SIMULATION SOFTWARE OF THE HYGROTHERMAL ENVIRONMENT OF BUILDINGS BASED ON DETAILED THERMODYNAMIC MODELS

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ABSTRACT

A Heat, Air and Moisture (HAM) simulation software program called THERB for has been developed for the purpose of estimating the hygrothermal environment within buildings. Authors have already developed THERB as a simulation software tool to estimate the thermal environment within residential buildings, however the new THERB program has been expanded to include complete HAM features including principles of moisture transfer within walls. 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 for HAM was developed to simulate humidity conditions in both building spaces and wall assemblies in detail. THERB for HAM excels in the theories for describing actual building physics. Most of thermal theories on radiation and convection and ventilation utilize existing models already developed for THERB, however the water potential, which is defined as thermodynamic energy, is a newly adopted feature of THERB, which incorporates moisture transfer including moisture sorption and desorption of walls. Authors have also proposed such a moisture transfer model called P-model and developed simulation software to analyze moisture behaviour in wall assemblies. Thus THERB for HAM represents the combined simulation software capabilities of the original THERB software and the new features of the P-model, which can now predict the hygrothermal environment of the whole building (all spaces and wall assemblies of the building) taking into consideration the complex relationship between heat and moisture transfer and air flow.

In this paper, the basic theories used in THERB for HAM are described. Accuracy of THERB for HAM is verified through the comparison of calculation and monitoring results of a residential building. Furthermore the difference of calculation results is clarified based whether or not moisture sorption and desorption of walls are taken into account.

INTRODUCTION

THERB for HAM is a dynamic simulation software which can estimate temperature, humidity, sensible temperature, and heating/cooling load for multiple zone buildings and wall assemblies. The heat and moisture transfer models used in THERB such as conduction, convection, radiation and ventilation (or air leakage) are based upon the detailed phenomena describing actual building physics [1], and can be applied to all forms of building design, structure or occupant schedules, etc. All the phenomena are calculated without simplification of the heat and moisture transfer principles of any building component or element. The paper explains prominent features of the models, and accuracy of THERB for HAM is also described.

THEORETICAL FEATURE OF THERB FOR HAM

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

Conductive Heat 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.

Convective Heat 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 [2] (based on the energy equation, the momentum equation and the fluid friction) or defined from the experimental findings according to natural or forced convection [3],[4]. 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 air-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

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. 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 [5]. Mutual radiation between the surfaces of cavities in walls and windows can also be calculated.

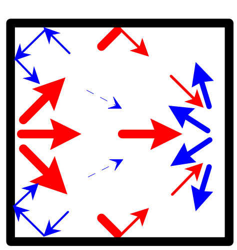


Fig.1 Multiple Reflection of Long-wave Radiation

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

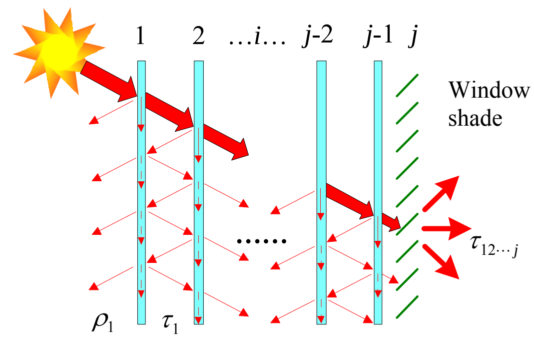


Fig.2 Multi-layer Window Model

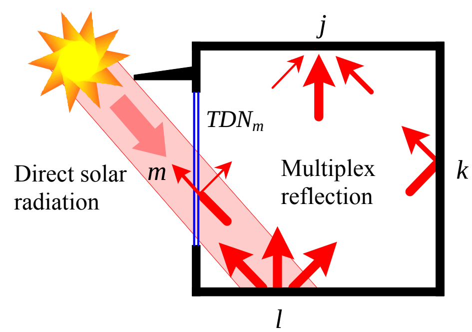


Fig.3 Multiplex Reflection of Transmitted Direct Solar Radiation

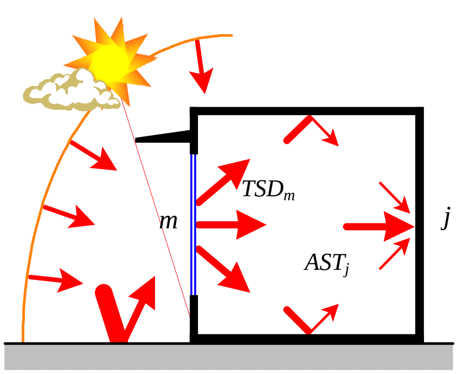
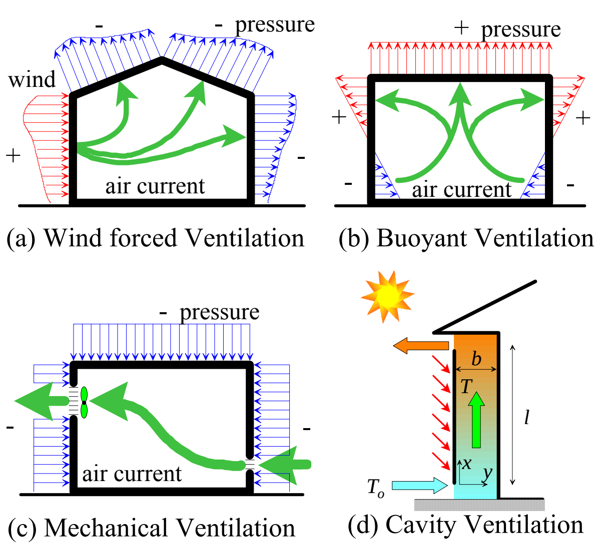


Fig.4 Multiplex Reflection of Transmitted Sky Diffuse Solar Radiation

all parts of the building in all directions using accurate geometric calculations of shaded and unshaded portions of the building by considering the influence of overhangs and wings. Isotropic model or anisotropic [6] models can be chosen for diffuse solar radiation. Transmitted solar radiation is calculated by the multi-layer window model [7] 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 [8]. Constant ventilation quantities can be also set every hour for all zones.



(a) Wind forced Ventilation (b) Buoyant Ventilation

(c) Mechanical Ventilation (d) Cavity Ventilation

Fig.5 Mechanical or Natural Ventilation

Conductive Moisture Transfer: Water Potential which is derived by applying the chemical potential of thermodynamics to moisture diffusion is used as the driving force of moisture transfer [9]. 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.

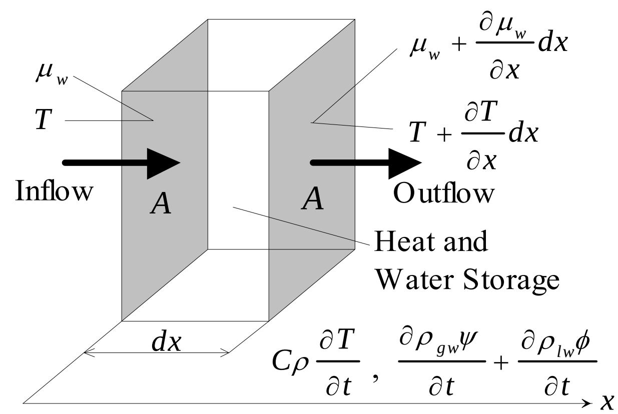


Fig.6 Conductive Heat and Moisture Transfer

Convective Moisture Transfer: 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.

Control of Space Conditioning: 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 air-conditioning.

Flow Chart: Fig.7 shows the flow chart of THERB for HAM. One of the characteristics of THERB for HAM is that calculation nodes are automatically numbered for each room component or element and associated both temperature and humidity calculation.

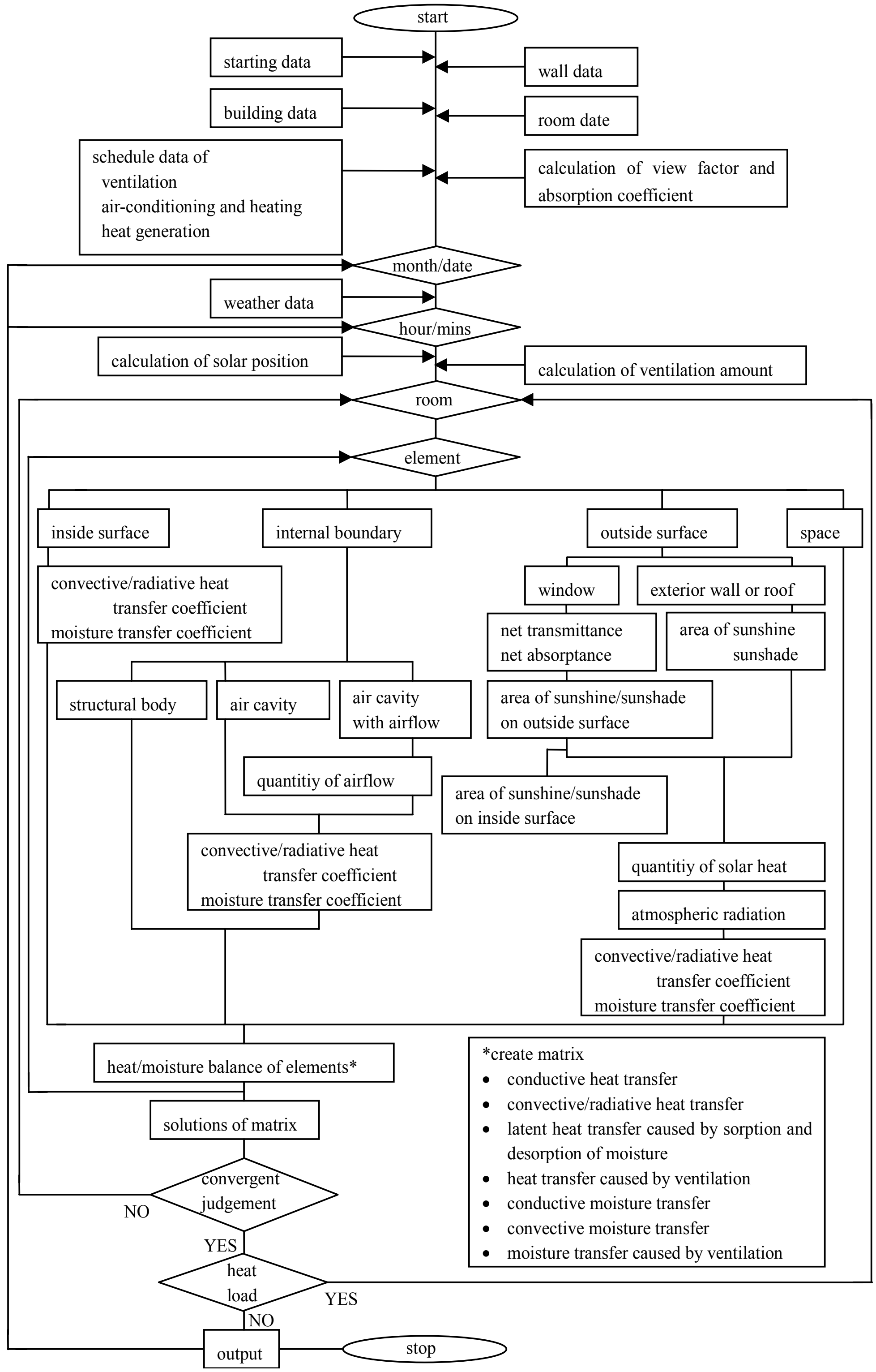


Fig.7 Flow Chart of THERB for HAM

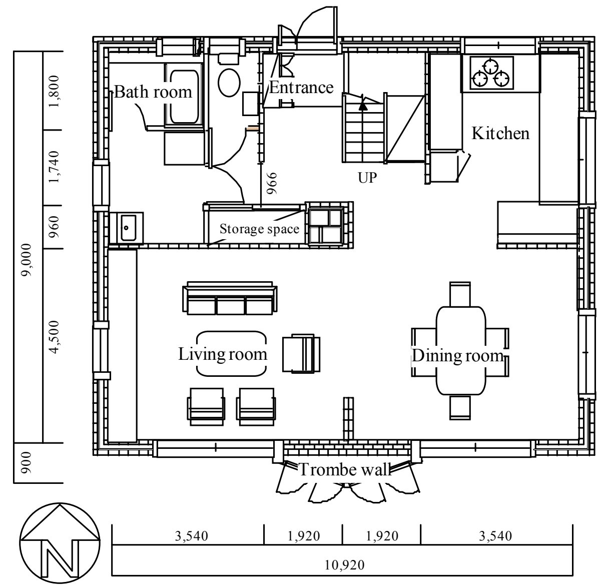
<u>SIMULATION OF HYGROTHERMAL ENVIRONMENT AND HEATING / COOLING LOAD</u>

Verification of THERB for HAM: The hygrothermal environment of the room and cavity in a wall of the house was calculated to verify accuracy of THERB for HAM. The influence of sorption and desorption of the wall on the hygrothermal environment of the room is also clarified.

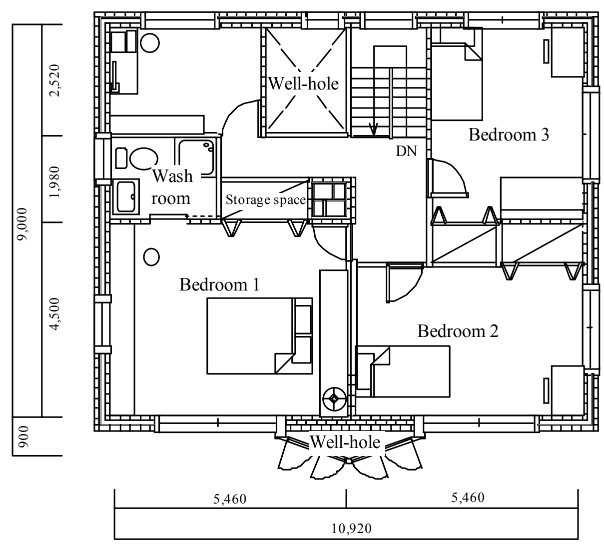
A brick house was built in Kumamoto, in the southern part of Japan (Pic.1 to 2). Fig.8 shows the plan of the brick house. The brick house is a two-story house and the total floor area is 194m^2. The exterior walls use a cavity brick structure with a vacuum insulation between brick walls (Fig.9). The vacuum insulation has high thermal resistance and works as a moistureproof material. Table 2 shows the components of wall structures.

Table 2 Components of Wall Structures

Roof	plywood	10mm
	clay tile	40mm
1F ceiling	plaster board	10mm
2F ceiling	plaster board	10mm
	thermal insulating board	50mm
Floor	plywood	10mm
Ground	concrete	200mm
	crushed stone	50mm
	soil	50mm
Foundation	brick	110mm
	thermal insulating board	50mm
	brick	110mm
Exterior wall	brick	110mm
	air cavity	50mm
	vacuum insulation	30mm
	air cavity	65mm
	brick	110mm
Trombe wall	brick	330mm
	air space	100mm
	double glazing	5+10+5mm
Interior wall I	brick	110mm
Interior wall II	plaster board	10mm
	air cavity	50mm
	plaster board	10mm



(a) First Floor Plan



(b) Second Floor Plan

Fig.8 Plans of Brick House [unit: mm]

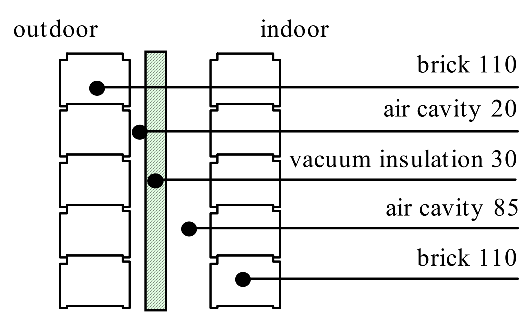


Fig.9 Exterior Wall Structure [unit: mm]

Pic.1 Outside View of the Brick House on the Southwest

Pic.2 Inside View of the Brick House (Living Room and Dining Room on the First Floor)

Calculation Conditions: Table 3 shows the calculation conditions. Weather data are based on actual measurements (or estimated values based on actual measurement). The brick house was not air-conditioned or heated, however it was ventilated (0.5 times per hour) all day. Results were compared at two points. One was the master bedroom on the southwest corner on the second floor and the other was the cavity of south brick wall of the master bedroom. All properties concerned with heat and moisture transfer were obtained from the catalogue or literature published by the Architectural Institute of Japan [10].

Comparison of Monitored and Calculated Results: Fig.10 shows monitored and calculated results of the temperature and the absolute humidity in the master bedroom. The difference of the temperatures between monitored and calculated results was 0.4K or less. The results of the calculated absolute humidity also showed good agreement with monitored data.
Fig.11 shows monitored and calculated results of the temperature and the absolute humidity in the cavity of the south wall of the master bedroom. Calculated temperature and absolute humidity agree well with monitored data.

Table 3 Calculation Conditions

Items		Conditions
Weather data	Outside air temperature Outside air absolute humidity	Measured
	Direct solar radiation Sky diffuse radiation	Calculated using measured data (Dr. Watanabe's Formula)
	Nocturnal radiation	Calculated using measured data
	Wind direction Wind velocity	Measured
Run-up		10 days
Calculation period		1 hour
Air-conditioning / heating		None
Air change rate		0.5 time per hour

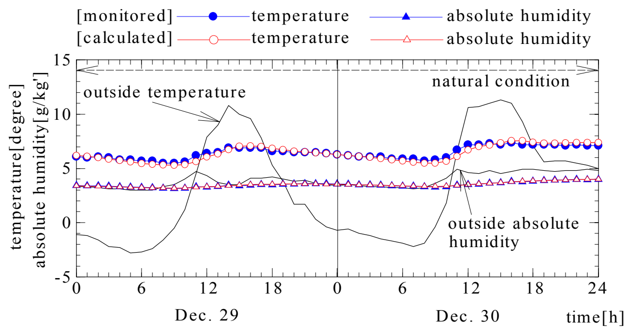


Fig.10 The Comparison of Monitored and Calculated Temperature and Absolute Humidity in the Master Bedroom

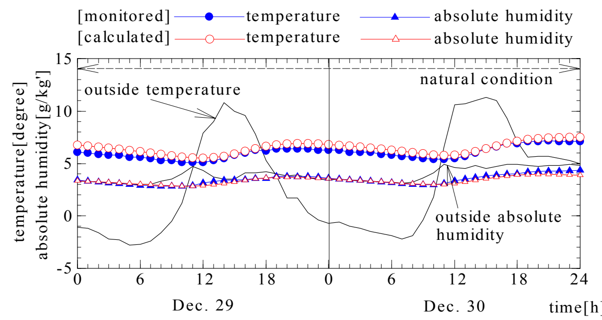


Fig.11 The Comparison of Monitored and Calculated Temperature and Absolute Humidity in the Cavity of the South Wall

The Influence of Sorption and Desorption of Walls on Hygrothermal Environment of Rooms: Fig.12 shows the calculated results under the six different conditions (Case 1 to Case 6) described in Table 4. The differences in conditions were whether sorption and desorption of the wall are taken into account or not, and differences in the imaginary moisture capacity involved in room air as most general simulation software supposes like that instead of the detail sorption and desorption calculation. In cases where imaginary moisture capacity is involved (sorption and desorption are ignored for a simplified calculation), 16.7 kg/m^3(kg/kg') of generally applied, 9.6, 19.3 and 38.6 kg/m^3(kg/kg') fit for moisture capacity of brick 5mm, 10mm and 20mm thickness were used.

Case 3 which has no imaginary moisture capacity differed significantly from monitored absolute humidity and Case 1 which used the detailed calculation method which includes sorption and desorption of the wall. Case 3 moved quickly and was much influenced by absolute humidity of outside air with ventilation. As imaginary moisture capacity increased, the calculated results became gradually closer to monitored data and slow moving. However, in comparison with Case 1 of detailed calculation, the resulting error of using a simplified calculation method was large.

The Influence of Sorption and Desorption of Walls on Cooling and Heating Loads: The cooling and heating load of the brick house was calculated with and without sorption and desorption calculation of wall under the living conditions. Table 5 shows the calculation conditions. The AMeDAS Weather Data in Fukuoka was used in the calculation. The heat and moisture generation in each room was derived by using Schedule Ver.2.0 which describes typical activities of Japanese within a home (proposed by The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan). Only the room where somebody was in was air-conditioned or heated.

Table 4 Calculation conditions of sorption and desorption

	sorption and desorption of walls	imaginary moisture capacity
Case 1	taken into account	None
Case 2	ignored	16.7 kg/m^3(kg/kg') of generally used
Case 3		None
Case 4		9.64 kg/m^3(kg/kg') (brick 5mm thickness)
Case 5		19.29 kg/m^3(kg/kg') (brick 10mm thickness)
Case 6		38.58 kg/m^3(kg/kg') (brick 20mm thickness)

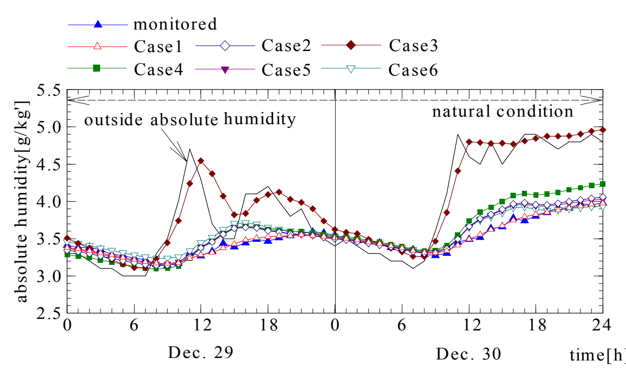


Fig.12 Comparison of Calculated Absolute Humidity with Different Conditions in Bedroom

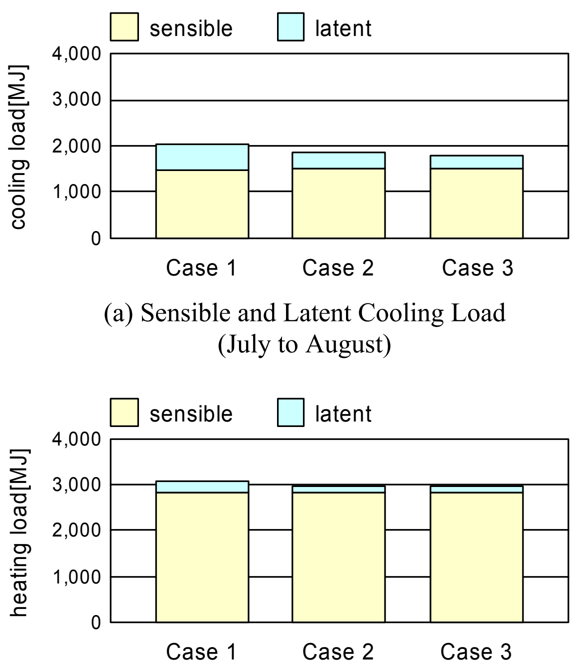
Table5 Calculation Conditions

Items	Conditions
Weather data	AMeDAS weather data in Fukuoka
Family structure	4 peoples (worker, house wife, high school student, junior high school student)
Run-up	3 months
Calculation period	15 minutes
Setting temperature and humidity	Air-conditioning (summer): 26 degrees, 60% Heating (winter): 20 degrees, 40% intermittent cooling and heating for the room with occupant schedule
Air-conditioning and heating time	0-7, 9-12, 14-15, 22-24 [hour]
Air change rate	0.5 time per hour

Fig.13 shows the cooling load from July to August and the heating load from January to February for Case 1 to Case 3 with and without sorption and desorption calculation of the wall. There were almost no differences in the sensible heat loads for Case 1 to Case 3. However when taking into consideration detailed sorption and desorption calculations (Case 1), there was an observed difference in the latent heat load compared to Case 2 and 3. In particular, Case 1 clearly demonstrates the impact of moisture storage and release due to sorption and desportion in increasing the latent heat load compared to Case 3 which only takes into account latent heat load associated with ventilation during air-conditioning. The latent heating load was also affected by the moisture storage in the room. However the influence of the moisture storage on the latent heating load was smaller than that of the latent cooling load.

Figure 14 shows the dehumidification (amount of moisture which must be removed) profiles in summer and humidification (amount of moisture which must be added) profiles in winter necessary to satisfy the humidity set-points for Case 1 to 3. In summer, Case 1 which uses the detailed sorption and desorption calculation and Case 2 which uses the simplified calculation with imaginary moisture capacity in room showed similar profiles. The dehumidification profile in Case 1 responded more slowly in proportion to changes in desorption of the wall, compared to that of Case 2. Case 2 responded or peaked more quickly in response to increases in desorption and very quickly dropped in response to a decrease in desoprtion, to the amounts represented by Case 3 which is the simplified calculation without imaginary moisture capacity in room. For the winter condition, Case 1 and Case 2 also show similar humidification profiles in proportion to changes in sorption and desorption of the wall with the peak for Case 1 and 2 occurring at the same time, however the difference in the humidification results for Case 1 and 2 was larger than that of the summer condition with dehumidification, particularly for the peak.

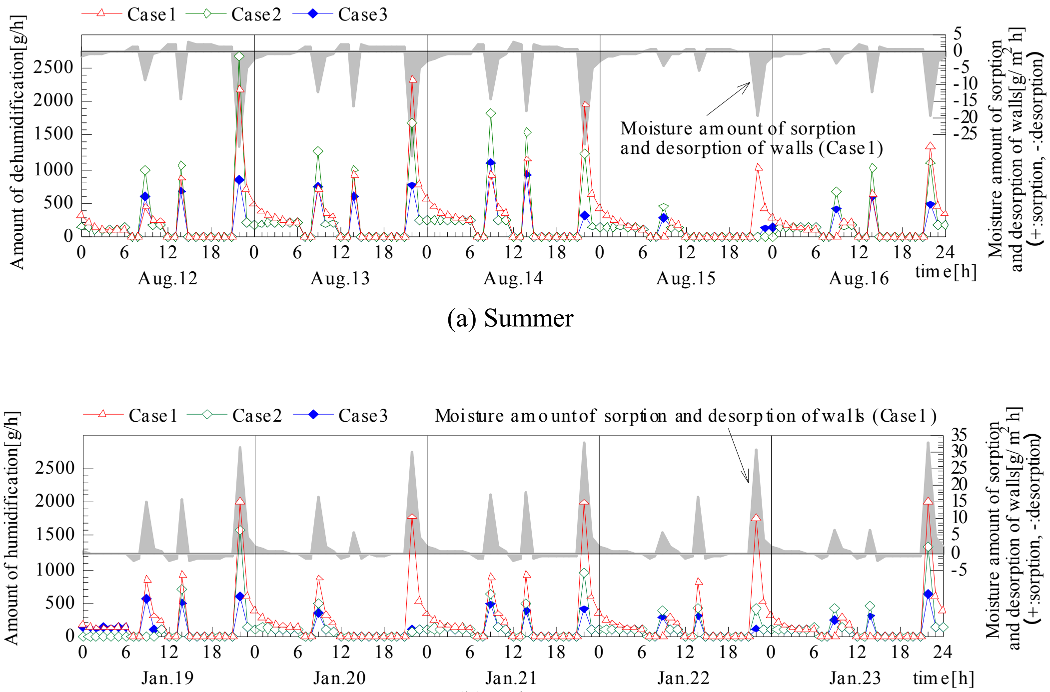
Fig.15 shows indoor absolute humidity for Case 1 to Case 3. The absolute humidity of Case 3 followed the outside air during periods of no air-conditioning and no heating. Although the absolute humidity of Case 1 and Case 2 were affected by outside air, their response to outdoor air was slower, particularly for Case 1.



(a) Sensible and Latent Cooling Load (July to August)

(b) Sensible and Latent Heating Load (January to February)

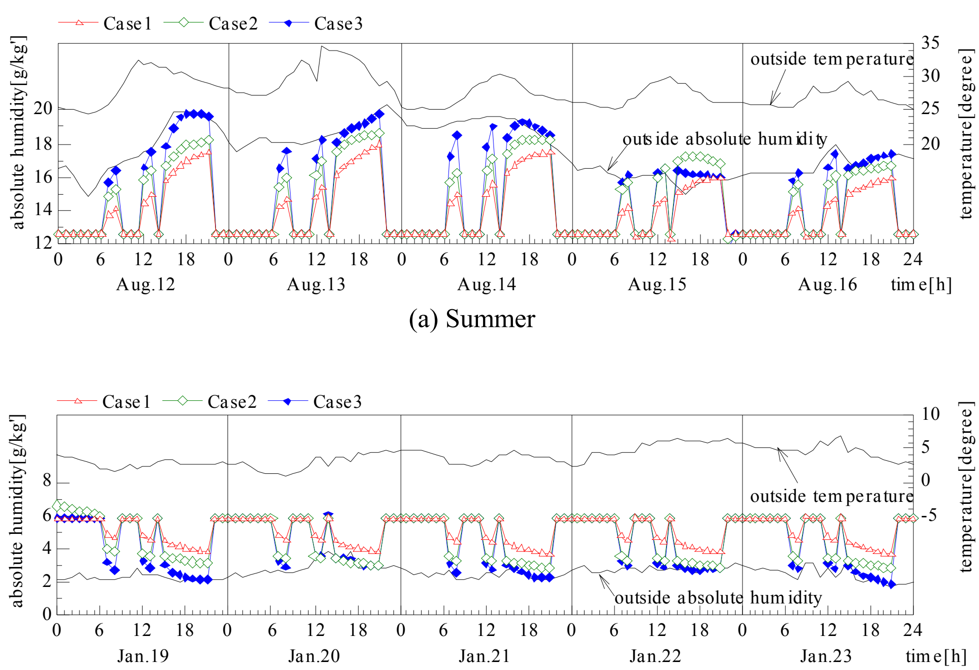
Fig.13 Cooling and Heating Load



(a) Summer

(b) Winter

Fig.14 Moisture Amount of Dehumidification and Humidification of Case 1 to Case 3



(a) Summer

(b) Winter

Fig.15 Absolute Humidity of Case 1 to Case 3

CONCLUSIONS

The theoretical models of combined heat and moisture transfer used in THERB for HAM were outlined. The accuracy of THERB for HAM was verified through the comparison of calculated and monitored results, and then the influences of sorption and desorption of wall on hygrothermal environment and cooling / heating load of the brick house was clarified.

1) The prominent features of the combined heat and moisture transfer models, such as dimensionless equations to calculate convective heat transfer coefficients, the long-wave and short-wave absorption coefficients to simulate the net absorption of radiant heat and transmitted solar radiation, a multi-layer window model to calculate solar transmission, and the potential model to calculate moisture transfer, were highlighted.
2) In comparison with monitored temperature and humidity of the room and wall assembly of the brick house, the calculated results obtained from THERB for HAM agreed well with monitored data.
3) The behaviour of the hygrothermal environment when using detailed sorption and desorption calculations was significantly affected by sorption and desorption of the wall. In particular the change of indoor absolute humidity responded much more slowly when taking into consideration sorption and desorption of the wall.
4) Simplified calculation methods using imaginary moisture capacity in a room as most general simulation software supposes like that instead of the detail sorption and desorption calculation could not adequately characterize the actual hygrothermal environment and the amount of moisture removal for dehumidification and moisture addition for humidification during cooling and heating respectively. When taking into account sorption and desorption the latent cooling and heating loads were increased compared to cases where the moisture capacity was simplified or not considered at all.
5) In the case where the imaginary moisture capacity was estimated as a small value, indoor absolute humidity was primarily affected by the latent load introduced by ventilation from outdoors. As a result the latent cooling and heating load were less than expected due to the fact that moisture storage was less than estimated.

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