# NUMERICAL SIMULATION ON HYGROTHERMAL ENVIRONMENT OF WHOLE BUILDINGS TAKING INTO ACCOUNT COMPLETE HAM FEATURES

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## ABSTRACT

Many simulation software to predict thermal environment of buildings, such as temperature, humidity, heating and cooling load of building spaces, have been developed. However, most of them do 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. Then, sensory index such as standard new effective temperature is even excluded from calculation. A Heat, Air and Moisture (HAM) simulation software 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. In this paper, the prominent features of THERB are highlighted. The calculation accuracy is verified through the comparison with monitoring results of a residential building. The difference of hygrothermal environment is clarified based whether or not moisture sorption and desorption of walls are incorporated. Sensitive analysis utilizing THERB is performed with the differences of calculation models on heat and moisture transfer and incident solar radiation into indoor surfaces. Furthermore thermal comfort under non-uniform thermal environment is indicated as the sensory index.

## INTRODUCTION

THERB is dynamic simulation software, which can estimate temperature, humidity, sensory index, 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, 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 moisture transfer model using the water potential, which is defined as thermodynamic energy, is a progressive feature, 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. This paper explains prominent features of the calculation models, and the accuracy of THERB through the comparison with temperature and humidity measurements of buildings. Sensitive analysis utilizing THERB are performed with a number of parameters based whether or not moisture sorption and desorption of walls are taken into account. Then sensory index 'COMSET*' based on hygrothermal balance of various parts of human body is calculated under non-uniform thermal environment with a combination of THERB.

## THEORETICAL FEATURE OF THERB

The following outlines the algorithms for heat and moisture transfer and airflow used in THERB, which are derived from building physics principles (Ozaki et al. 2006).

### Conductive Heat and Moisture Transfer

The finite difference method is applied to the model of one-dimensional transient hygrothermal 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 (Ozaki et al. 2001). This approach is proposed to be more theoretical and accurate than other models based on physical properties such as vapor pressure (Trechsel 2001). The model called P-model using water potential makes it possible to combine moisture transfer with heat transfer perfectly as thermodynamic system, and take into account internal energy and external forces such as pressure increment and gravity.

### Convective Heat and Moisture Transfer

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 (Fujii et al. 1972, Ozaki et al. 1990). 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 all parts of the building. The convective moisture transfer coefficients on all surfaces of the exterior, interior and cavities of buildings are calculated on the basis of the analogy between heat and mass transfer.

**Radiant Heat Transfer**

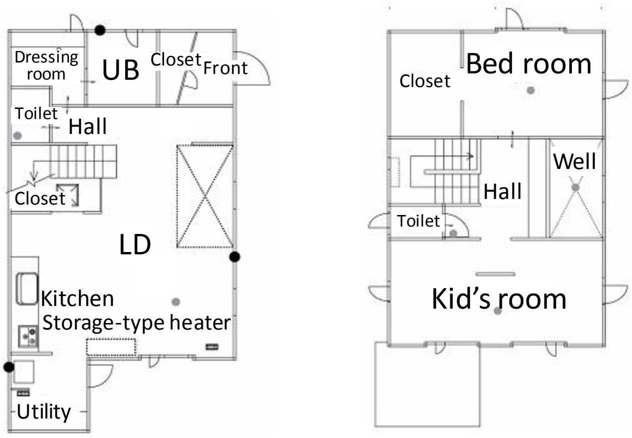
On the exterior surfaces of the buildings, the general method of using the radiant heat transfer coefficients and atmospheric radiation is applied in default. Interrelated radiation between both surfaces of building and the ground can be also calculated with temperature calculation of the ground. On the interior of buildings, 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 (Gebhart 1959). Mutual radiation between the surfaces of cavities in walls and windows can be also calculated. The long-wave absorption coefficient is applied to long-wave radiant heat emitted from lights and appliances and human bodies by assuming that such radiant heat is equally emitted from the ceiling or floor.

**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 shaded and unshaded portions of the building by considering the influence of overhangs and side walls. Transmitted solar radiation is calculated by the multi-layer window model which 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 transmitted 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 short wave are applied to radiant heat emitted from lights and appliances.

*Photograph 1*
*Exterior appearance*

*Photograph 2*
*Interior appearance*




*(1) First floor* *(2) Second floor*
*Figure 1 Floor plan*

*Table 1 Building specifications*

| | |
|---|---|
| Building specifications | Timber construction |
| Exterior wall | Mortar 10mm, Air space 11mm, Weather barrier, Phenolic foam 40mm, Polyethylene sheet, Red pine 30mm |
| Roof | Western tile 30mm, Asphalt felt 10mm, Roof board 12mm, Air space 11mm, Phenolic foam 50mm, Polyethylene sheet, Red pine 30mm |
| Floor | Red pine 60mm |
| Partition wall | Red pine 30mm, Air space 10mm,Red pine 30mm |
| Window | Low-E triple glazing |
| Location | Akashi |
| Weather condition | Measured values |

**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 cavities naturally ventilated 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 for all zones every hour.

**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. Indoor humidity is interrelated with moisture sorption and desorption of walls by applying the P-model of heat and moisture transfer. 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 temperature and humidity is automatically performed in the case when the sensible temperature such as SET* is set as the set-point of space conditioning.

## CALCULATION ACCURACY

**Outline of the Monitoring House**

The Photograph 1 and 2 show the exterior and interior appearance of the monitoring house. Figure 1 illustrates the first and second floor plan and Table 1 shows building specifications. This house was built in Akashi in May, 2009 with the timber construction. In view of constant temperature and humidity in rooms, Japanese red pine which has the high performance of heat storage and moisture sorption and desorption is used on overall indoor surfaces as interior materials (30mm thickness of wall, celling and roof, 60mm thickness of floor). This house demonstrates superior performance in thermal insulation and airtightness by applying the triple low-e glazing and exterior insulation and is mechanically designed for a certain amount of ventilation.

**Comparison of calculation and monitoring results**

The accuracy of THERB is verified by comparing the calculated and measured values for the monitoring house. Figure 2 and Figure 3 show the weather data and the calculation and monitoring results (whether or not moisture sorption and desorption of walls are incorporated) of indoor temperature and humidity (the first floor living room and the second floor main bed room) on October 14 to 18 in mild climate. A family consisting of a husband, his wife and two children lives there and no use a space conditioning system on these days. Heat and moisture generation in rooms is assumed on their living schedule. The period of previous calculation is three weeks and the initial values of temperature and humidity of whole

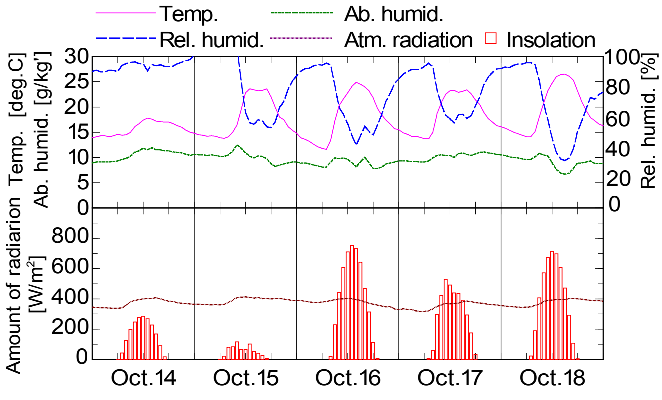
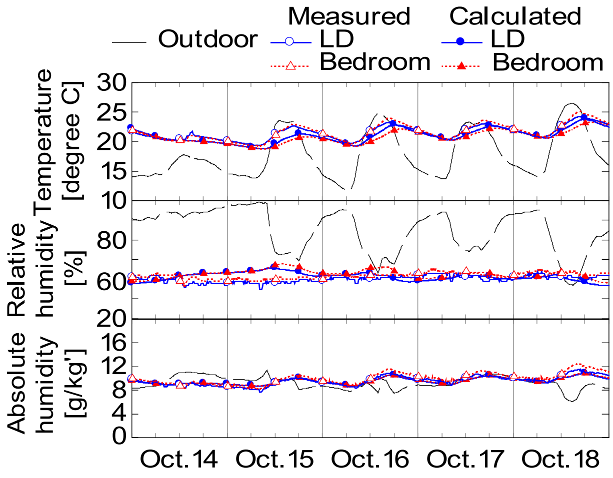
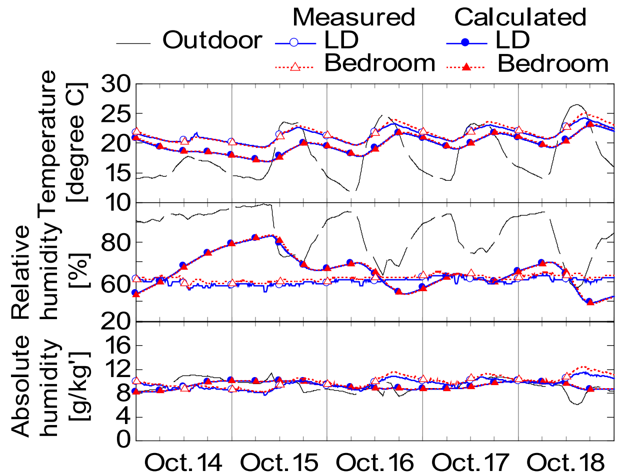



*Figure 2 Weather data in Akashi*



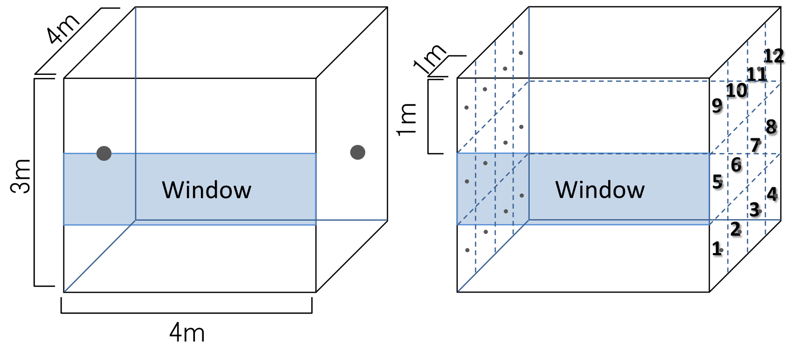

*(1) With moisture transfer*




*(2) Without moisture transfer*

*Figure 3 Comparison of calculated and measured*

building are set to outdoor temperature and humidity at the start time of calculation. The weather data for calculation is hourly observation value. In case moisture transfer (moisture sorption and desorption of walls) are incorporated, the calculated values of temperature and humidity are agree well with the measured values. While in case without moisture transfer, the calculated values are quite different from the measured values. Particularly the calculation error of relative humidity becomes up to 13%. There is also measurable temperature difference because adsorption and desorption heat is neglected, although it is not as much as relative humidity.




*(1) Macro-model* *(2) Meso-model*

*Figure 4 Building model*

## SENSITIVE ANALYSIS OF HYGROTHERMAL ENVIRONMENT

### Calculation Conditions

Figure 4 illustrates the building model used to sensitive analysis. The building model is composed of a single room (4 meters square and 3 meters high) with double glazing window (4 meters width and 1 meter high) at 1 meter above the floor on the south face. Walls, floor and ceiling are all insulated and facing the outdoor. The Japanese red pine is used as interior finishing material of walls. The calculation error caused by the differences of heat and moisture transfer model is clarified. Then the calculation error of a macro-model and a meso-model (a single node model and a multi node model of heat and moisture balance on a vertical

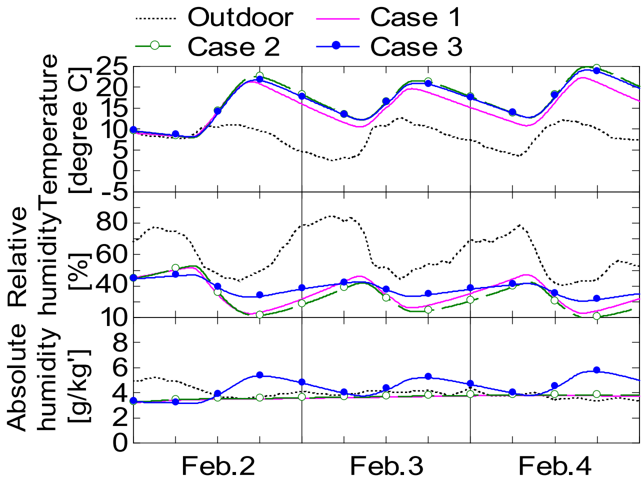



*Figure 5 Sensitive analysis of heat and moisture transfer coefficient*

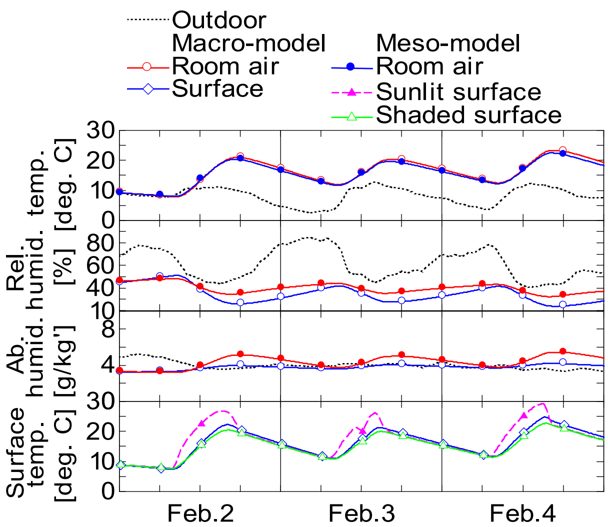



*Figure 6 Sensitive analysis of incident solar radiation into indoor surfaces*

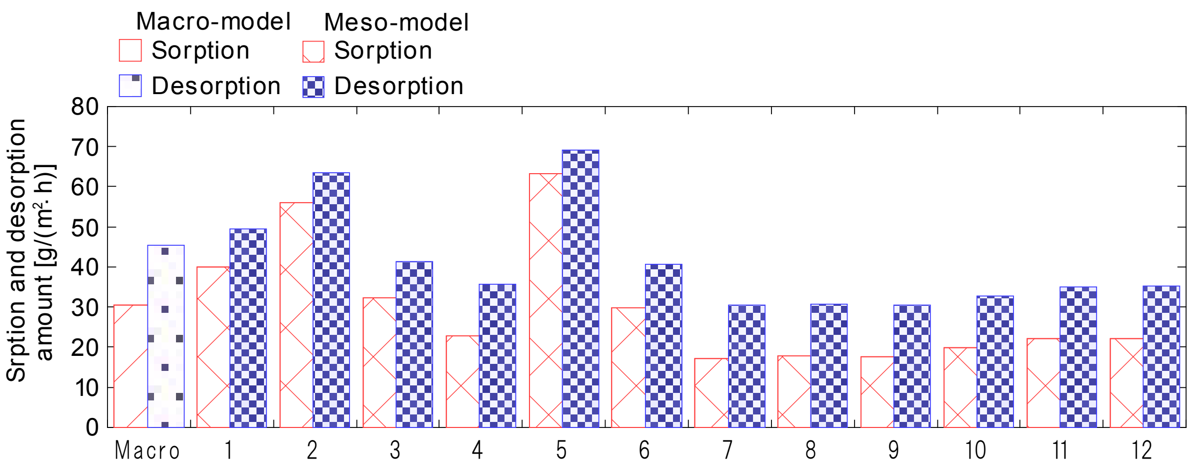



*Figure 7 Difference of moisture asorption and desorption amount between Macro-model and Meso-model*

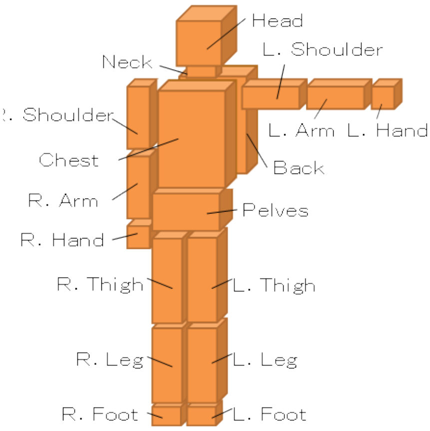



*Figure 8 Division of human body (COM)*

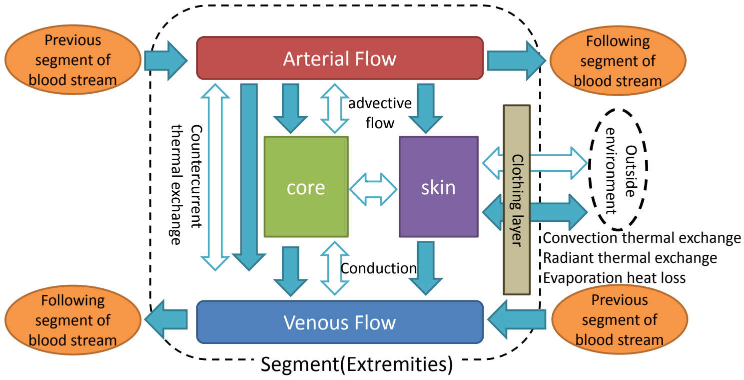



*Figure 9 Thermal exchange among core, skin, and blood of extremities*

plane), as shown in Figure 4, is demonstrated. Ventilation ratio of 0.5 times per hour and no heat and moisture generation are considered.

**Influence of heat and moisture transfer coefficient**

The following heat and moisture transfer models are applied to calculation; convective and radiant heat transfer coefficient assuming constant (Case 1), convective and radiant heat transfer coefficient assuming time-variable (Case 2), incorporating moisture transfer into Case 2 (Case 3). Figure 5 shows temperature and humidity fluctuation of Case 1 to 3 from February 2nd through the 4th in Tokyo. Temperature of Case 2 and 3 in which convective and radiant heat transfer coefficient is assuming time-variable rises over 3.0 degree higher than Case 1 in which heat transfer coefficient is constant. Then temperature phase of Case 3 and 4 lags a little behind Case 1. Regarding relative humidity, Case 3 with moisture transfer is moderately fluctuating more than Case 1 and 2 without moisture transfer because absolute humidity of Case 3 is widely changed as a result of moisture sorption and desorption of walls following temperature change.

**Influence of incident solar radiation into indoor surfaces**

Influence of the differences of solar absorption model of indoor surfaces on hygrothermal environment is demonstrated through the comparison of the macro-model and the meso-model. Twelve nodes of heat and moisture balance are set on a vertical plane in both the East and West in the meso-model. Incident solar radiation is equally-distributed into whole area of the wall in the macro-model, and so insolation intensity per unit area becomes lower than the actual sunlit area. While Incident solar radiation is just diffused within small area in the meso-model in which the plane is split into pieces. Therefore there are differences in sunlit area and insolation intensity between the macro-model and the meso-model.

Figure 6 shows the surface temperature of the east wall and indoor temperature and humidity. The surface temperature gets higher in order of solar

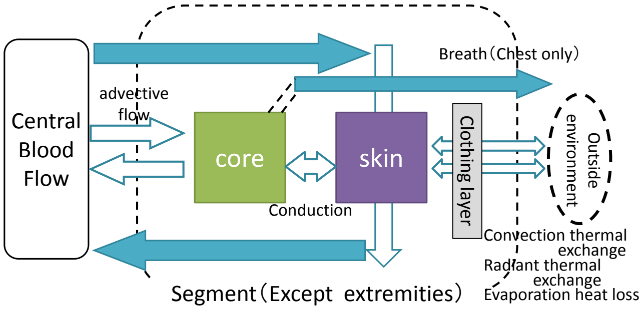



*Figure 10 Thermal exchange among core, skin, and blood of except extremities*

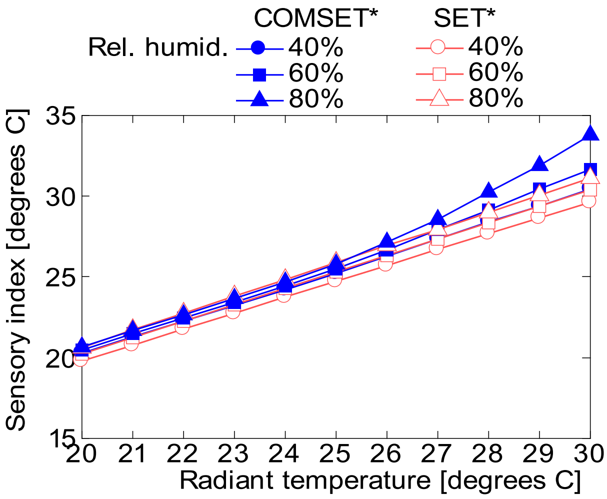



*Figure 11 SET* and COMSET* under the condition of uniform thermal environment*

shading area of the meso-model, the macro-model, sunlit area of the meso-model. The surface temperature of sunlit area of the meso-model becomes over 8.3 degrees C higher than the macro-model. However there is not much difference in indoor temperature between the macro-model and the meso-model. While absolute humidity of the meso-model becomes higher than the macro-model. The absolute humidity of the macro-model fluctuates slowly and is nearly equal to the outdoor air. Therefore the error of relative humidity between both models arises over 7%. Figure 7 shows sorption and desorption amount of hourly average of divided parts on interior surfaces of the east wall. There are large differences of such amount in each part. It is necessary to make an accurate calculation of solar transmission through windows and distributions of sunlit and shading area of interior surfaces because incident solar radiation and solar heat gain of walls cause the error of moisture sorption and desorption and indoor relative humidity.

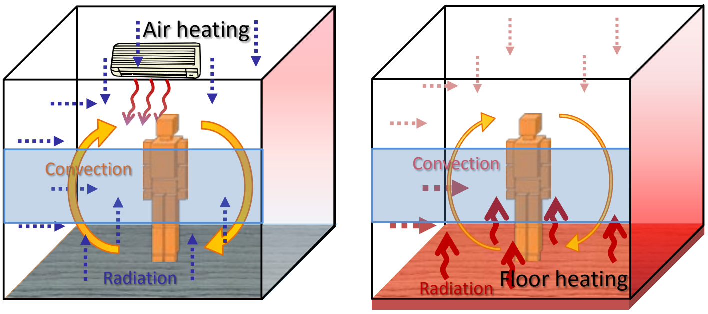
## PREDICTION OF SENSORY INDEX

The influence of non-uniform thermal environment on occupant comfort is evaluated by using the sensory index 'COMSET*' which is derived from the heat balance of body parts (Tanabe et al. 2006) in combination with THERB.

### COMSET*

COMSET* is a mathematical model of sensory index, such as standard new effective temperature 'SET*', derived from the detailed heat balance of body parts with consideration of blood circulation (arterial and venous flow) throughout the body involving the extremities. Figure 8, 9 and 10 illustrate the conceptual diagram of COMSET*. By breaking whole body into 17 segments with each skin and core layer, it can predict temperature distribution of skin and blood at 59 parts all over the body. Then COMSET* can calculate a generalized sensory index under the condition of non-uniform thermal environment by setting up the boundary conditions of surrounding air temperature and humidity, airflow velocity (convective heat flux), radiant heat flux and clothing amount for each body segment and metabolic energy.

Figure 11 shows the calculated values of SET* and COMSET* under the condition of uniform thermal environment of surrounding air and surface temperature. SET* and COMSET* become almost the same value at low and middle humidity range and temperature range below 27 degrees C. However, the higher humidity rises, the more calculation error between them increases in temperature range above 27 degrees C.




*(1) Air heating* *(2) Floor panel heating*

*Figure 12 Heating system*

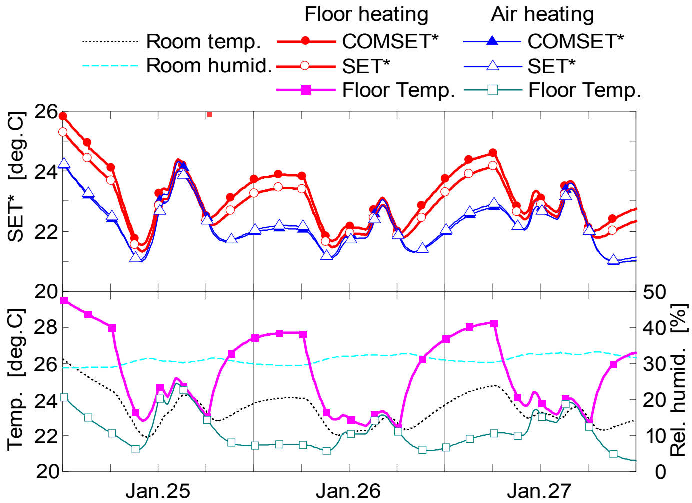



*Figure 13 Influence of heating system on thermal comfort*

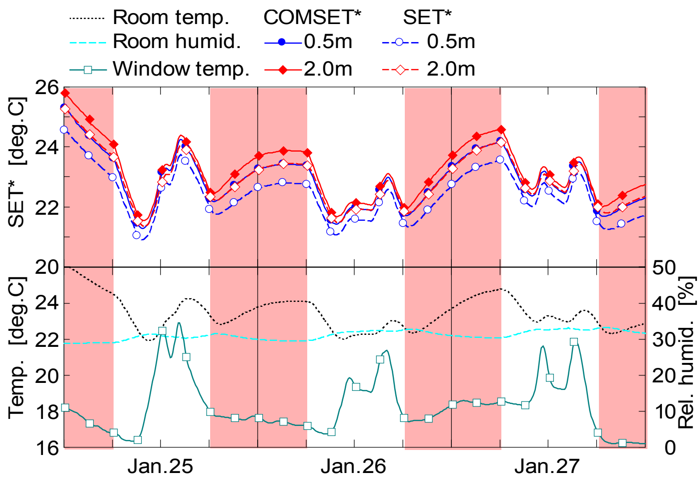



*Figure 14 Influence of radiant heat flow from window on thermal comfort*

### Calculation conditions

Figure 12 illustrates the building model and heating systems. The sensory indexes are compared under the conditions of different heating system (air heating and floor panel heating). Here, air temperature and humidity of air heating system is set up the same as floor panel heating to make clear the influence of long-wave radiation emitted from peripheral walls, floor and ceiling on thermal comfort. Incident radiant heat to each body segment is accurately calculated by completely-coupled calculation with THERB. Clothing amount and metabolic energy are assumed as 0.85clo (a long-sleeve shirt and trousers) and 58.2 W/m$^2$, respectively.

**Influence of heating system on thermal comfort**

Figure 13 shows calculated SET* and COMSET* from January 25th through 27th in Tokyo. Both of them become higher in floor panel heating system because of strong heat radiation in comparison with air heating system. Maximum differences between both heating systems are 1.1 degrees C at SET* and 1.9 degrees C at COMSET*. SET* is calculated by using mean radiant temperature, while COMSET* is derived from heat balance at 17 body segment. Thus COMSET* which incorporates the body segment intensely influenced by floor heating rises higher than SET*.

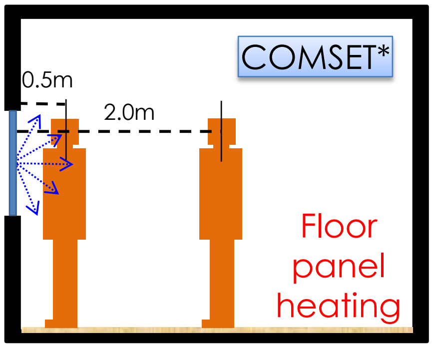
**Influence of radiant heat from window on thermal comfort**

Figure 14 shows variation of SET* and COMSET* across the standing point in the room applying floor panel heating system. Here, a person is supposed to stand at the point of 0.5m and 2.0m apart from the window. Both SET* and COMSET* at the point of 0.5m where the person is strongly affected by radiant heat from cooler window are decreased lower than that of 2.0m. As compared to COMSET*, SET* becomes much lower because the influence of window for SET* is larger than for COMSET* as shown in Figure 15. Namely, to evaluate thermal comfort under the condition of non-uniform thermal environment, it seems necessary to combine heat balance of building and human body in detail.

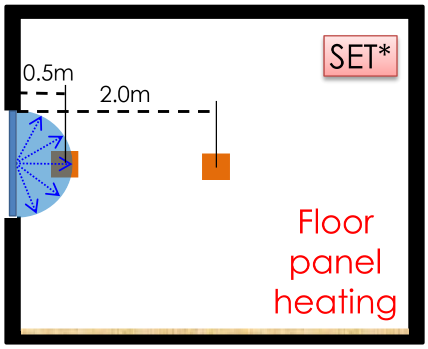
## CONCLUSIONS

The simulation software ‘THERB’ incorporateing complete features on heat, moisture and airflow has been developed to predict hygrothermal environment and sensory index within whole buildings. Hygrothermal theories on conduction, convection, radiation and ventilation of THERB are outlined, particularly algorithm on combined heat and moisture transfer using thermodynamic energy (referred to as water potential) is the progressive feature, which incorporates moisture transfer including moisture sorption and desorption of walls. The calculation precision of THERB allowing for the combination of heat and moisture transfer and airflow of whole buildings is verified through the comparison with monitoring results.

Furthermore, sensitive analyses of heat and moisture transfer and incident solar radiation into indoor surfaces get the following results; combined calculation of heat and moisture transfer is absolutely necessary to analyze hygrothermal environment




*(1) COMSET**




*(2) SET**

*Figure 15 calculated points of sensory index*

accurately, time-varying and nonlinearity of the coefficients of convective and radiant heat transfer in each part of buildings are important to raise prediction precision, the time shift of sunlit area on interior surfaces caused by transmitted solar radiation through windows influences greatly on indoor humidity, thermal sensation in various parts of the body affects generalized sensory index, it is possible to evaluate thermal comfort under the condition of non-uniform thermal environment by combineing heat balance of building and human body.

## REFERENCES

Conceicao E.Z.E. 2003, Numerical Simulation of Building Thermal Behaviour and Human Thermal Comfort Multi-Node Models, Proc. of the 8th International IBPSA Conference, p.227-234

Costola D., Blocken B., Hensen J. 2009, External Coupling Between BES and HAM Programs for Whole-Building Simulation, Proc. of the 11th International IBPSA Conference, p.316-323

Fujii W. and Imura H. 1972, Natural Convection Heat Transfer from a Plate with Arbitrary Inclination, Int. J. Heat Mass Transfer, Vol.15, p.755-767

Gebhart, B. 1959, A New Method for Calculating Radiant Exchanges, ASHRAE Transactions, Vol.65

Heinz R. Trechsel 2001. Moisture Analysis and Condensation Control in Building Envelopes, American Society for Testing and Materials, MNL40

Ozaki A., Watanabe T. et al., 1990, Heat and Mass Transfer at Outside Surface of Buildings – Wind Tunnel Tests of Heat and Mass Transfer on Horizontal Surfaces, Journal of Architecture, Planning and Environmental Engineering, Architectural Institute of Japan, No.407, p.11-25

Ozaki A., Watanabe T. et al. 2001, Systematic Analysis on Combined Heat and Water Transfer through Porous Materials Based on Thermodynamic Energy, Journal of Energy and Buildings, Vol.33, No.4, p.341-350

Ozaki A. and Kagawa H. 2006, Simulation Software to Describe the Hygrothermal Environment of Whole Buildings Based on detailed Physical Models, Proc. of the 7th International Conference of System Simulation in Buildings, P03 (24 pages)

Rode C., Woloszyn M. 2009, Common Exercises in Whole Building HAM Modelling, Proc. of the 11th International IBPSA Conference, p.346-353

Tanabe S., Kobayashi K. et al., 2006, Development of Numerical Thermoregulation-Model COM for Evaluation of Thermal Environment, Journal of Environmental Engineering, Architectural Institute of Japan, No.599, p.31-38