Analysis of an Indoor Environment with a Hydronic Floor-Heating System under the Sensory Index

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ABSTRACT
Recent building practice requires that buildings not only conserve energy but also provide a healthy and comfortable environment for the residents. However, most of the simulation software used to predict the temperature, humidity, and heating and cooling load of buildings does not take into account the human sensations under the non-uniform environment and contact thermal conductance such as the radiant heating and cooling system. A Heat, Air, and Moisture (HAM) simulation software, called THERB for HAM, has been developed for estimating the hygrothermal environment inside buildings. This software encompasses the complete set of HAM features, including the principles of moisture transfer within walls. The software can estimate the temperature, humidity, and the sensory index “COMSET*,” based on the hygrothermal balance of the human body, and the heating and cooling load for multiple-zone buildings and wall assemblies. The heat and moisture transfer models used in THERB, such as those for conduction, convection, radiation, and ventilation, are based on detailed phenomena describing the actual building physics. This paper highlights the features of the heat transfer models used for the detailed calculation of a hydronic floor-heating system. The accuracy of the calculations is verified by comparison with the monitoring results of a test house equipped with a hydronic floor-heating system. Furthermore, energy simulation for space heating and floor heating is performed to evaluate the energy conservation of both systems, based on the sensory index “COMSET*.”

KEYWORDS

INTRODUCTION
THERB is dynamic simulation software that can estimate temperature, humidity, the

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sensory index, and the heating and cooling load for multiple-zone buildings and wall assemblies. The heat and moisture transfer models used in THERB, such as those for conduction, convection, radiation, and ventilation (or air leakage), are based on detailed phenomena describing actual building physics. These models can therefore be applied to all forms of building design, structure, or occupant schedules. All of these phenomena are typically calculated without simplifying the heat and moisture transfer principles of any building component or element. The moisture transfer model, using water potential, which is defined as thermodynamic energy, is a progressive feature that incorporates moisture transfer, including the 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 the prominent features of the calculation models, and investigates the accuracy of THERB by comparison with a test house equipped with a hydronic floor-heating system. Subsequently, the sensory index “COMSET*,” based on the hygrothermal balance of the various parts of the human body, is calculated in case of the non-uniform thermal environment of floor heating, with a combination of THERB. Furthermore, the performance of the energy conservation of the space heating system and the hydronic floor-heating system is evaluated by coupling simulation.

THEORETICAL FEATURES OF THERB

The following paragraphs outline the algorithms used in THERB for heat and moisture transfer and airflow; this information was derived from building physics principles (Ozaki et al., 2006). Numerical models, such as that describing the fin efficiency, and convective and radiative heat transfer from the floor relating to the hydronic floor-heating system, the latter of which is newly incorporated into THERB, are particularly emphasized.

Fin efficiency

The fin efficiency, which refers to the ratio of actual heat transfer from the fin surfaces to hypothetical heat transfer (assuming that the fin temperature is equal to the temperature of hot water in a tube), is applied to the hydronic floor-heating system. Figure 1 illustrates the hydronic floor-heating system. Equations (1) to (8) show the formulae used to calculate the fin efficiency.

\[ \eta_f = \frac{1}{w} \left[ D + (w - D) \frac{\tanh mD}{mD} \right] \]  
\[ mD = \frac{C_f \cdot P}{\sqrt{\lambda_f \cdot t}} D \]  

Heat transmission coefficient from hot water to the tube surface

\[ K_p = \frac{A_f}{L_f \cdot R_p} \]
\[ R_b = \frac{D}{\lambda_w \cdot Nu} \] (4)

\[ Nu = \frac{0.0395 \cdot Re^{0.75} \cdot Pr}{1 + (1.99 \cdot Re^{-0.125} \cdot (Pr - 1.0))} \] (5)

- Heat balance of hot water

\[ C_w \cdot \rho_w \cdot V_w \frac{\partial T}{\partial t} = \eta_f \cdot K_p \cdot (T_m - T_w) \cdot L_f + Q_s \] (6)

\[ Q_s = q_f \cdot C_w \cdot \rho_w \cdot (T_{ws} - T_w) \] (7)

\[- \frac{\partial T}{\partial t} = \eta_f \cdot K_p \cdot (T_m - T_w) = \frac{1}{R_m} \cdot (T_m - T_{m-1}) + \frac{1}{R_{m+1}} \cdot (T_m - T_{m+1}) \] (8)

where \( A_f \) is the internal area of the tube [m²], \( C_f \) is the thermal conductance from the fin surface [W/(m².K)], \( C_w \) is the specific heat of the water [J/(kg.K)], \( D \) is the diameter of the tube [m], \( K_p \) is the apparent turbulent heat transfer coefficient in the tube [W/(m².K)], \( L_f \) is the length of the tube [m], \( Nu \) is the Nusselt number [-], \( P \) is the circumferenceal length of the tube [m], \( Pr \) is the Prandtl number [-], \( Q_s \) is the amount of heat [W], \( R_b \) is the thermal resistance per unit length from the inner surface to the outer surface of the tube [m².K/W], \( R_m \) is the thermal resistance of the material [m².K/W], \( Re \) is the Reynolds number [-], \( T_m \) is the temperature in the floor [K], \( T_w \) is the temperature in the tube [K], \( V_w \) is the amount of water [m³], \( q_f \) is the flow rate of the hot water [m³/s], \( t \) is the thickness of the tube [m], \( w \) is the pitch of the tube [m], \( \eta_f \) is the fin efficiency[-], \( \lambda_f \) is the thermal conductivity of the tube [W/(m.K)], \( \lambda_w \) is the thermal conductivity of the water [W/(m.K)], and \( \rho_w \) is the specific weight [kg/m³].

**Figure 1.** Hydronic floor-heating system

**Convective heat and moisture transfer**

The convective heat transfer coefficients are recalculated for each time step on all surfaces of the exterior, interior, and cavities of the buildings using dimensionless equations. These dimensionless equations are either derived from the profile method for the boundary layer (based on the energy equation, the momentum equation, and the fluid friction) or defined from 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 the surface and the room for the interior convective heat-transfer coefficients. It is also possible to set constant heat-transfer coefficients for the whole day, or to modify the coefficients to consider the space conditioning time for all parts of the building. The convective moisture-transfer coefficients for all the surfaces of the exterior, interior, and cavities of buildings are calculated based on 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 by default. Interrelated radiation between both the surfaces of the building and the ground can also be calculated based on temperature calculations for the ground. In the interiors of buildings, the use of the long-wave absorption coefficient makes it possible to simulate a net absorption of radiant heat because of multiplex reflection among the interior surfaces (Gebhart, 1959). Mutual radiation between the surfaces of the cavities in the walls and the windows can also be calculated. The long-wave absorption coefficient is applied to the long-wave radiant heat emitted from the lights and appliances and the human bodies, assuming that such radiant heat is equally emitted from the ceiling and the floor.

CALCULATION ACCURACY
Test house and experimental conditions
Figure 2 illustrates the test house equipped with the hydronic floor-heating system. The test house was the actual-sized structure and built in an environmental test laboratory. The hydronic floor-heating system was constructed in room 1 (3.6 × 4.98 × 2.6 m) and covered 70% of the floor area. The experimental conditions of the floor heating included maintaining the air temperature of the room constant at 21 degrees C using the on–off control of the hot-water circulation. The initial temperature of the test house was approximately 7 degrees C, the same temperature as the environmental test laboratory. Hot water at a temperature of 80 degrees C was supplied for the first hour. Subsequently, the hot water is supplied at a temperature of 60 degrees C during the turn-on circulation time.

Table 1 shows the calculation conditions. The calculation interval is one minute, and the measured temperature of the next room, hall, crawl space, and hot-water supply in each experiment are used as the input conditions.

Comparison of calculated and measured results
Figures 3 and 4 show the temperature of the room air, the floor surface, and the return hot water of the hydronic floor-heating system. The measured air temperature is bulk temperature, calculated as a volume-weighted average of 150 points in the room. The measured floor temperature is the average value of five diagonal points on the floor surface. There is good agreement between the calculated values and the measured values. Figures 5 and 6 show the variation in heating load with time and the average
heating loads for each hour. The estimate has a smaller margin of error. THERB can predict the thermal environment of a room equipped with the hydronic floor-heating system with absolute accuracy.

**PREDICTION OF SENSORY INDEX**

The influence of a non-uniform thermal environment, such as that achieved through floor heating, on the comfort of the occupant is evaluated by using the sensory index “COMSET*,” which was derived from the heat balance of body parts in combination with THERB (Ozaki et al., 2011).

**Table 1. Calculation conditions**

| Heat loss coefficient [W/(m²·K)] | Ceiling | 1.6 |
| Floor area of room 1 | 12.96 m² (3.6 m × 3.6 m) |
| Floor heating area | 2.62 m × 3.12 m (ratio of 70% of floor area) |
| Diameter of tube | 0.0098 m |
| Pitch of tube | 0.075 m |
| Input data | Temperature |
| Flow rate of hot-water supply | Measured values per one minute (hall, room 2, crawl space, hot-water supply) |
| Control method of hydronic floor-heating system | Room air temperature is kept constant at 21 degrees C by the on-off control of the hot-water circulation (Manual operation) |

**Figure 2. Plan of the experimental model**

**Figure 3. Room temperature and floor surface temperature**

**Figure 4. Supply water temperature and return water temperature**

**Figure 5. Heating load**

**Figure 6. Total heating load per hour**

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COMSET*
“COMSET*” is a mathematical model for a sensory index (Tanabe et al., 2006), such as the standard new effective temperature “SET*.” “COMSET*” is derived from the detailed heat balance of human body parts, taking into consideration the blood circulation (arterial and venous flow) throughout the body, and involving the extremities. By dividing the whole body into 17 segments, each with skin and a core layer, the temperature distribution of the skin and blood at 59 points over the whole body can be predicted. COMSET* can subsequently calculate a generalized sensory index, under conditions such as those of a non-uniform thermal environment. The COMSET* calculations are conducted by setting up the boundary conditions of the surrounding air temperature and humidity, airflow velocity (convective heat flux), radiant heat flux, clothing amount, contact area on the floor for each body segment, and metabolic energy.
The original COMSET* does not take into account heat conduction in the area in contact with the floor. In the present study, the influence of contact thermal conductance on the sensation of warmth is considered by linking the heat balance of buildings and the human body.

EVALUATION OF THERMAL ENVIRONMENT BY COMSET*
The thermal environment and energy conservation of a single-family house, equipped with a space conditioning system or a hydronic floor-heating system, are evaluated based on COMSET*. The prediction is done by linking the simulation of both the building and the human body, by THERB and COM, respectively.
Figure 7 and Table 2 show the building model and Table 3 explains the calculation conditions. The hydronic floor-heating system was constructed in the living room, at a rate of 70% of the floor area. The standing and sitting position in the center of the living room are assumed as the physical posture to calculate COMSET*. The space conditioning system in the living room was not used when the hydronic floor-heating system was operated. The living room is controlled by COMSET* at a comfortable thermal environment temperature (about 21 degrees C of COMSET*).
Figures 8 and 9 show the time variation of air and floor temperature, SET*, and COMSET* of the living room from January 20 to 22. Although the COMSET* is relatively constant for all heating conditions, the air temperature of the room and SET* increase in the following order: space conditioning, floor heating in the standing position, and floor heating in the sitting position.

Sitting position, which is affected significantly by radiative heat and contact thermal conductance from the floor, can lower the air temperature when the floor is heated, if the sensory index of COMSET* is used as a control requirement in keeping with the reality of human behavior.

Figures 10 and 11 show the temporal variation of the heating load and the term heating load for a month (January) in the living room. In comparison with the space conditioning system, the heating loads of the hydronic floor-heating system are

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<th>Table 3. Calculation conditions</th>
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<tr>
<td><strong>Calculation date</strong></td>
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<td>Air conditioning space</td>
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<td>Other rooms</td>
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<td>Family structure</td>
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<td>Posture</td>
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<td>Floor heating area</td>
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<td>Set temperature</td>
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<td>Heating</td>
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<td>Control of floor heating</td>
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<th>Table 2. Outline of building model</th>
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<td><strong>Gross floor area [m²]</strong></td>
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<td>120.07</td>
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**Figure 8. Room air temperature and internal floor temperature**

**Figure 9. SET* and COMSET***

**Figure 10. Heating load**

**Figure 11. Seasonal heating load per month**
decreased, particularly in the sitting position. It is necessary to consider the radiative heat and the contact thermal conductance from the floor for each part of the human body in the floor-heating system, because the sensation of warmth from the heated floor is obviously different from that of general space conditioning. If the sensory index of COMSET* is used as a control condition for heating, depending on the physical posture, it is possible that the floor-heating system could dramatically decrease the heating load.

CONCLUSION
The simulation software “THERB,” incorporating complete features regarding heat, moisture, and airflow, has been developed to predict the hygrothermal environment and sensory index within whole buildings. The calculation precision of the software with regard to floor heating is verified by comparison with monitoring results. It was found that THERB could predict the thermal environment of a room equipped with a hydronic floor-heating system with absolute accuracy. Furthermore, sensitivity analyses of the heating system and the sensory index provide the following results. 1) Even if the values of COMSET* remain constant, the room air temperature rises when the heating system is changed in the following order: space conditioning, floor heating in a standing position, and floor heating in a sitting position, to cause a sense of warmth. 2) The floor-heating system has the ability to decrease the heating load dramatically, depending on the physical posture, if the radiative heat and the contact thermal conductance from the floor for each part of the human body are realistically considered as control requirements of heating.

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