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Calculation of Human-body Exergy Balance for Investigating Thermal Comfort under Transient Conditions

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Abstract
Application of the concept of exergy to human-body thermo-physical phenomena has revealed so far the following: mean radiant temperature, which is a little higher than air temperature, provides the human body with the lowest possible exergy consumption rate for winter conditions; and a combination of mean radiant temperature, which is a little lower than air temperature, and moderate air velocity to be given by natural ventilation provides the human body with the lowest possible exergy consumption rate for summer conditions. Supposing that it will become important to have an exergetic understanding on the adaptive behaviour of occupants in the built environment, we have tried a couple of unsteady-state calculation of human-body exergy balance for summer and winter conditions. As the results, we confirmed that it is essential to take a variety of passive technology prior to that of active technology for realizing low-exergy space heating and cooling systems.

Keywords: Unsteady-state thermal phenomena, exergy consumption, environmental temperature, adaptive thermal comfort, human behaviour

1 Introduction

In order to develop low-exergy systems for controlling the built environment, in which occupants can reside with sufficient health and thermal comfort (IEA/ECBCS/Annex49, 2010), it is important to have a better understanding on the adaptability of human-body thermoregulatory system to thermal-environment variation. All of we humans live in a variety of thermal environment such as a case of walking into a room from outdoors with harsh weather or vice versa and a series of changes throughout one season or throughout a longer period from one season to the following season. Against these thermal environmental variations, the human thermoregulatory system works in order to make the body-core temperature remain unchanged within a narrow range that was developed over the long history of biological-system evolution.

Over the last ten years, human-body exergy balance model has been developed and its relation to thermal comfort in the built environment has been extensively investigated by Shukuya et al. It was found that there is a thermal environmental condition that the smallest human body exergy consumption rate emerges together with rational thermal comfort(Isawa, 2002; Iwamatsu, 2008; Simone, 2011) , but so far all of the analysis was done with an assumption of steady-state conditions. Some trial analyses on the un-steady state human body exergy balance in relations to human behaviours such as opening windows, or walking into or out from room spaces have been made by Schweiker et al(2007) and also by Tokunaga et al(2011), but the further investigations are needed. Under this circumstance, this paper demonstrates two examples of state-of-the-art unsteady-state analysis of the human-body exergy balance: one for summer conditions and the other for winter.

2 Short introduction to the concept of exergy

People often claim that "energy" is consumed; this is not only in everyday conversation but also even in scientific discussion associated with so-called energy and environmental issues. This claim, however, conflicts with the first law of thermodynamics stating that the total amount of energy is conserved even though forms of energy may change from one to another.

All macroscopic natural phenomena happening around us involve the dispersion of energy and matter, which in due course change their forms from one to another, but the total amount of energy and matter involved is never consumed but necessarily conserved.

When we use such expressions as "energy consumption", "energy saving", and even "energy conservation", we implicitly refer to "energy" as intense energy available from fossil fuels or from condensed uranium. But, it is confusing to use one of the most well-established scientific terms, energy, to mean "to be conserved" and "to be consumed" simultaneously. This is why we need to use the thermodynamic concept, exergy, to articulate what is consumed.

In addition to the importance of the exergy concept that allows us to show explicitly what and how much is really consumed, it is also important that the exergy concept enables us to articulate how a system in question including human body works in the condition of dynamic equilibrium; that is a series of process from exergy supply, consumption, and the resultant generation of entropy, and finally the entropy disposal.

3 Exergy balance equation in general

The concept of exergy, which is derived by combining the energy and entropy balance equations together with environmental temperature, indicates the ability of energy and matter to make dispersion occur relative to their environmental space. The general form of exergy balance equation for a system in question is expressed as follows(Shukuya, 2010):

$$\begin{aligned}&[\text{Exergy Input}] - [\text{Exergy Consumed}] \\ &\qquad = [\text{Exergy Storage}] + [\text{Exergy Output}]\end{aligned} \tag{1}$$

The unique feature of this balance equation is that there is the term of "consumed". Also unique is that, in the other three terms, there are either of "warm" or "cool" exergy together with either of "wet" or "dry" exergy depending on the indoor and outdoor conditions of temperature and water vapour pressure.

In the case of human body, exergy input is the sum of “warm” exergy generated by metabolism, “warm/cool” and “wet/dry” exergies contained by moist-air inhaled, those contained by liquid water as sweat, and “warm/cool” radiant exergy from the internal surface of the building envelope systems that is absorbed by the human body. On the other hand, exergy output is the sum of moist-air exhaled, “warm/cool” exergy transfer by convection, outgoing “warm/cool” radiant exergy, and exergy contained by water vapour. Exergy storage consists of two parts: that in the body core and in the body shell.

All terms except the exergy consumed can be calculated from the equations given in Shukuya et al(2010) substituting the body-core, body-shell temperatures and clothing surface temperature obtained from, for example, the calculation of Standard Effective Temperature (SET*). Using their values, the rate of exergy consumption is determined so that eq. (1) is satisfied.

4 Data-bases used for the present human-body exergy calculation

Indoor and outdoor environmental conditions in summer measured in a subjective experiment performed at Yokohama campus, TCU, on 6th of August in 2009 were used for the summer-case calculation under unsteady state conditions(Tokunaga, 2010). There are two experimental rooms whose thermal conditions were controlled by two distinctive ways. In one room, which we call “Naturally-Ventilated (NV) room”, the south-facing windows and two doors on the opposite side were kept open for cross natural ventilation. In the other room, which we call “Mechanically Air-Conditioned(MC) room”, the windows and doors were all kept closed and air-conditioning unit were kept running with the set point temperature of around 24°C. Both rooms are identical and each floor area is about 55 m^2. For both windows of NV and MC rooms, there are quite effective overhang and side fin so that the transmitted solar radiation is almost minimal necessary for daylighting.

Figure 1 shows indoor and outdoor thermal conditions in the vicinity of the subjects. Mean radiant temperature (MRT) was estimated from an empirical equation to be applied for a 38mm globe given by Thorsson et al(2007) by substituting the measured

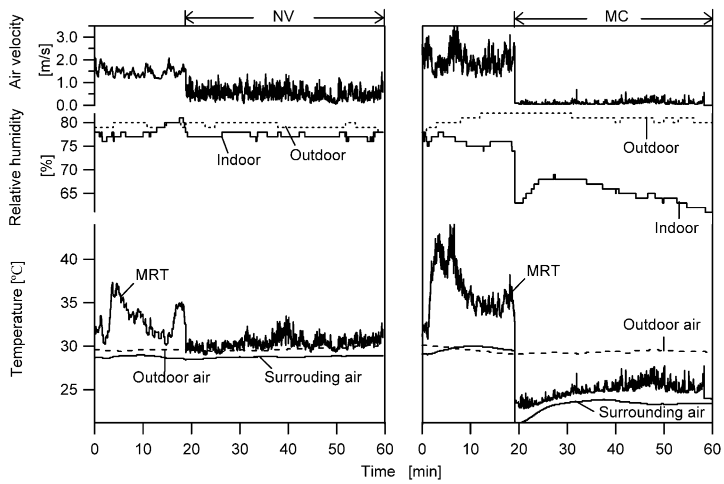

Fig. 1. The variation of indoor and outdoor thermal conditions in the vicinity of the subjects in an experiment performed at Yokohama campus, TCU, on 6th of August, 2009.

values of grey-coloured globe temperature, air temperature and air-current velocity.

Outdoor temperature and relative humidity measured at the roof of a building in our campus were about 30°C and 80% throughout the whole period of the experiment on 6^{th} of August. Temperature of the surrounding air exposing the subjects while they were both walking and staying in NV room was almost constant at around 29°C. Relative humidity was also almost constant at 77%. Mean radiant temperature while they were walking outside was about 3°C higher than that while they were staying in the room. It is due both to the solar radiation incident on the subjects and to thermal radiation received from the road and exterior building wall surfaces on the subjects. As can been seen in the top of Fig.1, air velocity in NV room fluctuated between 0.2 and 1.2 m/s with the average of 0.5 m/s. Before entering NV room, air velocity was in the range of 1.2 and 2 m/s. The air velocity in MC room was quite constant at about 0.1 m/s in comparison to that fluctuating between 1.2 and 3.5 m/s outdoors. After walking outdoors at 30 °C and 80%rh, the subjects were exposed to the air in MC room at around 23°C which was about 6°C lower than the outside. The difference in MRT between MC room and walking area was about 12 °C and larger than that in air temperature about 7 °C. The relative humidity drops sharply right after entering MC room, but it increases from about 60% to about 70% in the following five minutes, and then it decreases again towards 65%. The difference in relative humidity in MC room and the outside was about 16%. The increase in humidity for the first five minutes is caused by the sweat secretion from the subjects' body surface.

As a whole, on the one hand, the subjects were exposed to high temperature, high humidity and moderate air current in NV room, while on the other hand, they were exposed to low temperature, low humidity and still air in MC room.

Indoor and outdoor environmental conditions in winter measured in another subjective experiment performed on 4^{th} of February at an experimental site in Fuji, Asahi-Kasei Homes Co., Ltd., were used for the winter-case exergy calculation. There are two identical rooms, each of which is about $17m^2$. One of them is equipped with an air-conditioning unit and the other with a floor heating system. The walls and window of both rooms are thermally well insulated. We call the former room as CH room due to the primary use of "convective heating" and the latter room as FH room for the use of "floor heating".

Figure 2 shows the indoor and outdoor thermal conditions in the vicinity of the subjects. Mean radiant temperature was obtained from the measured interior surface temperatures of the walls and the window by calculating their average. The subjects walk outside for five minutes before entering either of the two rooms and then they stayed for sixty minutes in either of these rooms. At the moment of forty minutes after they started to stay in the rooms, the windows and the door were opened for five minutes and then closed again. This is for simulating a human action taken to bring in an amount of outdoor air for ventilation. Such an action is not unusual especially in the case of vacuum cleaning for the room space in residential buildings at least in Japan.

The average air temperatures during the period of time while the window was kept closed are 24.1°C in CH room and 23.5°C in FH room. Those while the window was open are 19.5°C in CH room and 21.3°C in FH room. The mean radiant temperature

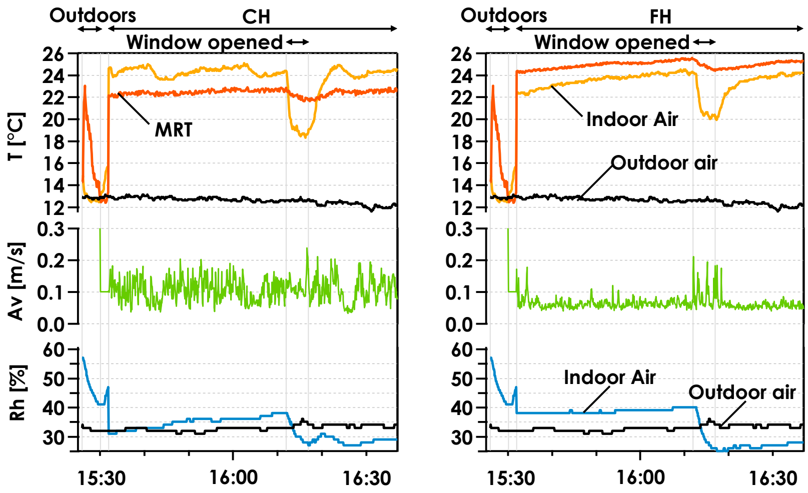

Fig. 2. The variation of indoor and outdoor thermal conditions in the vicinity of the subjects in an experiment performed at an experimental house in Fuji, on 4th of February, 2011.

while closed are 22.4°C in CH room and 24.9°C in FH room; those while open 22.1°C in CH room and 24.9°C in FH room. As the window is opened in CH room, the room air temperature decreases and turns out to be lower than mean radiant temperature. On the other hand, in FH room, the mean radiant temperature is always higher than the room air temperature. The operative temperatures are 23°C in CH room and 24.2°C in FH room. Average air velocity in CH room is 0.1m/s and that in FH room is 0.06m/s. During the period of time while the windows was open, the average air velocity was 0.12m/s in CH room and 0.1m/s in FH room. Outdoor air temperature decreases slightly from the beginning to the end of experiment, but stays rather constant around 12°C for the whole period of experiment. According to the record of weather bureau in Fuji, the average outdoor air temperature in February is 11.5°C so that the experiment was done under average weather condition.

5 Results and discussion

Using the calculated body-core and body-shell temperatures and the calculated sweat evaporation rate described above together with the measured outdoor air temperature and relative humidity for environmental temperature necessary for exergy calculation, we determined the human-body exergy balance in NV and MC rooms for summer conditions as shown in **Figure 3**.

Generally, the major exergy inputs are metabolic exergy generation rate in the body-core, wet exergy generation rate of liquid water as sweat, and the rate of warm or cool radiant exergy incident on the body surface, but in summer conditions, wet exergy generation rate of liquid water occupies the second largest part of the whole exergy input and the “warm” or “cool” radiant exergy incident on the body surface becomes very small. Although the sweat evaporation rates in NV and MC rooms were in the same order, the value of “wet” exergy appeared in MC room is much larger than that in NV room. The output rate consists mainly of convective transfer of “warm” exergy and outgoing “warm” radiant exergy. The exergy consumption rate, which is unique feature in exergy balance, turns out to be 60 to 80 % of the whole of exergy input rate.

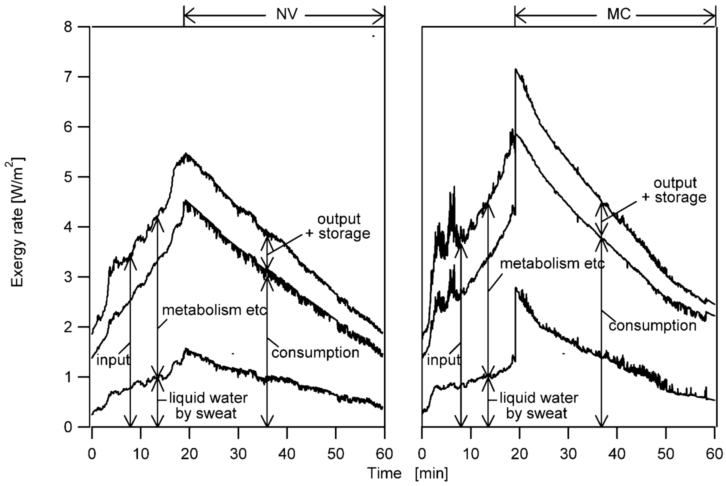

Fig. 3. Variation of human-body exergy balance calculated for the conditions in NV and MC rooms on 6th of August, 2009.

Both the input and output exergy rates increase by walking and they decrease while staying in the respective room. The exergy consumption rate also increases by walking and decreases as time goes on while staying in the respective rooms.

Comparing the exergy consumption rate in NV room with that in MC room right after the subject enter the rooms, the latter, 5.8 W/m^2 in MC room is 1.3 time larger than the former 4.5 W/m^2 in NV room. The average of exergy consumption rate in the whole period of stay is about 3 W/m^2 in NV room and about 4 W/m^2 in MC room. The change in exergy consumption rate between right before and after entering the rooms is 0.2 W/m^2 in the case of NV room and 1.5 W/m^2 in the case of MC room. It is almost seven time larger in MC room than that in NV room. While staying in the rooms, the exergy consumption rate gradually decreases. The slope of the exergy consumption rate in MC room is steeper than that in NV room; this implies that the rate at which the exergy consumption rate decreases is much larger in MC room than in NV room.

As mentioned above, warm exergy generated by metabolism and wet exergy contained by liquid water as sweat occupy the large part of the input exergy rate. Warm exergies generated by metabolism in both rooms are almost the same, but wet exergy rate of liquid water as sweat in MC room is about twice larger than that in NV room right after entering the rooms. This means that the liquid water as sweat in the body shell right after entering MC room has a larger potential to disperse than that in NV room. Since the air in MC room is dry due to dehumidification by the air-conditioning unit there is much more space for liquid water in MC room to disperse than in NV room.

The amount of sweat secretion itself in MC room is smaller than that in NV room as described above, but the amount of wet exergy, the potential of dispersion, of liquid water as sweat in MC room is larger than that in NV room in particular right after entering MC room. A large amount of wet exergy of liquid water as sweat makes the human-body exergy consumption rate large especially in MC room.

According to a series of previous research with respect to steady-state conditions, it has become clear that the smallest possible exergy consumption rate relates to thermal comfort. In other words, a large exergy consumption rate may cause thermal discomfort. A large gap in the human-body exergy consumption rate between before and after entering MC rooms must have caused thermal discomfort inevitably even if one cannot be conscious. The exergy consumption rate after spending for forty minutes may well corresponds to that under steady-state condition.

Figure 4 demonstrates the variation of human-body exergy balance under the environmental conditions shown in Figure 3. The two graphs in the left-hand side are for CH room and the other two in right for FH room. The upper graphs indicate the set of exergy inputs and the lower graphs the rate of exergy consumption, stored and outputs.

While walking outside before entering CH and FH rooms, the whole rate of exergy input and output decreases gradually in consistent with each other, but the rate of exergy consumption increases slightly. This is because the exergy stored becomes negative, that is the skin surface temperature tends to decrease so that the amount of exergy stored in the skin decreases. After entering CH or FH room, the whole rate of input and output gradually decreases, since the difference in temperature between the surrounding space and the human body becomes small and the skin temperature increases gradually.

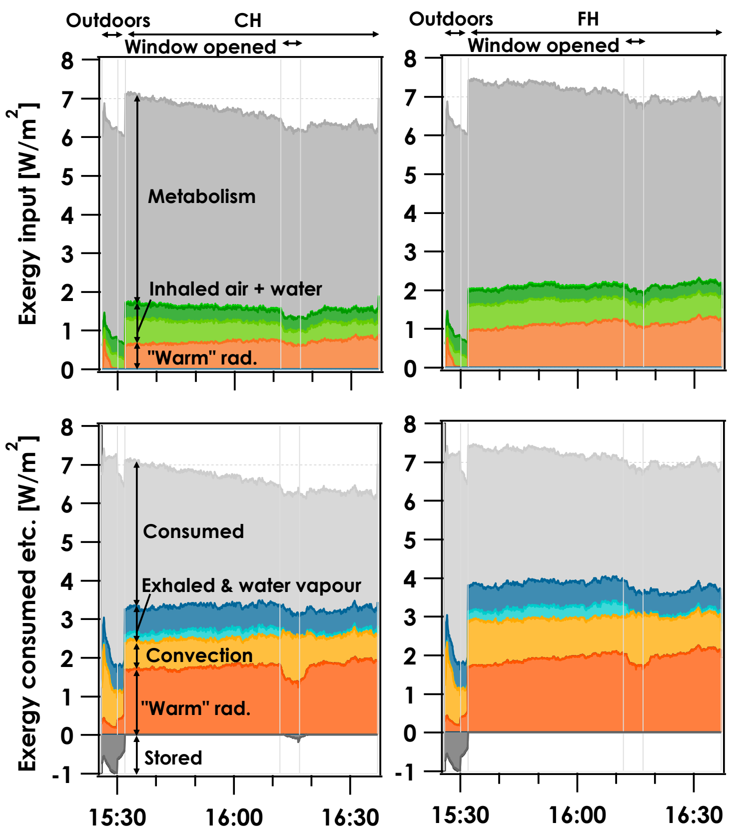

Fig. 4. Variation of human-body exergy balance calculated for the conditions in CH and FH rooms on 4th of February, 2011.

There are no large difference in exergy inputs between CH and FH rooms. The same applies to the rate of exergy consumption. It is due to the thermal insulation level was quite good for both rooms, though it looks contradictory to what was found by Isawa et al(2002) at first glance. The “warm” radiant exergy coming onto the human body in FH room is 0.3 to 0.5W/m^2 larger than that in CH room. This is because the mean radiant temperature in FH room is higher than that in CH room. The outgoing “warm” exergies by convection and radiation in FH room are also larger than those in CH room. This result is owing to the fact that the skin and clothing surface temperature calculated in the case of FH room are higher due to a higher mean radiant temperature than those in CH room.

While the window is open, there is a slight decrease in the rate of exergy stored in CH room and also a sudden increase in the rate of “warm” exergy transfer emission. Such a tendency appears clearer in CH room than in FH room.

6 Conclusions

For the next step, it must be very important for us to have a better understanding the adaptive behaviour of occupants in the built environment from the viewpoint of exergy. For this purpose, we have tried a couple of the unsteady-state calculation of human-body exergy balance for summer and winter conditions. We confirmed that it is essential to take a variety of passive technology prior to that of active technology for realizing low-exergy space heating and cooling systems.

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