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ANALYSIS OF TEMPERATURE AND HUMIDITY IN THE BEDROOM OF A JAPANESE DWELLING HOUSE IN WINTER

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Introduction

Accurate prediction of indoor temperature and humidity is important for the design of a healthy and comfortable living environment[1-5]. In this study, we conducted an analysis of the temperature and humidity of a bedroom based on simultaneous heat and moisture transfer theory, and the results were compared with those from field measurements. At the same time, the effect of the renovation (adding thermal insulation) for the target bedroom was quantitatively evaluated using the validated analytical model.

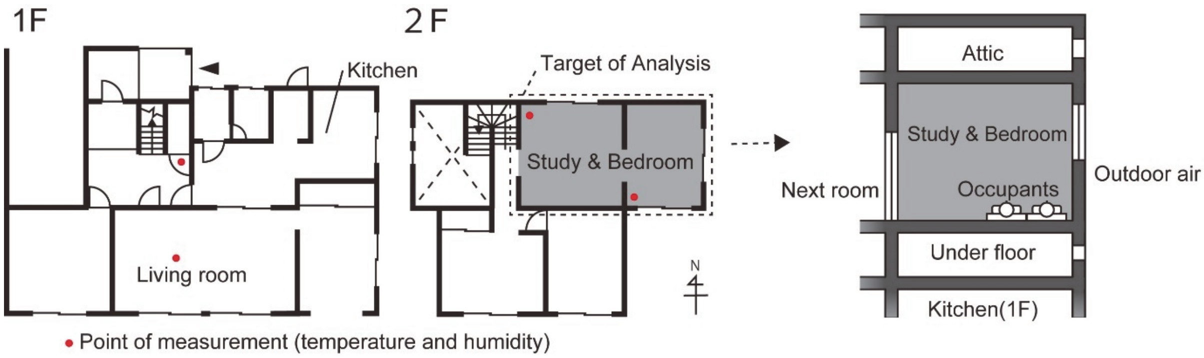

Fig.1 Plan of whole house (left) and vertical section of room targeted for analysis (right)

Methods

The target is a bedroom on the second floor of a two-storied dwelling house in Hokkaido, Japan that was built 34 years ago. In the analytical model, the bedroom and study were treated as a single room with dimensions of W6.2 m × D3.5 m × H2.4 m, giving a volume of 52.1 m^3. The points at which temperature and humidity were measured are shown on the plan of the whole house in Fig.1. The two inhabitants of the house used the bedroom only between 10 pm and 7 am without the use of heating or air-conditioning. Measurements were conducted between January 14 and March 15, 2014. Between February 3 and 13, the bedroom was renovated: insulation was added to the existing outer walls, floor, and ceiling of the bedroom, and the door leading to the staircase was replaced with a more airtight one. The components of wall of the target room before and after renovation are shown in Table 1.

Table.1 Components of walls of target room

Segment	Material		Thickness [mm]	Area [m^2]
Window	Glass		-	4.6
Outer walls	After renovation	Gypsum board	12	24.9
		Styrofoam	30	
	Before renovation	Gypsum board	12	
		Moisture barrier	-	
		Glass wool	120	
Partition		Gypsum board	12	24.9
		Moisture barrier	-	
		Glass wool	120	

Segment	Material		Thickness [mm]	Area [m^2]
Floor	After renovation	Wooden floor	6	21.7
		Veneer	12	
		Styrofoam	25	
	Before renovation	Plywood	12	
		Air layer	-	
		Gypsum board	12	
Ceiling	Before renovation	Gypsum board	12	21.7
	After renovation	Styrofoam	25	
		Glass wool	100	

Table.2 Values used in calculation

Heat generation rate [W/person]			70
Moisture generation rate [g/h/person]			20
Solar absorptivity of window [-]			0.4
Solar absorptivity of surface of outer wall [-]			0.8
Thermal resistance between living room and kitchen* [m^{2}K/W]			0.5
Ventilation rate [times/h] (Before/After renovation) Daytime 7:00–22:00 Nighttime 22:00–7:00	Next room	Daytime	0.2/0.2
		Night	0.05/0.01
	Outside air	Daytime	0.05/0.01
		Night	0.05/0.01

*The kitchen immediately beneath the bedroom was not measured. The boundary condition of temperature for the first floor was given at the living room, and an apparent thermal resistance between the living room and the kitchen was determined.

Table.3 Heat and moisture balance equation of the air in the target room as a concentrated mass

Non-steady-state heat balance equation

$$\rho_a c_a V \frac{dX_i}{dt} = \sum_{k=1}^{5}\{\alpha_i S_k(\theta_{s,k}-\theta_i)\} + \rho_a c_a Q_o(\theta_o-\theta_i) + \rho_a c_a Q_n(\theta_n-\theta_i) + P + \eta_1 J S_1 \quad (1)$$

Non-steady-state moisture balance equation

$$\rho_a V \frac{dX_i}{dt} = K'_2 S_2(X_o - X_i) + K'_3 S_3(X_n - X_i) + \alpha'_i S_5(X_{s,5} - X_i) + \alpha'_i S_{4bed}(X_{s,4bed} - X_i) + \rho_a Q_o(X_o - X_i) + \rho_a Q_n(X_n - X_i) + G + \alpha'_i\{X_{sat}(\theta_s) - X_i\}S_1 \quad (2)$$

Symbols

θ: Temperature[℃], t: Time[s], ρ: Density[kg/m^3], c: Specific heat[J/kg/K], V: Volume of room[m^3], S: Surface area[m^2], α: Overall heat transfer coefficient[W/m^2/K], Q: Ventilation rate[m^3/s], P: Heat production rate[W], η: Solar heat gain coefficient[-], J: Solar radiation at window[W/m^2], X: Humidity ratio[g/kg'], K': Moisture transmission coefficient [kg/m^2/s/(kg/kg')], α': Moisture transfer coefficient[kg/m^2/s/(kg/kg')]

Subscripts

a: Air, i: Indoor, o: Outdoor, n: Nextroom, s: Surface, sat: Saturated
1: Window, 2: Outer walls, 3: Partition, 4: Floor, 5: Ceiling

Heat and moisture balance equations for the air in the target room, treated as a concentrated mass solved numerically. The equations considered ventilation with the staircase and outdoor air. Non-steady-state heat conduction for the solid (walls, floor, and ceiling) were solved coupled with equations (1), (2). For windows, transmission of solar radiation was considered as well as heat transmission. The temperatures of the outdoor air, staircase, and living room were the measured values. Solar radiation was taken from the local meteorological data, and incident not only on the window but also on the outer wall surface was taken into account, based on the aspect of the surface. The air temperature of the space under the floor of the bedroom was solved with a heat balance equation similar to that used for the bedroom itself. The upper surface of the ceiling of the bedroom was treated as being thermally insulated. For moisture, measured values of absolute humidity of the outdoor air and the staircase air were used in the calculation of ventilation, and the surfaces surrounding the bedroom were treated as being sealed, except for the gypsum board ceiling, the moisture capacitance of which was considered using simultaneous heat and moisture transfer equations for hygroscopic range. Heat and moisture generation by the two inhabitants was applied in the heat and moisture balance equation only in the period from 10 pm to 7 am (during sleep). The door leading to the staircase, was assumed to be open except at nighttime, and contributed to the variation in the ventilation rate. The numerical values used in the analysis are summarized in Table 2. Table 3 gives the heat and moisture balance equations respectively.

Results

The air temperature in the bedroom (Figure 2) peaked at 2 pm and then fell, in the daily variation mainly due to solar transmission. This trend was reproduced in the calculated results, both before and after renovation. The absolute humidity in the bedroom (Figure 2) peaked twice daily, at 2 am and 3 pm. The former peak was due to moisture generated by the human inhabitants, and the latter to desorption from the ceiling caused by the rise in temperature. The latter peak was higher, and again the trend was reproduced in the calculated values. Overall the analytical model was validated.

Using this analytical model, the effect of the renovation was then evaluated under the same climatic conditions (Figure 3). After renovation, the air temperature in the bedroom increased by 0.9 °C in the daytime and 1.2 °C at night. This was due to the reduced heat loss from the outer wall and the increase in the storage of solar heat in the surface materials. The absolute humidity was higher after renovation by 0.6 g/kg', because of the increased air-tightness of the bedroom.

Conclusions

It was shown that the trends in temperature and humidity measured in the bedroom of a dwelling house in winter were reproduced by an analytical model based on heat and moisture transfer theory. The model took account of the boundary conditions for the adjacent space, and considered the real wall components and the effect of the occupancy patterns on the ventilation rates and the generation of heat and moisture. In addition, the validated model was then used to quantitatively outdoor temperature and humidity and solar radiation.

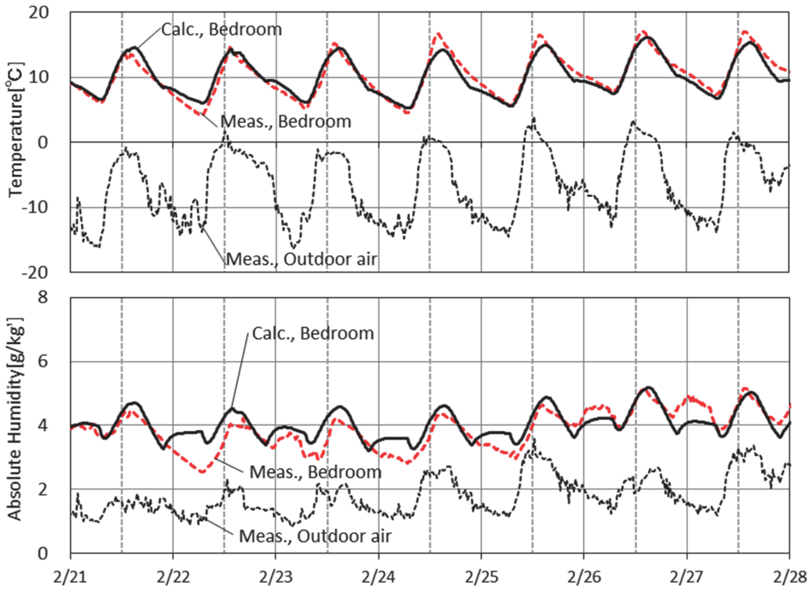

Fig.2 Measured and calculated temperature and humidity of air in the bedroom and outdoor

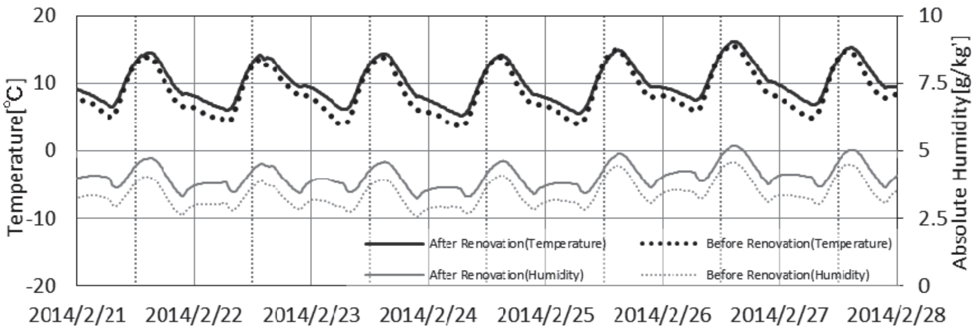

Fig.3 Temperature and humidity of air in the bedroom before and after renovation calculated under the same climatic conditions

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