PREDICTION OF HYGROTHERMAL ENVIRONMENT OF BUILDINGS BASED UPON COMBINED SIMULATION OF HEAT AND MOISTURE TRANSFER AND AIRFLOW

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ABSTRACT

The hygrothermal environment of the Japanese traditional house constructed by wet process with clay wall and the recent house constructed with industrial building materials are estimated through the interrelated simulation of heat and moisture transfer and airflow using THERB. Thermal theories on conduction, convection, radiation and ventilation of THERB are outlined, particularly algorithm on combined heat and moiture transfer based on thermodynamics. The consequences of this paper highlights that an indoor humidity variation is largely affected by sorption and desorption of walls, the excessive dryness during heating condition can be alleviated by increasing moisture capacity for interior finish material, and THERB has a capability to predict temperature and humidity conditions of buildings.

INTRODUCTION

Japanese houses of recent years tend to be insulated and built airtight to improve indoor thermal environment and to decrease heating and cooling load, and putting more emphasis on handiness in construction and certainty of precision, the building method and materials have both changed from the traditional house of wet type with clay wall to the house of dry type in which industrial building materials such as ceramic siding and plasterboard are used.

Due to the enforcement of the “Energy Conservation Standard for Housing” and the “Housing Performance Indication Law” in Japan, insulation and air-tightness have been all the more emphasized, and concomitantly, the qualitative descriptive explanation in the past about the housing thermal performance has shifted to numerical quantitative evaluation. As a result, insulation and air-tightness have drastically advanced, and yet, the performance is indicated by “specification standard” or “thermal loss coefficient” without reflecting ventilation, solar heat gain, thermal storage in building frame, and internal heat generation from dynamic heat transfer phenomena from human living.

In addition, the factors significantly interconnected to the comfort such as indoor humidity variation with moisture sorption and desorption of walls and thermal radiation have also been disregarded. In other words, the characteristics as variation in temperature and moisture property, specific to the individual construction method and building materials used for wet and dry types respectively have not been taken into account. This has slashed demand for the wet construction method and exponentially driven up contrariwise the demand for dry method.

It has been generally evaluated that although the wet construction method is excellent in heat storage and moisture sorption and desorption of walls (constant or equilibrium temperature and humidity) compared to the dry method, it is very limited in energy conservation due to inferior insulation and air-tightness.

In the following, the hygrothermal environment and energy conservation of the wet and dry methods respectively are examined to compare the hygrothermal performance of both houses on an interrelated simulation of heat and moisture transfer and airflow by employing THERB.

SIMULATION SOFTWARE OF HYGROTHERMAL ENVIRONMENT

A Heat, Air and Moisture (HAM) simulation software program called THERB has been developed for the purpose of estimating the hygrothermal environment within buildings. This software has complete HAM features including principles of moisture transfer within walls and has been validated through the standardized test in Japan like BESTEST procedure. THERB is one of the official software approved by Japanese government.

Generally simulation software to predict temperature, humidity, heating and cooling load of building spaces does not take into account moisture transfer in wall assemblies. Humidity calculation in most software is simply affected by ventilation and focuses on just the building spaces. THERB was developed to simulate humidity conditions in both building spaces and wall assemblies in detail.

Thermal theories on conduction, convection, radiation and ventilation are based upon the detailed phenomena. The P-model using the water potential, which is defined as thermodynamic energy, is a progressive feature of THERB, which incorporates moisture transfer including moisture sorption and desorption of walls. Thus THERB can predict the hygrothermal environment of the whole building taking into consideration the complex relationship between heat and moisture transfer and airflow.

The following outlines the algorithms for heat and moisture transfer used in THERB, which are derived from fundamental building physics principles.

Theoretical Feature of THERB

Conductive Heat and Moisture Transfer: The finite difference method is applied to the model of one-dimensional transient thermal conduction of multi-layer walls. Regarding thermal conduction to the ground, the finite difference method of two or three dimensions is applied to the previous calculation of the ground temperature and then the results are used as the input excitation for conductive calculation of the earthen floor and basement walls.

Water Potential which is derived by applying the chemical potential of thermodynamics to moisture diffusion is used as the driving force of moisture transfer. This approach is proposed to be more accurate than other models based on physical properties such as vapour pressure. The model called P-model using water potential makes it possible to combine moisture transfer with heat transfer perfectly, and take into account internal energy and external forces such as gravity.

Balance equations of heat and moisture transfer in material is obtained as follows.

- Heat Balance

$$\frac{\partial C\rho T}{\partial t} + c_{lw} j_{lw} \nabla T = \nabla \lambda \nabla T + r_v \nabla \lambda'_g \nabla\left(\mu_w + \mu_f\right) \quad (1)$$

- Moisture Balance

$$\rho_{lw} \frac{\partial \phi}{\partial \mu} \frac{\partial \mu}{\partial t} = \nabla \lambda'_g \nabla\left(\mu_w + \mu_f\right) + \nabla \lambda'_l \nabla\left(\mu + \mu_f\right) \quad (2)$$

where C and ρ are specific heat and specific weight of material containing water. c_{lw} , ρ_{lw} and j_{lw} are specific heat, specific weight and flux of liquid phase water. λ is thermal conductivity. λ'_g and λ'_l are gaseous and liquid phase water conductivity for μ_w and μ gradients. r_v is heat of sorption (= latent heat of evaporation).

μ_w is the water potential and defined from the basic thermodynamic principles as Eq.(3) to Eq.(5). The water potential is composed by saturated water potential μ_w^o and unsaturated water potential μ . μ_w^o expresses the thermodynamic energy of saturated vapour and μ expresses the difference of thermodynamic energy between saturated vapour and unsaturated vapour of moisten air.

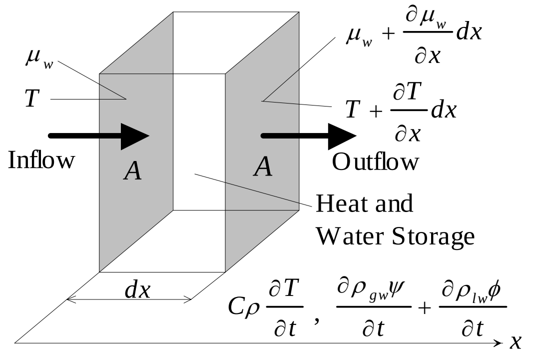


Figure 1 Conductive heat and moisture transfer

$$\mu_w(p,T) = \mu_w^o(T) + \mu(p) \quad (3)$$

$$\mu_w^o(T) = 6.44243 \times 10^5 + c_{p,w_{kg}}(T - 273.15) - Tc_{p,w_{kg}} \ln\frac{T}{273.15} + R_{w_{kg}} T \ln\frac{p_s}{1.01325 \times 10^5} \quad (4)$$

$$\mu(p) = R_{w_{kg}} T \ln\frac{p_w}{p_s} \quad (5)$$

where p_w is the vapor pressure of the humid air, and p_s is the saturated vapor pressure at temperature T . $c_{p,w_{kg}}$ is the specific heat which is expressed in units of [J/(kg K)] and $R_{w_{kg}}$ = 461.50 [J/(kg K)] which is calculated by dividing the gas constant R = 8.31441 [J/(mol K)] by the molecular weight of water 18.016x103 [kg/mol].

μ_f is the force water potential caused by internal energy and external forces. For instance, the force water potential which includes the influences of gravity and internal pressure is calculated by Eq.(6).

$$\mu_f = gz + p\overline{V}_w \quad (6)$$

where g is gravitational constant, z is height from reference position, $\overline{V}_w$ is the volume per unit weight of water and $p\overline{V}_w$ is equal to $R_{w_{kg}} T$.

Convective Heat and Moisture Transfer: By default, the convective heat transfer coefficients are recalculated at every time step on all surfaces of the exterior, interior and cavities of buildings using dimensionless equations which are derived from either the profile method for boundary layer (based on the energy equation, the momentum equation and the fluid friction) or defined from the experimental findings according to natural or forced convection. Furthermore the natural convective heat transfer coefficients are classified into either vertical or horizontal surfaces. It is possible to use the functional equations of the wind direction and velocity for the exterior convective heat transfer coefficients and the functional equations of the temperature difference between surface and room for the interior convective heat transfer coefficients. It is also possible to set constant heat transfer coefficients all day long or modify the coefficients to take into consideration space conditioning time for every part of the building.

Table 1 Convective Heat Transfer Coefficient

Part of Buildings	Dimensionless Number
Exterior	$Nu = 0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}$
Interior (Vertical Plane)	$Nu = 0.241(Gr_i \cdot \mathrm{Pr})^{0.4}$ $Gr_i = g\beta\Delta T_a l^3 / \upsilon^2$
Interior (Horizontal Plane)	$Nu = C \cdot Ra_f^m$ $Ra_f = Gr_i \cdot \mathrm{Pr}$ $f = (T_s + T_\infty)/2$
Upward	C=0.58, m=1/5
Downward	C=0.54, m=1/4 (Ra_f : 2E4 to 8E6) C=0.15, m=1/3 (Ra_f : 8E6 to 1E11)
Cavity (ventilated)	$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$
Cavity (closed)	$Nu = 0.035(Gr_c \cdot \mathrm{Pr})^{0.38}$ $Gr_c = g\Delta T_s l^3 / T_m \upsilon^2$

Gr: Grashof number, *Nu*: Nusselt number, *Pr*: Prandtle number, *Ra*: Rayleigh number, *Re*: Reynolds number, T_m: mean temperature of surfaces, ΔT_a: temperature difference between surface and air, ΔT_s: temperature difference between surfaces, *g*: gravitational constant, *l*: length, β :expansion coefficient, υ : kinematic viscosity

The convective moisture transfer coefficients on all surfaces of the exterior, interior and cavities of buildings are calculated from the dimensionless Sherwood number, which is derived on the basis of the analogy between heat and mass transfer. The Sherwood number can be calculated by replacing the Prandtle number with Schmidt number shown in Table 1.

Thus boundary conditions of heat and moisture balance equations are expressed as follows.

- Boundary conditions

$$-\lambda\frac{\partial T}{\partial n_v} - r_v \cdot \lambda'_g \frac{\partial \mu_w}{\partial n_v} = \alpha_c (T_a - T_s) + r_v \cdot \alpha'_\mu (\mu_{w,a} - \mu_{w,s}) + q_s \quad (7)$$

$$-\lambda'_g \frac{\partial \mu_w}{\partial n_v} = \alpha'_\mu (\mu_{w,a} - \mu_{w,s}) \quad (8)$$

where n_v is normal line vector directed inward on a boundary surface, q_s is quantity of radiant heat. T_a, T_s, $\mu_{w,a}$ and $\mu_{w,s}$ are the temperature and water potential of the air and surface, respectively. α_c is convective heat transfer coefficient and α'_μ is convective moisture transfer coefficient for the water potential gradient. α'_μ can be calculated from general convective moisture transfer coefficient α'_p for the vapour pressure gradient on the basis of Eq.(3).

$$\alpha'_\mu = \alpha'_p \left(\frac{\partial p_w}{\partial \mu_w}\right) = \alpha'_p \frac{p_s}{R_{w_{kg}} T} e^{\mu / R_{w_{kg}} T} \quad (9)$$

Radiant Heat Transfer: On the exterior surfaces of the buildings, the standard method of using the radiant heat transfer coefficients and atmospheric radiation is applied in default. Interrelated radiation between both surfaces of building and the ground can be also calculated with temperature calculation of the ground. On the interior of buildings, instead of the general method (that is, the calculation of heat transfer between surface and indoor air and radiation between surfaces), the use of the long-wave absorption coefficient makes it possible to simulate a net absorption of radiant heat as a consequence of multiplex reflection among interior surfaces. Mutual radiation between the surfaces of cavities in walls and windows can be also calculated.

Incident Solar Radiation: Incident solar radiation on the exterior and into the interior of buildings is divided into direct and diffuse solar radiation and calculated for all parts of the building in all directions using accurate geometric calculations of

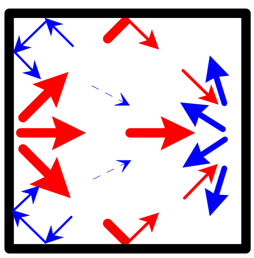


Figure 2 Multiple reflection of long-wave radiation

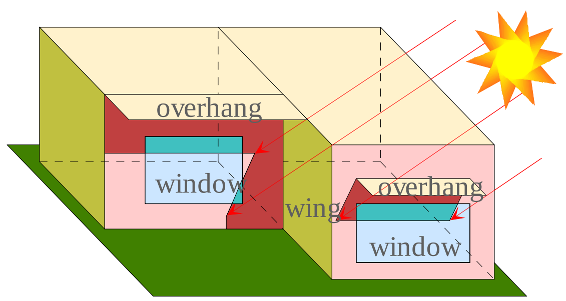


Figure 3 Geometric calculations of shaded and unshaded portions of the building

shaded and unshaded portions of the building by considering the influence of overhangs and wings. Isotropic model or anisotropic models can be chosen for diffuse solar radiation. Transmitted solar radiation is calculated by the multi-layer window model and considers multiplex reflection (depending on an incidence angle of solar radiation) between not only the glazing layers but also between the window and interior shade at every time step. The multiplex reflection of both direct and diffuse solar radiation among interior surfaces including re-transmission of solar radiation from the inside to the outside through the windows is calculated by using the short-wave absorption coefficient. In addition the absorption coefficients of long and short wave are applied to radiant heat emitted from lights and appliances, etc.

Ventilation: The network airflow model integrating a thermal model with a plant model estimates natural and forced ventilation quantities of each zone (rooms and cavities) caused by air leakage, infiltration and mechanical ventilation. As for independent ventilated cavities in the walls, it is possible to estimate airflow quantities by hydrodynamic analysis as the solution to the equations of motion, energy and continuity. Constant ventilation quantities can be also set every hour for all zones.

Space Conditioning: Indoor air temperature and humidity can be calculated from heat and moisture balance of a space based on convection, ventilation, internal generation of heat and moisture. By default, indoor humidity is interrelated with sorption and desorption of walls through the application of P-model. General humidity calculation that is just affected by ventilation is also available.

Sensible and latent heat load are obtained from the equations of heat and moisture balance, in which unknown quantities are space heating and cooling load, on condition that temperature and humidity are set at reference ones. Control methods for space conditioning are classified into three types: heating, cooling, and simultaneous heating and cooling. By default, humidity control and temperature control are linked. Temperature and humidity set-point and ranges can be optionally set every hour. Moreover the control of humidity is automatically performed in the case when the sensible temperature such as PMV is set as the set-point of space conditioning.

HYGROTHERMAL PERFORMANCE OF HOUSES CONSTRUCTED BY DRY AND WET PROCESS

Building Model

Figure 8 and 9, and Table 2 illustrate the 1st and 2nd floor plans and wall assemblies of the building

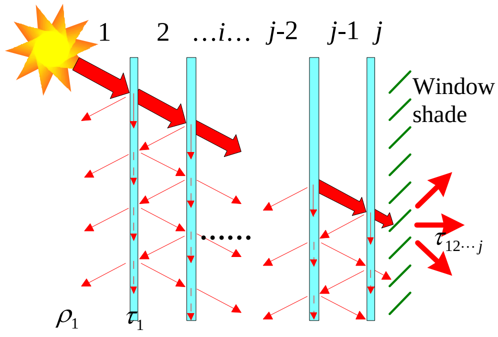


Figure 4 Multi-layer window model

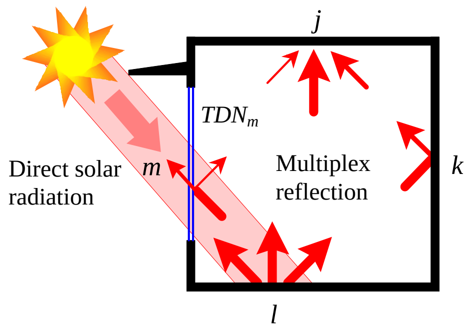


Figure 5 Multiplex reflection of transmitted direct solar radiation

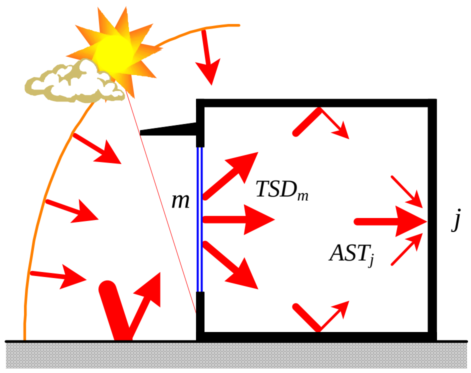
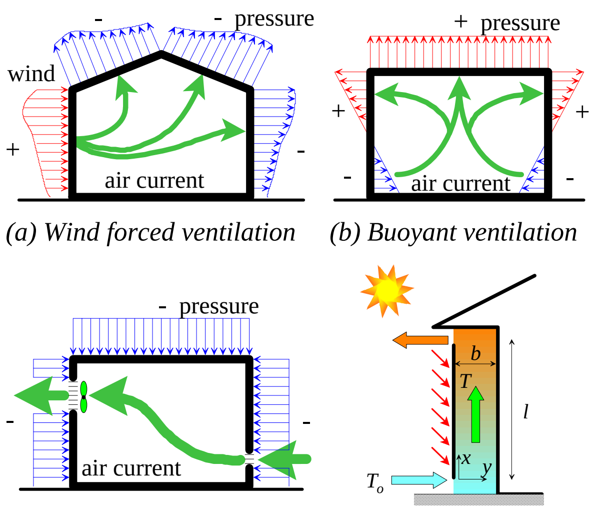


Figure 6 Multiplex reflection of transmitted sky diffuse solar radiation

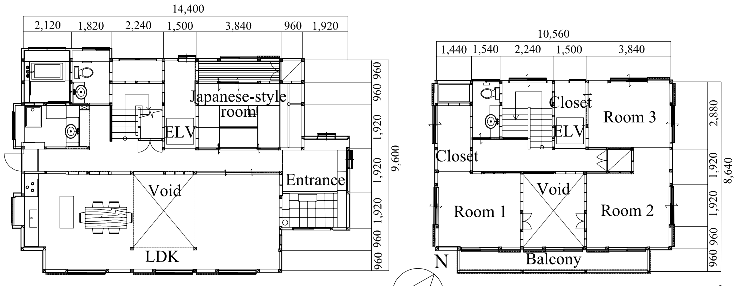


(a) Wind forced ventilation *(b) Buoyant ventilation*

(c) Mechanical ventilation *(d) Cavity ventilation*

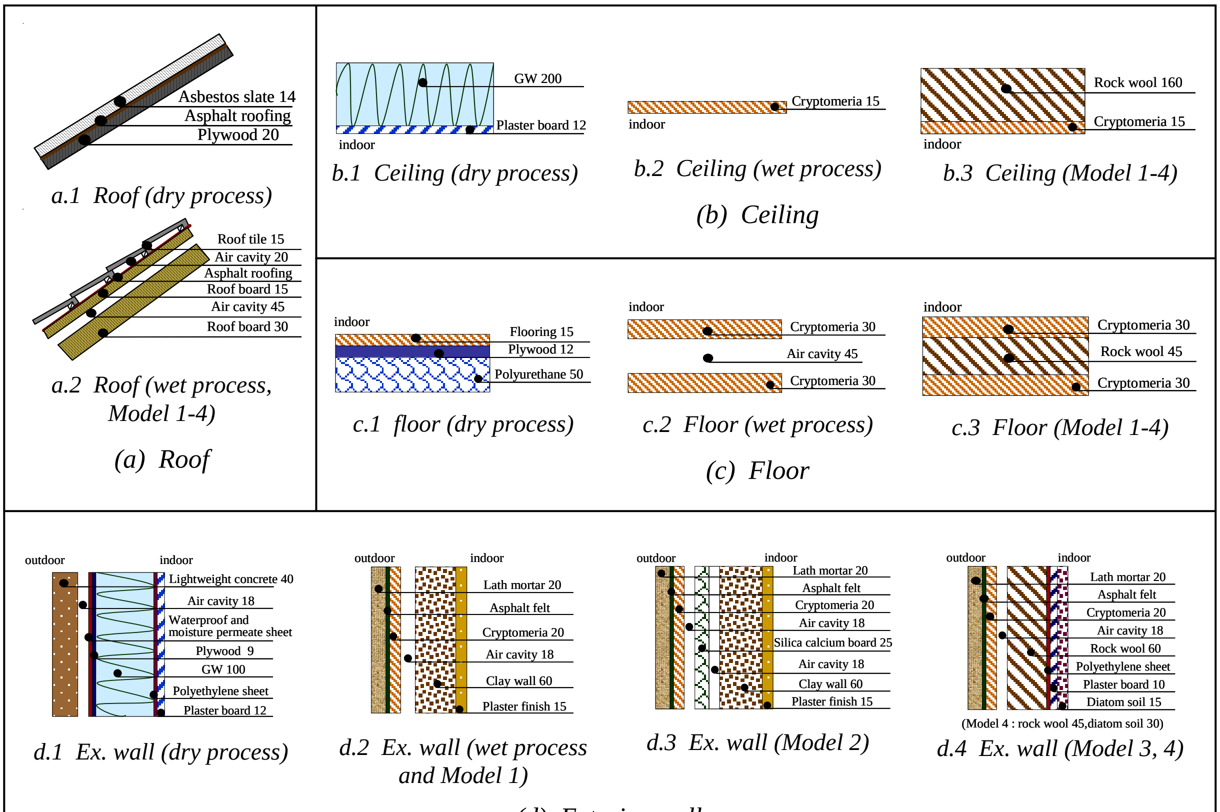
Figure 7 Mechanical or natural ventilation

Photo 1 Building model (Japanese traditional house)



(a) First floor plan 116.728 m² (b) Second floor plan 76.161 m²

Figure 8 The first and second floor plans



a.1 Roof (dry process)
a.2 Roof (wet process, Model 1-4)
(a) Roof

b.1 Ceiling (dry process) *b.2 Ceiling (wet process)* *b.3 Ceiling (Model 1-4)*
(b) Ceiling

c.1 floor (dry process) *c.2 Floor (wet process)* *c.3 Floor (Model 1-4)*
(c) Floor

d.1 Ex. wall (dry process) *d.2 Ex. wall (wet process and Model 1)* *d.3 Ex. wall (Model 2)* *d.4 Ex. wall (Model 3, 4)*
(d) Exterior wall

Figure 9 Wall assemblies of building model

model used for simulation. The real house for the building model, as shown in Photo 1, is constructed by traditional wet process with clay wall and no insulation (hereinafter termed as “wet type”) in Fukuoka, Japan. The air layer between 2 cryptomeria boards, 15mm respectively, compose the floor and roof, giving insulating effect. The house of dry construction method (hereinafter referred to as “dry type”) uses the same building plan, and the floor, ceiling, and wall were respectively made to conform to a general structure to meet the Japanese energy conservation standard. The structure for the wall, floor, ceiling, and roof were altered to compare the wet and dry types in models from 1-4. The insulation performance of the floor, ceiling and roof in models from 1-4 are respectively equivalent to the

Table 2 Wall assemblies of the building model and U values

Model	Ceiling		Floor		Exterior wall	
Dry type	b.1	0.22	c.1	0.39	d.1	0.39
Wet type	b.2	2.96	c.2	0.96	d.2	1.73
Model 1	b.3	0.22	c.3	0.47	d.2	1.73
Model 2					d.3	0.81
Model 3					d.4	0.45
Model 4					d.4	0.57

[unit: W/(m^2 K)]

specification for the energy conservation standard and considered as the improved ones from the wet type. The wall composition is clay for model 1 (same as wet type), clay wall with exterior thermal insulation of 25mm silica calcium board for model 2, and a simple wet wall, for model 3, instead of clay wall, of diatomaceous soil for 15mm of surface finish with 10mm plasterboard for interior groundwork, with 60mm rock wool filling insulation inserted in between. The construction method for model 4 is the same as in model 3 except for the altered thickness of the rock wool and diatomaceous soil to 45mm and 30mm respectively.

Calculation Conditions

Table 3 shows the calculation conditions. Here, winter heating load and sorption/desorption performance of wall (alleviation of indoor excess dryness during heating) are examined. The standard weather data in Fukuoka was used for input data, where set-point of temperature for spasce conditioning is 22 degree with natural humidity (no humidifying) and constant indoor ventilation 0.5 times/hour all day. The space conditioning schedule for a family of 4 is made, and in order to study on the basic performance of the housing, the internal thermal generation from human living and moisture generation were disregarded. Space conditioned rooms are LDK (living room, dining room, and kitchen), a main bedroom and children's rooms.

Table 3 Calculation conditions

Weather data	Standard weather data in Fukuoka
Run-up	3 months
Calculation interval	30 minutes
Set-point of temperature	22 degree
Heat and moisture generation	none
Space conditioning time	6-9, 12-13, 17-22 (LDK) (Living schedule of a family)
Air change rate	0.5 times per hour

Heating Load

Figure 10 illustrates comparative values for term heating load for the dry and wet types, and for models 1-4 between December and March. Compared to dry type, the heating load for wet type and model 1 (same clay wall as wet type with heat insulation for floor and ceiling) exceeds by as much as 65% and 37% respectively. The heating load for model 2 (clay wall with 25mm silicate calcium board for exterior thermal insulation) is large compared to dry type, but the difference shrinks to 9%. The over-all coefficient of heat transfer (U value) for model 1

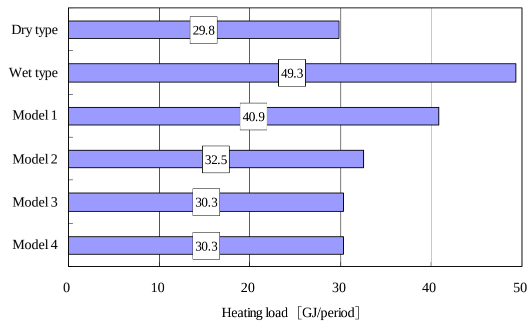


Figure 10 Term heating load

and 2 is 1.73W/(m^{2}K) and 0.81W/(m^{2}K) respectively, each of which corresponds to 4.4 and 2.1 times the coefficient of 0.39W/(m^{2}K) for the dry type, thus making the difference of heating load between the dry type and model 2 not very large. Since the room temperature of model 2 during nighttime without heating is higher than that of dry type (refer to Figure 12), it is regarded that the heat storage of wall in daytime due to solar heat gain contributes to the decrease in heating load. This is also clear when model 3 and 4 are compared. The heat transfer coefficient for model 3 and 4 is 0.45W/(m^{2}K) and 0.57W/(m^{2}K) respectively, and despite the fact that the U value for model 3 is smaller, the room temperature of model 4 with higher heat storage shows slightly higher value during nighttime without heating. (The interior for model 3 and 4 is plaster finish, 15mm and 30mm respectively as shown in Figure 9) Consequently, it is regarded that the heating load for both turned out to be the same. Incidentally, since there is not so much difference in the room temperature between wet (clay wall) and dry types, having appropriate exterior insulation looks rather realistic aiming at utilizeing the solar heat gain in order to expect the effect from the daytime heat storage.

Indoor Humidity

Figure 11 shows the typical winter weather condition (between January 20 and 22) in Fukuoka, Japan. Figure 12 shows indoor temperature and humidity in LDK for the dry and wet types and for models 1-4. The indoor relative humidity decreases remarkably during heating, and especially the value drops less than 30% for dry type (lowest value 27%) creating excessively dry condition. On the other hand, the relative humidity for the wet type, models 1 and 2 (clay wall for both) roughly shows 40% or more.

Upon comparing the absolute humidity, the dry type shows approximately a constant value but the value for the wet type, model 1 and 2 tends to increase during heating, following the room temperature, and decrease during hours without heating. Due to its sorption and desorption property, the clay wall is effective to regulate the excessive dry condition

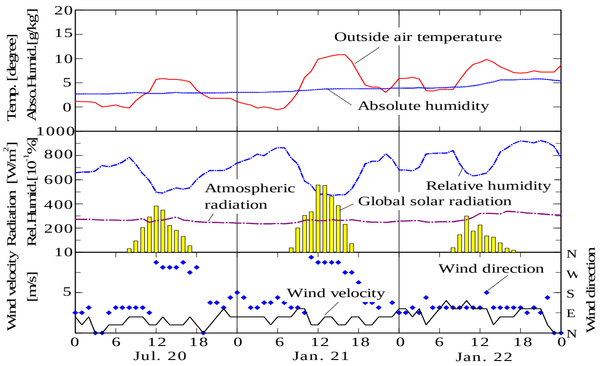


Figure 11 weather condition in Fukuoka

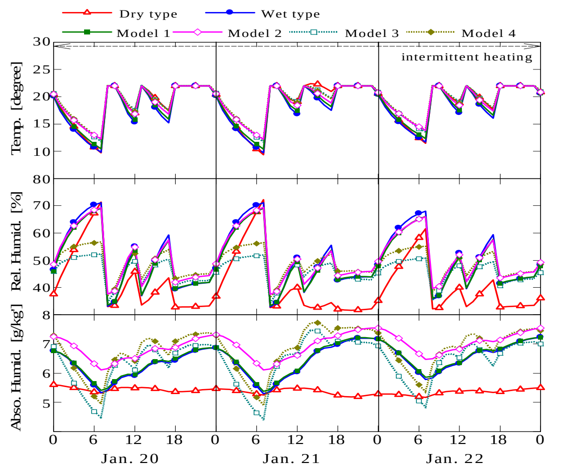


Figure 12 Indoor temperature and humidity in LDK

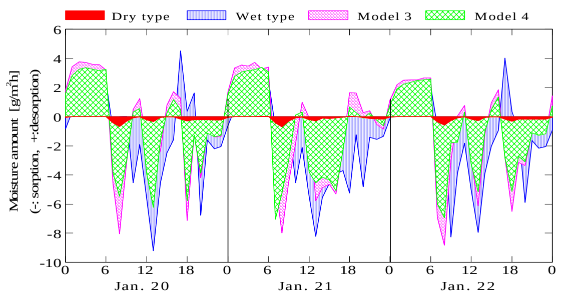


Figure 13 Moisture amount of sorption and desorption of walls

during winter heating. Incidentally, the indoor absolute humidity for model 2 (with exterior thermal insulation) is 0.4g/kg'-0.8g/kg' higher than the wet type and model 1.

The indoor humidity for model 3 and 4 with interior finish of 15 and 30mm diatom soil, respectively, fluctuates in similar manner as wet type. Equivalent effect as clay wall is achieved by using an excellent material in sorption and desorption property for the interior.

Figure 13 illustrates the moisture quantity of sorption and desorption for unit area for the dry, wet, model 3 and 4. The dry type shows nearly no moisture transfer but the wet type evaporates moisture as

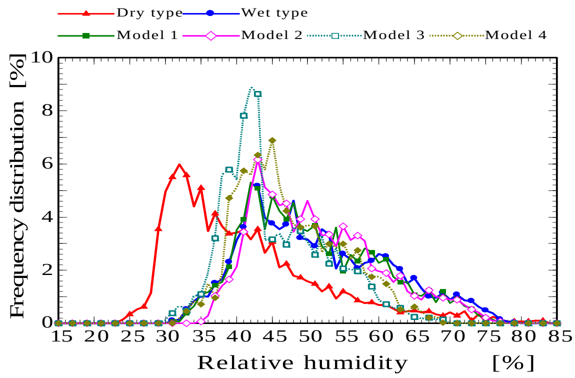


Figure 14 Frequency distribution of indoor relative humidity during December and March

much as 9.1g/(m^{2}h) at maximum. Model 3 and 4 evaporate 8.0g/(m^{2}h) and 8.7g/(m^{2}h) respectively at maximum. Figure 14 illustrates the frequency distribution of indoor relative humidity for the dry and wet types, and models 1-4 during December and March. The indoor humidity for the dry type concentrates in low humidity zone between 28% and 45% (32% at peak), extremely dry condition. On the other hand, the indoor humidity for the wet type, model 1 and 2 is widely distributed in the mean humidity zone between 40% and 54%. The indoor humidity for model 3 and 4 is also distributed in the mean humidity zone between 37% and 55% with 42% and 45% at peak respectively. The indoor humidity variation is largely affected by sorption and desorption of walls, and the excessive dryness during heating condition can be alleviated by increasing moisture capacity for interior material.

CONCLUSION

In this paper, the hygrothermal environment of houses is estimated by using the simulation software THERB which has been developed to include complete features on heat, moisture and air. Thermal theories on conduction, convection, radiation and ventilation of THERB are outlined, particularly algorithm on combined heat and moiture transfer using water potential (thermodynamic energy).

Then the difference of the hygrothermal environment among the Japanese traditional house (the wet type) constructed by wet process with clay wall, the recent house (the dry type) constructed with industrial building materials, and the simple wet type with higher moisture capacity (interior finish of diatomaceous soil) are compared through the interrelated simulation of heat and moisture transfer and airflow.

The results of the simulation show these major conclusions:

- the indoor humidity variation of the wet type slows down with sorption and desorption of walls

- the wet type and the simple wet type can alleviate excessive dryness during heating condition through sorption and desorption of walls
- the wet type is extremely inferior to the dry type on energy conservation even if thermal storage is taken account of
- THERB has a capability to predict temperature and humidity conditions in both building spaces and wall assemblies in detail.

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NOMENCLATURE

C specific heat [J/(kg K)]
c_{lw} specific heat of liquid phase water [J/(kg K)]
Gr Grashof number [-]
g gravitational constant [m/s^2]
j_{lw} flux of liquid phase water [kg/(m^2 s)]
l length [m]
Nu Nusselt number [-]
Pr Prandtle number [-]
p pressure [Pa]
p_s saturated vapour pressure [Pa]
p_w vapor pressure of the humid air [Pa]
q_s radiant heat [W/m^2]
Ra Rayleigh number [-]
Re Reynolds number [-]
r_v heat of sorption [J/kg]
T temperature [K]
T_m mean temperature of cavity surfaces [K]
$\overline{V}_w$ volume per unit weight of water [m^3/kg]
z height from reference position [m]
α_c convective heat transfer coefficient [W/(m^2 K)]
α'_p convective moisture transfer coefficient for the vapour pressure gradient [kg/(m^2 s J/kg)]
α'_μ convective moisture transfer coefficient for the water potential gradient [kg/(m^2 s J/kg)]
β expansion coefficient [1/K]
ΔT_a temperature difference between surface and air
ΔT_s temperature difference between cavity surfaces
ϕ water content [m^3/m^3]
λ thermal conductivity [W/(m K)]
λ'_g gaseous phase water conductivity [kg/(ms J/kg)]
λ'_l liquid phase water conductivity [kg/(m s J/kg)]
μ unsaturated water potential [J/kg]
μ_f force water potential [J/kg]
μ_w water potential [J/kg]
μ_w^o saturated water potential [J/kg]
υ kinematic viscosity [m^2/s]
ρ specific weight [kg/m^3]
ρ_{lw} specific weight of liquid phase water [kg/m^3]