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Sensitivity Numerical Analysis of Human Body Exergy Balance under an Unsteady-State Thermal Environment

—Behavioral Adaptation Induced by Undesirable Cold Storage by Building Envelope in Winter

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Abstract

We analyzed the relationships between the human body exergy balance and behavioral adaptations induced by undesirable cold storage by a building envelope under an unsteady-state thermal environment in winter. The complex interaction of the warm exergy production by shivering, lifting of the shell ratio, and reduction of the blood flow rate was considered to constitute the physiological adaptation necessary for maintaining the constant core temperature, which was an important aspect in living organisms. In the case of intermittent use room, it was suggested that better thermal comfort and desirable behavioral adaptations, which decreased the consumption of fossil fuels, could be achieved if interior wooden cladding was used in constructions with building envelopes that had a comparatively large heat capacity, or in cases of wooden constructions in which the building envelope heat capacity was comparatively small.

Keywords

Passive System, Exergy, Human Body, Adaptive Comfort, Unsteady State

1. Introduction

It is as important to strive for comfort and energy saving with regard to a resident's thermal adaptation (software) as it is to optimize the environmental system of a building (hardware), because energy use by building equip-

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ment is influenced considerably by the turning on/off the air-conditioning/heating units and the clothing of the residents [1].

The adaptive comfort temperature in an adaptive model is predicted on the basis of the outside air temperature [2] [3]. Since, exergy is calculated by considering the outside air temperature as the environmental temperature [1], it can be surmised that there is a certain relationship between adaptation and exergy.

Behavioral adaptation (the cycle from sensation to behavior [4]) in an unsteady-state thermal environment is influenced both by long-term and short-termvariations. Therefore, it is considered that thermal adaptation reflects the unsteady state. The consideration of the pattern of the unsteady-state human body exergy balance can help in the design of environmental systems of buildings, which is to provide both thermal comfort and desirable adaptations that decrease consumption of fossil fuels. It can also clarify, to some extent, the mechanisms of physiological adaptation.

Therefore, in this research, we performed a sensitivity analysis that focused on the relationships between thermal adaptations and the pattern of the human body exergy balance. Using numerical analysis, we investigated the human body exergy balance under an unsteady-state thermal environment surrounding the human body in the course of individuals moving indoors after having been outside for a while in winter.

2. Application of Exergy to the Built Environmental System

In terms of the energy (*i.e.*, electricity and heat) and matter (*i.e.*, air and water) flowing in and out of an architectural environmental space, it is inevitable that the natural phenomenon of diffusion occurs. Therefore, although the "quantities" of these energies and matters are conserved, their "qualities" are consumed. Thus, when evaluating the function of an architectural environmental system, we consider it important to use the concept of exergy, because this can evaluate explicitly the "diffusing capacity" of energy and matter [5].

According to natural rhythms, such as the annual and daily fluctuations of external air temperature and humidity, exergy is repeatedly generated and quenched. The concept of exergy can quantify the ability of energy and matter to disperse within an outdoor environment and it can clarify the relationship between "resources" and the "environment". In addition, exergy can be used to quantify the consumption of energy and matter penetrating a "system" while diffusing, according to the spatial variation of temperature and relative humidity with time. Thus, it can be claimed that the merit of an evaluation of exergy is the evaluation of process for the effective use of resources.

3. Application of Exergy to the Human Body System

Oshida, a pioneer of exergy research, has claimed that thermal comfort might relate more to the speed of energy flowing in and out of the human body than to the temperature of the surrounding environment. Furthermore, there could be a strong relationship between thermal comfort and the speed of exergy flowing in and out of the human body rather than the speed of the energy flow [6]. Hence, to complement the conventional index for the evaluation of thermal comfort based on the human body "energy" balance, we focus on a new evaluation index based on the human body "exergy" balance. Because the diffusion of energy and matter, *i.e.*, natural deterioration, occurs randomly in an architectural environmental space and in the human body, it must be expected that thermal sensations such as "hot" and "cold" correspond to the human body exergy balance.

3.1. Steady-State Valuation Using Steady-State Models

Saito and Shukuya were the first to find a relationship between thermal comfort and the exergy balance. They found that the smallest exergy-consumption rate appears at approximately 23˚C, which corresponds roughly to the neutral condition [7]. They also found that greater exergy consumption burdens the human body [8]. It has also become clear that there is an optimal combination of indoor thermal environmental elements, such as air temperature and mean radiant temperature, that provide the lowest possible human body exergy consumption rate in both winter [9] and summer [10]. A series of research projects on the relationship between the human body exergy balance and thermal comfort revealed that the minimal exergy consumption provides thermal comfort [11]. Asada developed software to calculate the human body exergy balance [12]. Simone *et al.* analyzed the relationship between human body exergy consumption rates and subjectively assessed thermal sensations [13]. Schweiker compared the predicted mean vote approach, adaptive comfort model, and a calculation of the human body exergy consumption rate [14]. Ala-Juuselaand Shukuya used the human body exergy analysis to evaluate the case of office workers in typical and extreme weather conditions in Finland [15]. Dovjak *et al.* analyzed thermal exergy flows through the building envelope jointly with the human body exergy balance in four typical climates (temperate, cold, hot/dry, and hot/humid) [16].

3.2. Unsteady-State Valuation Using Steady-State Models

Saito and Shukuya were the first to conduct a numerical analysis to investigate how the transition between thermal environments, *i.e.*, from outdoors into indoors, affects the human body exergy balance [17]. Tokunaga and others have performed unsteady-state human-body analyses using a steady state model for cases in the summer [18] and winter [19]. There were differences in body-core and skin-layer temperatures, which cannot be disregarded, between a subject's actual value and the computed value when a human moves to the indoors from the outdoors.

3.3. Unsteady-State Valuation Using Unsteady-State Models

The original calculation model, *i.e.*, the famous 2-node model, was not really an unsteady-state model because the one-hour periods for the calculation of the body-core and skin-layer temperature were assumed in between the time steps representing the actual unsteady-state condition [20]-[22]. Therefore, Shukuya reviewed the entire calculation procedure for the body-core and skin-layer temperature and modified the calculation method to perform under unsteady-state conditions [23]. Using the modified method, Schweiker *et al.* explored the relationship between the human-body exergy consumption rate and the subjective assessment of the thermal environment represented by thermal sensations and extended the investigation to thermal acceptability votes [24].

4. Positioning of the Current Paper

The originality of this paper and its differences from previous research are as follows. First, we preformed the unsteady-state sensitivity analysis using an unsteady-state model. Few studies have used this approach so that further analysis is necessary. Second, we set a unique case-study situation, *i.e.*, "undesirable cold storage by the building envelope in winter", described in Section 5.1. Third, we set a "step transition" in the numerical analysis in contrast to the "ramp transition" used in previous research [24]. Fourth, we reflected the "behavioral adaptation" using a calculation condition described in Section 5.4. Fifth, we tried to clarify the mechanisms of "physiological adaptation" from the exergetic viewpoint, *i.e.*, we investigated each term of the human body exergy balance equation thoroughly, as described in Section 6.

5. Numerical Analysis

5.1. Situation of Case Study

Spaces such as school lecture rooms and office conference rooms tend to be used for short periods on an intermittent basis, and the periods when they may remain unheated (e.g., during holidays or overnight) can be comparatively long. Furthermore, "undesirable cold storage in winter" can arise because a building envelope can be cooled by external air brought in via a ventilation system, even when thermal insulation of the building envelope is installed, particularly in the case of a building envelope that has a comparatively large heat capacity, e.g., concrete.

The feeling of "cold", which cool radiation (shortage of warm radiant exergy) from the interior surfaces of a building envelope can cause when a person walks into a room, could induce the behavioral adaptation in the occupants of presetting the air-conditioner/heating temperature to be relatively high. It is thought that the period during which the stored coldness within a building envelope becomes warm, after the heating is started, requires a large amount of exergy and that during this period the thermal comfort is comparatively low.

5.2. Human Body System and Exergy Balance Equation

The exergy balance equation is derived from energy and entropy together with the environmental temperature. Exergy balance equation for the system can be set up in a general form as follows:

$$[\text{Exergy input}]-[\text{Exergy consumed}]=[\text{Exergy stored}]+[\text{Exergy output}] \quad (1)$$

Figure 1 shows the human body system. The human body exergy balance equation is also derived by combining the following three elements: a human body energy balance equation, a human body entropy balance equation, and the environmental temperature (outdoor air temperature). The human body exergy balance equation is expressed as follows [1]:

$$\begin{aligned}
&[\text{Warm exergy generated by metabolism}]\\
&+[\text{Warm/Cool and wet/dry exergies of inhaled humid air}]\\
&+[\text{Warm and wet exergies of liquid water generated in the core by metabolism}]\\
&+[\text{Warm/Cool and wet/dry exergies of the sum of the liquid water generated in the shell}\\
&\quad \text{by metabolism and dry air to let the liquid water disperse}]\\
&+[\text{Warm/Cool radiant exergy absorbed by the entire surface of the skin and clothing}]\\
&-[\text{Exergy consumption}]\\
&=[\text{Warm exergy stored in the core and shell}]\\
&+[\text{Warm and wet exergies of exhaled humid air}]\\
&+[\text{Warm/cool exergy of water vapor originating from sweat and the wet/dry exergy of}\\
&\quad \text{humid air containing evaporated water from sweat}]\\
&+[\text{Warm/cool radiant exergy discharged from the entire surface of the skin and clothing}]\\
&+[\text{Warm/cool exergy transferred by convection from the entire surface of the skin}\\
&\quad \text{and clothing into the surrounding air}]\\
&+[\text{External work}].
\end{aligned} \quad (2)$$

5.3. Calculation Method

The temperatures of the core, shell, and clothing under "steady-state" conditions are determined by the two-node model (human body energy balance model), which was originally developed by Gagge *et al.* [20]-[22]. The body-core and skin-layer temperatures under "unsteady-state" conditions can be calculated using a modified method based on the two-node model. This method enables us to conduct unsteady-state human-body exergy analyses [23]. In the modified method, the two-node thermal "energy" balance equations for the calculation of the human-body core, skin-layer, and clothing surface temperatures are numerically solved using the explicit finite-difference method (forward differencing). We set the calculation interval to 1 minute to stabilize the calculation in this study since such calculations become unstable when the time interval is equal to or greater than 2 minutes. The detailed procedure is described in [23] [24].

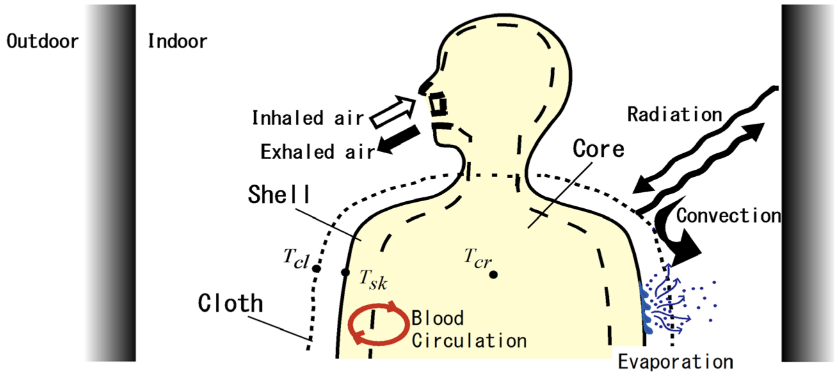

Figure 1. Human body system.

5.4. Fixed Conditions

The fixed conditions of the experiment are shown in **Table 1**. The calculation considered a period of 240 minutes, which assumed a transfer (e.g., commute to school or work) of 0 - 60 minutes in the outdoor environment and a period of 60 - 240 minutes within the indoor space (room). The metabolic rate and the amount of clothing were set to reflect the outdoor transit period and the period indoors.

5.5. Comparative Conditions

Four Cases are shown in **Table 2** for comparison. In Case 1 and Case 2, both the room air temperature and the mean radiant temperature (MRT) were 10˚C. These values represent the ambient temperatures when heating was inactive. It was assumed that the occupants removed a coat (outside clothing) after entering the room space in Case 1, while they kept wearing the coat in Case 2. Both Case 3 and Case 4 considered a room air temperature of 20˚C and an MRT of 15˚C and 20˚C, respectively. The temperatures in both cases represent the activation of convective heating immediately after the occupants entered a room that has not been in use for a long period of time. Case 3 represents a building envelope that has a comparatively large heat capacity, whereas Case 4 represents a room where wood paneling was installed on the interior surfaces of a building envelope with a comparatively large heat capacity (such as concrete), or a wooden construction where the building envelope has a comparatively small heat capacity.

6. Results and Discussion

6.1. Body Temperature

The temperatures of the core, shell, and clothing are shown in **Figures 2-4**, respectively. During the time of the outdoor transfer, all four cases changed at the same rate in response to the external environment. In the indoor period in **Figure 2**, the core temperature in Case 1, Case 2, and Case 3 dropped, whereas that in Case 4 remained almost stable. In the indoor period in **Figure 3**, the shell temperature in Case 1, Case 2, and Case 3 dropped, whereas that in Case 4 rose gradually. It is considered in Case 4 that the shell temperature that dropped during

Table 1. Fixed conditions.

	Element	Outdoors	Indoors
Environment	Air temperature	5˚C	Refer to **Table 2**
	MRT	5˚C	Refer to **Table 2**
	Relative humidity	40%	40%
	Air velocity	0.1 m/s	0.1 m/s
Human Body	Metabolic rate	1.5 met	1.0 met
	Clothing resistance	2 clo	Refer to **Table 2**
Other	Work rate accomplished	0 W/m^2	0 W/m^2
	Ratio of body's radiating area to total surface area	0.7	0.7
	Longwave radiation emissivity of clothing surface (= absorptivity)	0.95	0.95

Table 2. Comparative conditions.

	Case 1	Case 2	Case 3	Case 4
Air Temperature	10˚C	10˚C	20˚C	20˚C
MRT	10˚C	10˚C	15˚C	20˚C
Clothing resistanc	0.9 clo	2 clo	0.9 clo	0.9 clo

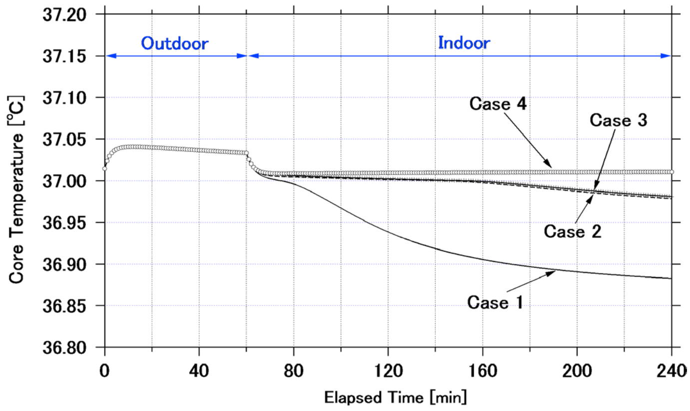

Figure 2. Core temperature [˚C].

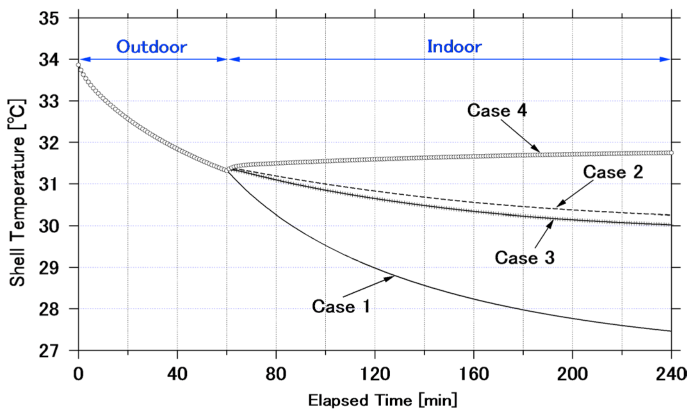

Figure 3. Shell temperature [˚C].

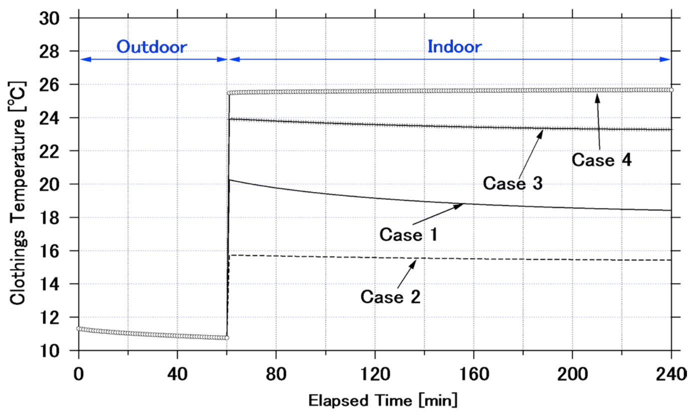

Figure 4. Clothings temperature [˚C].

the outdoor transfer period started to recover during the indoor period. In the indoor period in **Figure 4**, the clothing temperature in Case 3, Case 1, and Case 2 dropped slightly, whereas that in Case 4 rose slightly.

6.2. Physiological Adaptation

The shell ratio and blood flow rate are shown in **Figure 5** and **Figure 6**, respectively. During the indoor period in Case 1, Case 2, and Case 3, the shell ratio increased gently (**Figure 5**) and the blood flow rate decreased (**Figure 6**). Conversely, in Case 4, the shell ratio became smaller and the blood flow rate increased. It is thought that the physiological adaptation that increased the shell ratio and decreased the blood flow rate in Case 1, Case

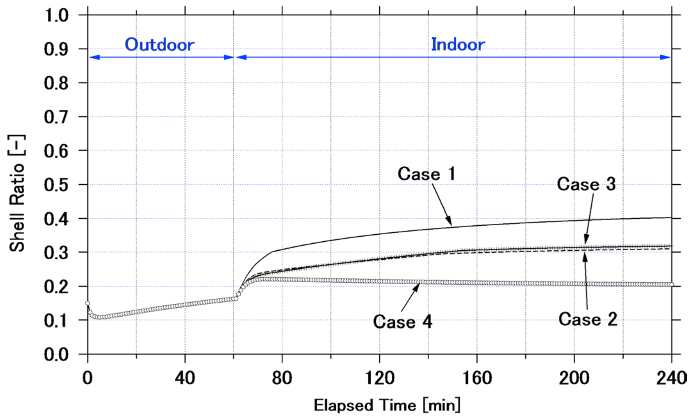

Figure 5. Shell ratio [-].

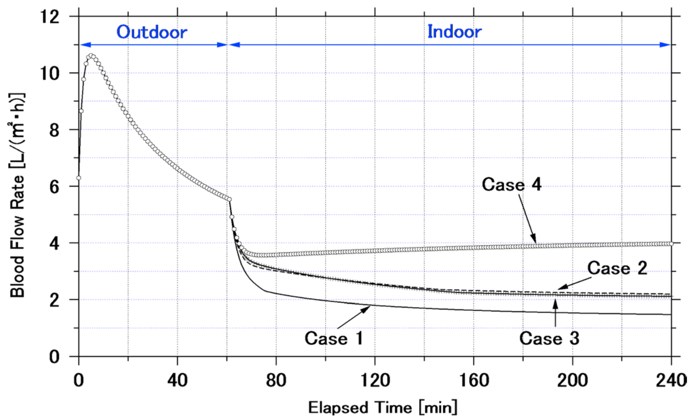

Figure 6. Blood flow rate [L/(m^2 h)].

2, and Case 3, prevented superfluous heat (warm exergy) release. However, in Case 4, it is thought that a moderate rate of heat release (discarding of entropy) occurred.

6.3. Exergy Balance

6.3.1. Input

The warm exergy production rate by the metabolism is shown in **Figure 7**. The fall from 8 to 6 W/m^2 immediately after entering the room is influenced by the calculation condition, whereby the metabolic rate alters instantaneously (outdoor 1.5 met → indoor 1.0 met). In Case 1, the exergy production rate by the metabolism increased rapidly after about 80 minutes. This was because shivering started to prevent the core temperature from falling rapidly and thus, the warm exergy production increased. A warm radiant exergy input rate is shown in **Figure 8**, which during the period in the room, decreased in the order Case 4 > Case 3 > Case 2 = Case 1, according to calculation conditions (**Table 2**, MRT).

6.3.2. Consumed

The exergy consumption rate of a human body is shown in **Figure 9**. The exergy consumed is a part of exergy inputted to the human body (**Figure 7** and **Figure 8**). During the time in the room, the decreasing order of exergy consumption was Case 1 > Case 2 > Case 3 > Case 4. It is confirmed that behavioral adaptations such as activating the air-conditioning/heating switch (Case 3 and Case 4) and wearing clothes (Case 2) decrease the rate of exergy consumption within the human body. The comparatively small value of Case 4 suggests that thermal comfort and desirable behavioral adaptation, which decreases the consumption of fossil fuels, could be achieved by installing wooden cladding in rooms that has not been in use for a long period of time, the building envelope has a comparatively large heat capacity, or in wooden structures where the building envelope has a comparatively

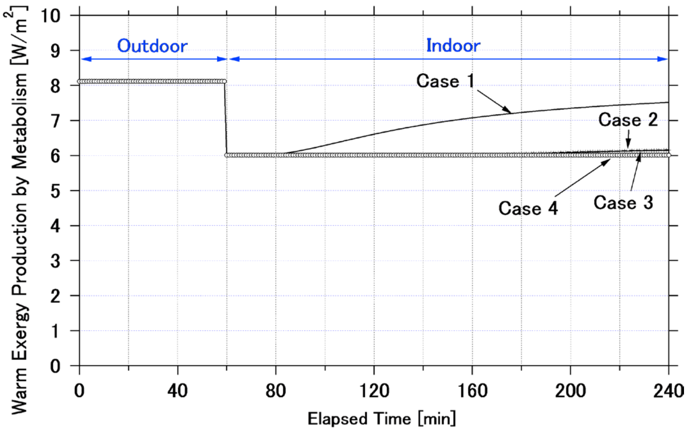

Figure 7. Warm exergy production rate by metabolism [W/m^2].

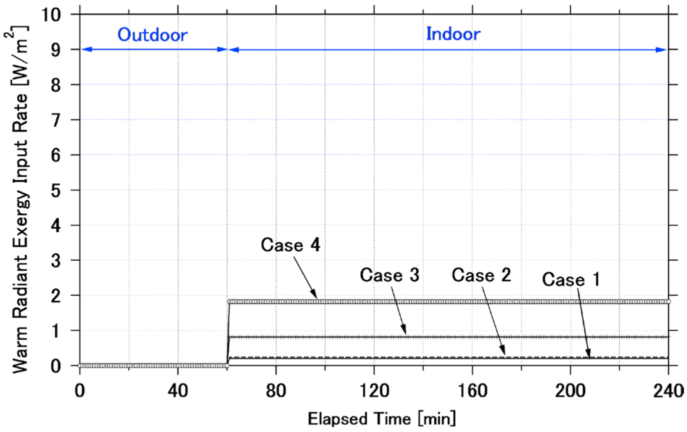

Figure 8. Warm radiant exergy input rate [W/m^2].

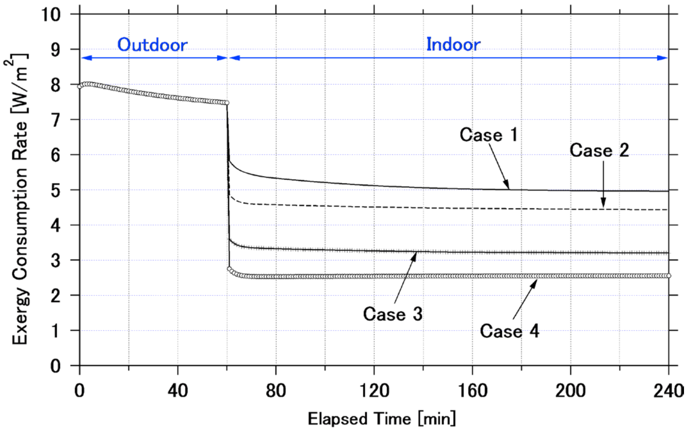

Figure 9. Human body exergy consumption rate [W/m^2].

small heat capacity. The human body exergy consumption rate (**Figure 9**) is the sum of the exergy consumption between the core and the shell, and between the shell and the clothing. Hence, a greater temperature difference across the core, shell, and clothing means greater exergy consumption within the human body. Even though the shell temperature in Case 2 was higher than that in Case 3 (**Figure 3**), the rate of exergy consumption by the human body in Case 2 was larger (**Figure 9**). The reason for this could be that the clothing temperature in Case 2 was lower than that in Case 3 (**Figure 4**).

6.3.3. Stored

The rate of accumulation of warm exergy in the core is shown in **Figure 10**. This value was negative (*i.e.*, decreasing) in all cases immediately after entering the room. It is considered that the change in the rate of warm exergy accumulation from increasing to decreasing is due to insufficient production of warm exergy. This is something that is influenced by the change in the metabolic rate, when moving indoors from outside (outdoor 1.5 met → indoor 1.0 met), in the calculation condition.

The warm exergy accumulation rate in the shell is shown in **Figure 11**. The rate increased in all cases immediately after entering the room. It is thought that the clothing temperature also rose because the ambient temperature of the room was higher than that in the outdoor temperature; hence, the rate of warm exergy flow from the shell to the clothing fell.

The rate of exergy accumulation in the core and shell recovered toward zero as the duration of the period in the room increased. It is thought that the complex interaction of the warm exergy production by shivering (**Figure 7**), lifting of the shell ratio (**Figure 5**), and reduction of the blood flow rate (**Figure 6**) constitutes the physiological adaptation necessary for maintaining the constant core temperature, which is an important aspect in living organisms.

6.3.4. Output

The rate of warm radiant exergy output is shown in **Figure 12**. The decreasing order of Case 4 > Case 3 > Case 1 > Case 2 corresponds to the order of clothing temperature (**Figure 4**).

The rate of warm convective exergy output is shown in **Figure 13**. Unlike **Figure 12**, the decreasing order is Case 1 > Case 4 > Case 2 > Case 1, which corresponds to the decreasing order of the temperature difference between the clothing (**Figure 4**) and indoor air (**Table 2**).

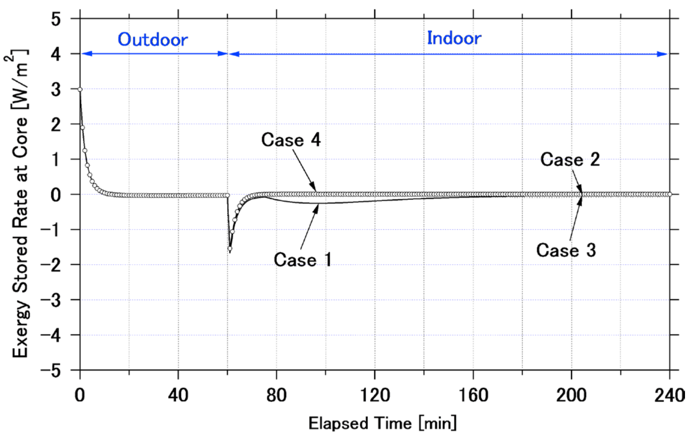

Figure 10. Warm exergy accumulation rate in the core [W/m^2].

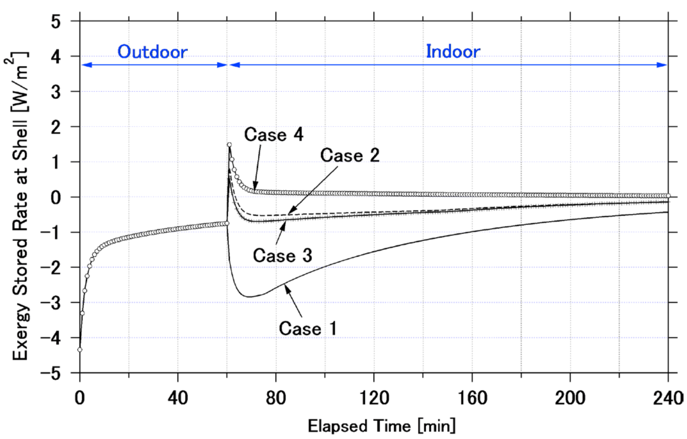

Figure 11. Warm exergy accumulation rate in the shell [W/m^2].

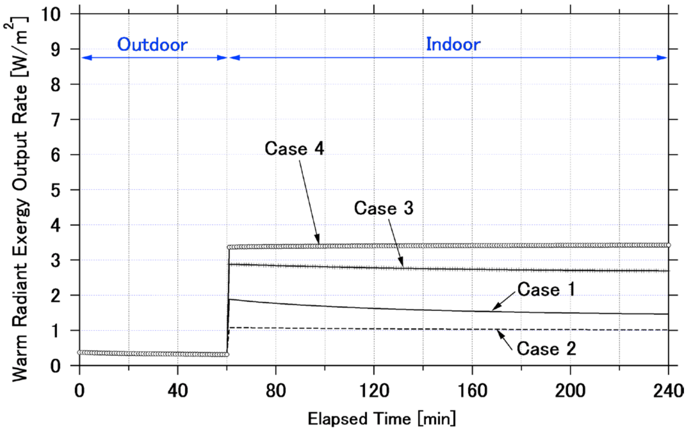

Figure 12. Warm radiant exergy output rate [W/m^2].

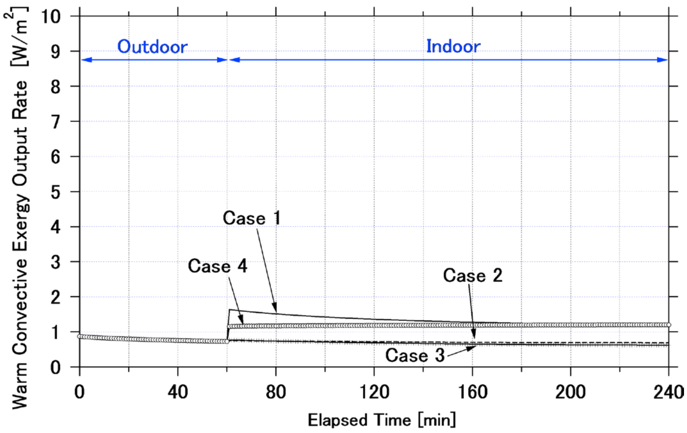

Figure 13. Warm convective exergy output rate [W/m^2].

7. Conclusions

We performed an unsteady-state sensitivity analysis by using the unsteady-state two-node model, focusing on the relationships between behavioral adaptations and the pattern of the human body exergy balance. Using numerical analysis, we investigated the variation of thermal environment surrounding the human body when individuals moved indoors after having been outside in winter.

1) This study confirmed that behavioral adaptations such as wearing clothing and activating an air-conditioning/heating unit could cause the rate of exergy consumption within a human body to decrease.

2) The mechanisms of "physiological adaptation" were clarified from the exergetic viewpoint to some extent. It was thought that the complex interaction of the warm exergy production by shivering, lifting of the shell ratio, and reduction of the blood flow rate constituted the physiological adaptation necessary for maintaining the constant core temperature, which was an important aspect in living organisms.

3) In the case of intermittent use room, it was suggested that greater thermal comfort and desirable behavioral adaptations, which decreased the consumption of fossil fuels, could be achieved for rooms used infrequently if interior wooden cladding was used in constructions with building envelopes that had a comparatively large heat capacity, or in cases of wooden constructions in which the building envelope heat capacity was comparatively small.

8. Future Work

The question of whether the human body exergy balance could be used to indicate the thermal comfort provided by passive strategies should be investigated in future work. If this could be developed as an adequate indicator, passive design might become more accepted in many buildings. To facilitate such research, future studies should consider the use of meteorological data, obtained at 1-minute intervals, for performing quantitative investigations of the exergy resulting from adaptations (physiological and behavioral) that may arise from daily (day and night) or seasonal (spring, summer, autumn, and winter) rhythms.

Acknowledgements

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References

[1] Shukuya, M. (2012) Exergy-Theory and Applications in the Built Environment. Springer, London, 69-79, 107-113, 305-335.

[2] Nicol, F., Humphreys, M. and Roaf, S. (2012) Adaptive Thermal Comfort: Principles and Practice. Routledge, Oxon and New York, 23-43.

[3] Humphreys, M., Nicol, F. and Roaf, S. (2016) Adaptive Thermal Comfort: Foundations and Analysis. Routledge, Oxon UK and New York, 296-318.

[4] Shukuya, M. (2015) An Overview of the Cyclic Process from Sensation to Adaptive Behavior—Interaction between Body Proper, Brain and Built Environment. *Proceedings of AIJ Annual Meeting*, Kanagawa, September 2015, 467-470.

[5] Ala-Juusela, M. (2003) Heating and Cooling with Focus on Increased Energy Efficiency and Improved Comfort—Guidebook to IEA ECBCS Annex 37 Low Exergy Systems for Heating and Cooling of Buildings. VTT Technical Research Centre of Finland.

[6] Oshida, I. (1981) Solar Energy, NHK Books, Nippon Houso Kyoukai (Japan Broadcasting Association). (In Japanese)

[7] Saito, M. and Shukuya, M. (2001) The Human Body Consumes Exergy for Thermal Comfort. International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems (ECBCS)-Annex 37, Low-Ex News No.2, 5-6.

[8] Saito, M. and Shukuya, M. (2001) Study on the Sensation of Tiredness Due to Cyclic Exposing to Air-Conditioned Rooms and Outdoors (Part 3. Analysis on the Exergy Consumption within a Human Body). *Proceedings of AIJ Annual Meeting*, Tokyo, September 2001, 445-446. (In Japanese)

[9] Isawa, K., Komizo, T. and Shukuya, M. (2002) Human-Body Exergy Consumption and Thermal Comfort. International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems(ECBCS)-Annex 37, Low-Ex News No.5, 5-6.

[10] Shukuya, M. (2015) Indoor-Environmental Requirement for the Optimization of Human-Body Exergy Balance under Hot/Humid Summer Climate. *Proceedings of the PLEA* 2015, Bologna, 9-11 September 2015, No. 0280.

[11] Shukuya, M., Saito, M., Isawa, K., Iwamatsu, T. and Asada, H. (2010) Low Exergy Systems for High-Performance Buildings and Communities: Human-Body Exergy Balance and Thermal Comfort. Working Report of IEA-ECBCS-Annex 49.

[12] Iwamatsu, T. and Asada, H. (2009) A Calculation Tool for Human Body Exergy Balance. The International Energy Agency, Energy Conservation in Buildings and Community Systems Annex 49 Newsletter, No. 6, 4-5.

[13] Simone, A., Kolarik, J., Iwamatsu, T., Asada, H., Dovjak, M., Schellen, L., Shukuya, M. and Olesen, B.W. (2011) A Relation between Calculated Human Body Exergy Consumption Rate and Subjectively Assessed Thermal Sensation. *Energy and Buildings*, **43**, 1-9. http://dx.doi.org/10.1016/j.enbuild.2010.08.007

[14] Schweiker, M. and Shukuya, M. (2012) Adaptive Comfort from the Viewpoint of Human Body Exergy Consumption. *Building and Environment*, **51**, 351-360. http://dx.doi.org/10.1016/j.buildenv.2011.11.012

[15] Ala-Juusela, M. and Shukuya, M. (2014) Human Body Exergy Consumption and Thermal Comfort of an Office Worker in Typical and Extreme Weather Conditions in Finland. *Energy and Buildings*, **76**, 249-257. http://dx.doi.org/10.1016/j.enbuild.2014.02.067

[16] Dovjak, M., Shukuya, M. and Krainer, A. (2015) Connective Thinking on Building Envelope—Human Body Exergy Analysis. *International Journal of Heat and Mass Transfer*, **90**, 1015-1025. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.07.021

[17] Saito, M. and Shukuya, M. (2001) Exergy Balance of a Human Body Caused by Changes in Thermal Environment. Architectural Institute of Japan, Hokkaido Affiliate, 163-1666. (In Japanese)

[18] Tokunaga, K. and Shukuya, M. (2011) Human Body Exergy Balance Calculation under Un-Steady State Conditions. *Building and Environment*, **46**, 2220-2229. http://dx.doi.org/10.1016/j.buildenv.2011.04.036

[19] Shukuya, M., Tokunaga, K., Onoma, M. and Itoh, Y. (2012) Calculation of Human-Body Exergy Balance for Investigating Thermal Comfort under Transient Conditions. *Proceedings of 7th Windsor Conference*, Windsor, 12-15 April

2012.

[20] Gagge, A.P., Nishi, Y. and Gonzalez, R.R. (1973) Standard Effective Temperature—A Single Temperature Index of Temperature Sensation and Thermal Discomfort. *Proceedings of the CIB Commission W*45 *Symposium*, London, 1972, 229-250.

[21] Gagge, A.P., Stolwijk, J. and Nishi, Y. (1971) An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatory Response. *ASHRAE Transactions*, **77**, 247-262.

[22] Gagge, A.P., Fobelets, A.P. and Berglund, L.G. (1986) A Standard Predictive Index of Human Response to the Thermal Environment. *ASHRAE Transactions*, **92**, 709-731.

[23] Shukuya, M. (2015) Calculation of Human Body-Core and Skin-Layer Temperatures under Unsteady-State Conditions—For Unsteady-State Human Body Exergy Analysis. Internal Report of Exergy-Research Group, Technical Report, KIT/TCU, July 2015. http://www.researchgate.net/publication/284486168

[24] Schweiker, M., Kolarik, J., Dovjak, M. and Shukuya, M. (2016) Unsteady-State Human-Body Exergy Consumption Rate and Its Relation to Subjective Assessment of Unsteady-State Thermal Environments. *Energy and Buildings*, **116**, 164-180. http://dx.doi.org/10.1016/j.enbuild.2016.01.002