOMENCLATURE

cp specific heat at constant pressure (w s kg^{-1} k^{-1})

g gravity (m s^{-2})

H enthalpy { = cpdT } (J kg^{-1})

K Darcy's permeability (m^2) { k_a = K// }

P pressure (pa)

p pressure based on a hydrostatic and adiabatic reference value (pa)

R universal gas constant (N m $kmol^{-1}$ k^{-1})

r phase change enthalpy of vapor water adsorbed { $r = H_{av} - H_w$ } (J kg^{-1})

T temperature(k)

T_o reference temperature (k)

t time (s)

V velocity (m s^{-1})

W mass of water vapor adsorbed (kg m^{-3} s^{-1})

x horizontal distance of the fiberglass (m)

y vertical distance of the fiberglass (m)

Greek symbols

thermal expansion coefficient (k^{-1})

adsorptive coefficient of corresponding to the variation in water vapor pressure (kg m^{-3} pa^{-1})

thermal conductivity (w m^{-1} k^{-1})

$_{pv}$ moisture conductivity related to vapor pressure (kg m^{-1} s^{-1} pa^{-1})

viscosity (pa s)

adsorptive coefficient of corresponding to the variation in temperature (kg m^{-3} k^{-1})

density (kg m^{-3})

true porosity

moisture content

Subscripts

av : humid air s : solid v : vapor water

w : liquid water x : horizontal direction y : vertical direction

Dimensionless values

D : thickness of the fiberglass (m) L : height of the fiberglass (m)

T_c : cold surface temperature (k) T_h : hot surface temperature (k)

Pv_c : cold surface vapor pressure (pa) Pv_h : hot surface vapor pressure (pa)

T : T_h-T_c Pv : Pv_c-Pv_h

$\overline{T}$: dimensionless temperature { $\overline{T} = \dfrac{(T - T_c)}{\Delta T}$ }

$\overline{P_v}$: dimensionless water vapor pressure { $\overline{P_v} = \dfrac{(P_v - P_{vc})}{\Delta P_v}$ }

$\overline{V_{avi}}$: dimensionless velocity { $\overline{V_{avi}} = \dfrac{Dcp_{av}\rho_{av}V_{avi}}{\lambda}$ (i ; x or y) }

$\overline{p_{av}}$: dimensionless humid air pressure { $\overline{p_{av}} = \dfrac{k_a cp_{av}\rho_{av}p_{av}}{\lambda}$ }

$\overline{x}, \overline{y}$: dimensionless distance { $\overline{x} = \dfrac{x}{D}$, $\overline{y} = \dfrac{y}{D}$ }

$\overline{t}$: dimensionless time { $\overline{t} = \dfrac{\lambda t}{c\rho LD}$ } A : aspect ratio { $A = \dfrac{L}{D}$ }

$C1$: dimensionless value in equation (A1) { $C1 = \dfrac{c\rho}{cp_{uv}\rho_{uv}}$ }

Le : dimensionless value in equation (A1) { $Le = \dfrac{\lambda}{c\rho}\dfrac{1}{R_v T\lambda'_{pv}}$ }

Pe : dimensionless value in equation (A1) { $Pe = \dfrac{Pv_c}{\Delta Pv}$ }

Te : dimensionless value in equation (A2) { $Te = \dfrac{T_c}{\Delta T}$ }

$C3$: dimensionless value in equation (A3) { $C3 = \dfrac{k_a c\rho R_{av} T\rho_{av}}{\lambda}$ }

Ra^* : Rayleigh number { $Ra^* = Dk_a\rho_{av}\beta\Delta T\dfrac{cp_{av}\rho_{av}}{\lambda}$ }

[dimensionless moisture balance equation]

$$\frac{\partial \overline{P_v}}{\partial \overline{t}} = -C1\times A\{\frac{\partial(Pe+\overline{P_v})\overline{V_{avx}}}{\partial \overline{x}} + \frac{\partial(Pe+\overline{P_v})\overline{V_{avy}}}{\partial \overline{y}}\} + \frac{A}{\Phi Le}(\frac{\partial^2 \overline{P_v}}{\partial \overline{x}^2} + \frac{\partial^2 \overline{P_v}}{\partial \overline{y}^2}) \qquad (A1)$$

$$c\rho = cp_s\rho_s + cp_{av}\rho_{av}$$

[dimensionless heat balance equation]

$$\frac{\partial \overline{T}}{\partial \overline{t}} = -\Phi\times A\{\frac{\partial(Te+\overline{T})\overline{V_{avx}}}{\partial \overline{x}} + \frac{\partial(Te+\overline{T})\overline{V_{avy}}}{\partial \overline{y}}\} + A\frac{\partial^2 \overline{T}}{\partial \overline{x}^2} + A\frac{\partial^2 \overline{T}}{\partial \overline{y}^2} \qquad (A2)$$

[dimensionless humid air balance equation]

$$\frac{\partial \overline{p_{av}}}{\partial \overline{t}} = -C3\times A(\frac{\partial \overline{V_{avx}}}{\partial \overline{x}} + \frac{\partial \overline{V_{avy}}}{\partial \overline{y}}) \qquad (A3)$$

[dimension less moment equations]

$$\overline{V_{avx}} = -\frac{\partial \overline{p_{av}}}{\partial x} \quad , \quad \overline{V_{avy}} = -\frac{\partial \overline{p_{av}}}{\partial y} + Ra^*\overline{T} \qquad (A4)$$