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Research on Thermal Comfort by Analyzing LF/HF Value and Heat Flow Rate

Ziyang Wang*, Ryuji Matsuhashi*

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Abstract

In recent years, energy consumption in residential buildings account for about 40% of global energy consumption and contribute more than 30% of CO_2 emissions. A large proportion of it is used for thermal comfort satisfaction in residential buildings. On the one hand, saving energy only by reducing air conditioning will reduce human thermal comfort level. Therefore, to solve this issue, balancing between energy conservation and thermal comfort is significant. On the other hand, it is possible to estimate human thermal comfort level by analyzing the LF/HF value. Additionally, the heat flow rate between human skin surface and the surrounding air does has correlations with the LF/HF value, which has not been discovered before, this paper shows that there is a possibility to utilize heat flow rate and the LF/HF value to evaluate human thermal comfort level.

Key words : Residential building; thermal comfort; LF/HF value; heat flow rate; energy saving;

1. Introduction

Energy consumption in residential buildings account for about 40% of the global consumption and contribute more than 30% of the CO_2 emissions. A large proportion of it is used for thermal comfort satisfaction in residential buildings. It is meaningful to ensure thermal comfortability as well as to promote energy-saving in air-conditioning rooms. It has been revealed that it is possible to measure human heartbeat data and use the LF/HF value to evaluate real-time human thermal comfort level to some extent [1]. However, this method is only applicable for analysis in thermal steady state. Therefore, we proposed an improved method also applicable for analysis of thermal comfortability in thermal transient state. Due to the fact that an accurate evaluation of thermal comfort can be useful for avoiding energy waste caused by setting air-conditioning room temperature too low in summer period and setting the room temperature too high in winter period, the proposed method in this paper is also very helpful for energy saving.

2. Background

Previous studies focused on thermal steady state, revealed the fact that as for the same person, the higher the LF/HF is, the more uncomfortable he or she will feel, the lower the value is, the more relaxed he or she will feel [1]. However, this is just quantitative analysis of thermal comfort evaluation in thermal steady state. What is desirable is quantitative analysis not only in thermal steady state but also in thermal transient state. In short, dynamic analysis is required. On the other hand, previous studies lack of physical evidence (only subjective evidence). Concretely, the subjects said they feel hot or cold when under different thermal environments. There have been no things directly connecting with LF/HF value and any thermal physical quantities, yet.

Definition of the LF/HF value:

Figure 1 shows an example of human heartbeat data. In the heartbeat graph, the most prominent peak is called the R wave, and the interval between two nearest R waves is called the R-R Interval.

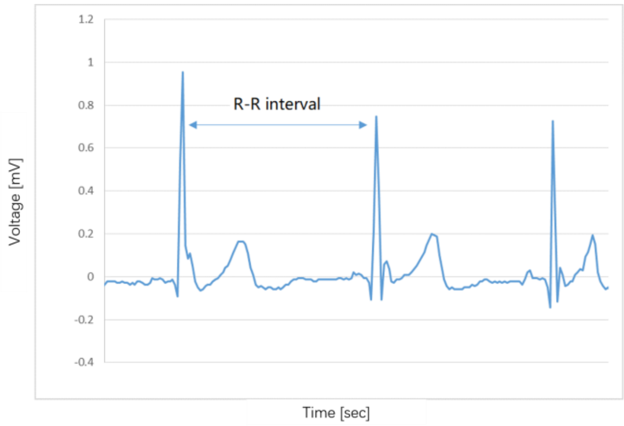

Figure 1 Heart wave form [1]

Corresponding author: Ryuji Matsuhashi, E -mail: matu@enesys.t.u-tokyo.ac.jp
*Department of EEIS, the University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

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Figure 2 shows the relationship between the heartbeat rate and the R-R Interval. When the heartbeat is fast, the R-R Interval becomes short, and when the heartbeat is slow, the R-R Interval becomes long. This is called heart rate variability.

Figure 2 Heart rate variability [3]

Instantaneous heart rate IHR [bpm (beats per minute)] can be obtained by substituting the R-R Interval into the equation (IHR = 60/R-R Interval). Then, by resampling the IHR data by linear interpolation, trend graph can be obtained. The trend graph is shown in **Figure 3** below.

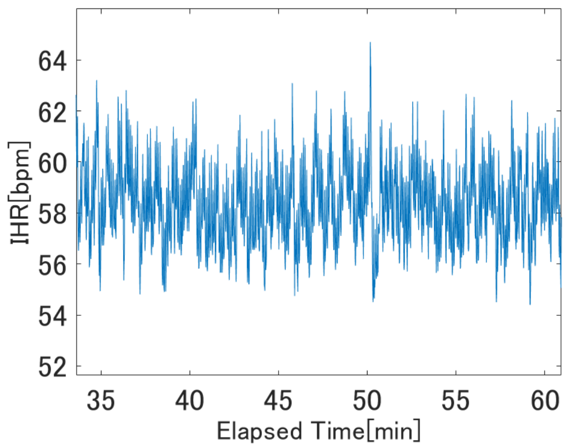

Figure 3 Trend graph of IHR

The interpolation method used in this study is linear interpolation, and resampling was performed every 0.1 second. By using the maximum entropy method (MEM) or Fast Fourier Transform (FFT) for the data of the trend graph, spectral can be obtained. Then, it is transformed into power spectral density, as is shown in **Figure 4**. Fast Fourier Transform was used in this study. In **Figure 4**, two large peaks are observed around 0.07 Hz and around 0.23 Hz. The red portion is called low frequency component (LF, Low Frequency), and the green portion is called high frequency component (HF, High Frequency). Comparing the sizes of these two mountains makes it possible to evaluate the degree of stress felt by humans. The ratio of the two mountains is called the LF/HF value.

There are two methods to calculate the LF/HF value. One way is to take the ratio of the height of the mountains. Another way is to integrate the two mountains on the horizontal axis and take the ratio of the areas of the two mountains. Sometimes it is difficult to identify peaks in the mountains, the latter method is more robust than the former method. Therefore, we selected the latter method in this study. The integration range of LF is 0.05Hz ~ 0.15 Hz while the integration range of HF is 0.15Hz ~ 0.4 Hz.

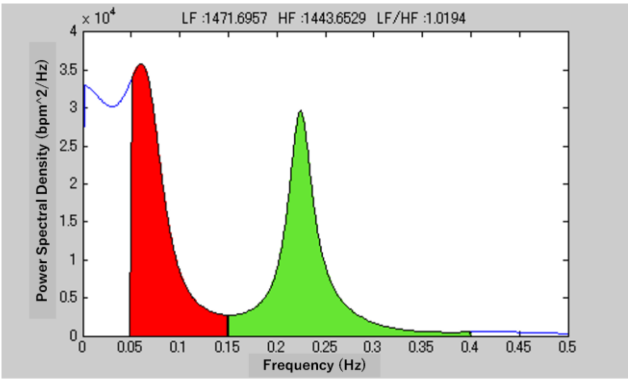

Figure 4 Concept and range of integration of LF / HF value [3]

3. Proposed Idea

Regarding the novelty of this research, previous studies have only focused on statistical thermal comfort evaluation (PMV etc), while individual difference has not been considered, yet. Moreover, since real-time thermal sensation has not been studied yet, either, we focused on individual differences and real-time characteristics. Then, we introduced LF/HF value with individual differences into this research. We creatively introduced a thermophysical quantity as a parameter to this issue, which is the heat flow rate between human skin surface and the surrounding air, as heat flow rate is a time-domain parameter and thus has very good real-time characteristics, then we conducted our research. By analyzing the correlation between the heat flow rate and the LF/HF value, we finally found the physical evidence of the validity of the method of utilizing the LF/HF value to evaluate human thermal comfort level, and this correlation feature gives us a new sight for thermal comfort analysis in thermal transient state.

$$T = \\ T_{head} \times 0.091 + T_{Uarm} \times 0.095 + \\ T_{Larm} \times 0.065 + (T_{chest} + T_{abdomen}) \times 0.252 + \\ T_{thigh} \times 0.246 + T_{leg} \times 0.078 + T_{foot} \times 0.141 \quad (1)$$

$$\Delta T = T - T_{surrounding} \quad (2)$$

$$\text{Heat flow rate} = 3.235 + 0.881 \times \Delta T^{0.368} \quad (3)$$

Where T denotes the mean body surface temperature calculated by several local body surface temperatures multiplied by respective weighting coefficients [2]. Weighting coefficient is the local heat transfer area of a region area of the body to the heat transfer area of entire body. ΔT denotes the temperature difference between skin surface and surrounding air temperature. The heat flow rate can be finally calculated by equation (3) according to reference [2]. Certainly, the radiant heat from the wall has an influence. However, in Reference paper [2], the radiant heat flowrate is regarded as a constant value. Therefore, in this paper, we proceeded analysis with the same assumption. In our future work, we would also like to handle analysis in consideration of the case where the radiant heat flow rate is not constant.

In this experiment, we used the Environmental Test Room A owned by Tokyo Gas Senju Techno Station B as our experiment site. There was an inner house in the Test Room A, outside of the inner house was able to set the temperature and humidity of inner house freely. The state of the room was as shown in **Figure 5**. **Figure 6** shows the device for measuring heartbeat data in our experiment. **Figure 7** shows the state of measuring body surface temperature in our experiment.

Figure 5 State of the inner house of Test Room A

Eight subjects participated in this experiment, four in 20s, four in 40s, all men, no health problem. Subjects were in light dress (long pants or short sleeve shirt).

Experiment date:

September 12, 2018 (One subject).

September 14, 2018 (Two subjects).

September 26, 2018 (Three subjects).

September 27, 2018 (Two subjects).

Table 1 shows our experiment schedule.

Table 1 Experiment schedule

Experiment time:	Procedures:
Start.	Put thermocouples and the heartbeat measuring device on the subjects.
10 minutes later,	Let the subjects lie down under a slightly hot temperature of 28°C.
20 minutes later,	Turn on the cooling system of the air-conditioner, the subjects may fall asleep in this procedure.
30 minutes later,	Turn on the heating system (29°C) of the air-conditioner, when the temperature reached sufficiently high, turn down the heating system.
30 minutes later,	Experiment ends.
Total experiment time:	90 minutes.

In this experiment, the temperature of eight parts of the subject's body surface and the air temperature near the subjects were measured, and the temperature data was substituted into the formula to calculate the heat flow rate. The humidity of the experimental environment was 70%, and we assume that this humidity cannot affect the thermal comfort because it was not so high. Concerning the airflow velocity, in the experiment of this time, the place where the subject was in was not the place where the air current of the air conditioner hit, in order to avoid the influence of wind. Therefore, there is almost no influence from the air velocity. As for the influence on radiation, since the heat flow rate by radiation is regarded as a constant in the heat flow rate calculation formula in the reference we used, the change of the peripheral wall temperature was not large under the experiment condition of this time, therefore, it is thought that the heat release rate by radiation hardly changes.

Figure 6 State of heartbeat measurement on human body

Figure 7 State of body surface temperature measurement on human body

4. Discussion

We have got eight data points in total.

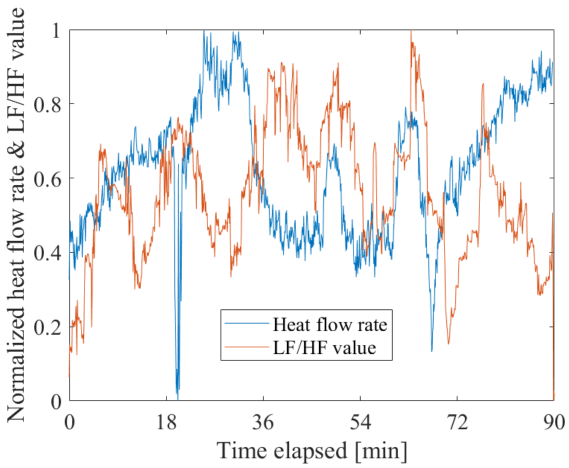

Figure 8 An example data point of heat flow rate and LF/HF value

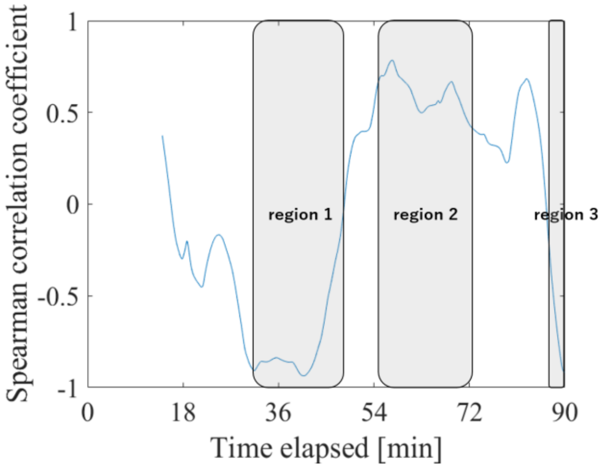

Figure 9 Spearman correlation analysis of the smoothed two curves in the data example

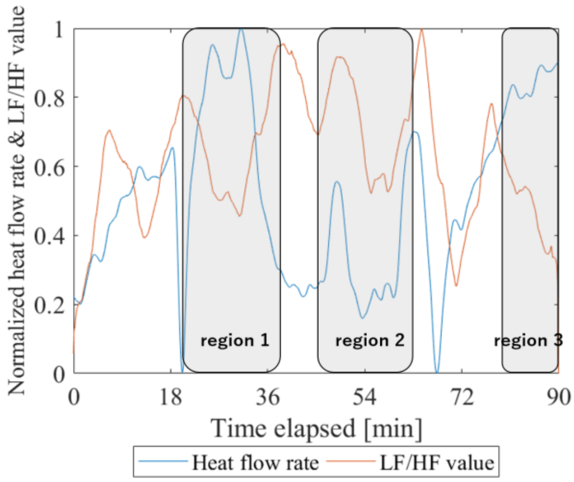

Figure 10 Broad region correlation feature of heat flow rate and LF/HF value

Figure 8 shows an example data point of heat flow rate and LF/HF value measured in one subject. We used moving average smoothing method to make the two curves smooth and by making spearman correlation analysis of the smoothed data, we got **Figure 9** and **Figure 10**, where region 1 and region 3 represent negative correlation while region 2 represents positive correlation. In **Figure 9**, in region 1, the average spearman correlation coefficient is -0.77, in region 3, the average spearman correlation coefficient is -0.66, in region 2, the average spearman correlation coefficient is 0.63. These spearman correlation values show the fact that heat flow rate and LF/HF value are strongly correlated in these regions.

According to **Figure 10** it is very clear to find that in the three broad regions marked in gray boxes the two curves perform as negative correlation relationship and positive correlation relationship. We call this feature as broad region correlation feature.

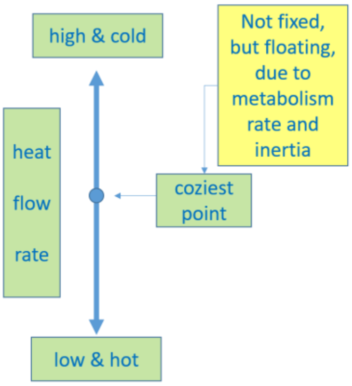

Figure 11 Hypothesis of the correlation of heat flow rate and thermal comfort level

Figure 11 demonstrates our hypothesis regarding the heat flow rate and the thermal comfort level (LF/HF value). Assume that the air temperature is lower than human mean skin temperature.

When the heat flow rate is too low, it means the air temperature is almost the same to skin temperature and human will feel hot, thus this will lead to high LF/HF value. On the contrary, when the heat flow rate is too high, it means the air temperature must be too low and thus can cause extreme coldness, and the LF/HF value will also be high, too. Then, we can obtain that, when human beings feel hot, the heat flow rate and the LF/HF value will be negative correlation, when human beings feel cold, the heat flow rate and the LF/HF value will be positive correlation. Moreover, there must exist a coziest heat flow rate which may suggest the coziest feeling and in which the LF/HF value will be lowest.

Considering human beings have a heat capacity and inertia nature & relative feature of the thermal feelings, and the metabolism rate also changes from time to time, the coziest heat flow rate is not a fixed rate, it varies from time to time.

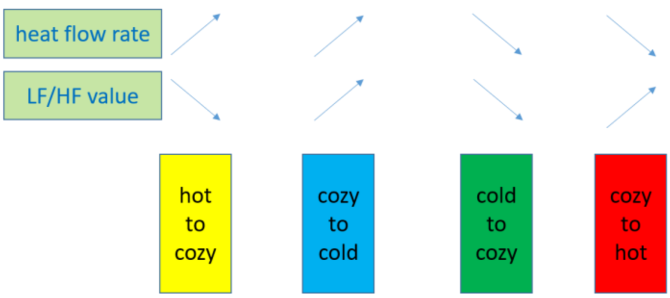

Figure 12 Four patterns of the thermal transition diagram

In **Figure 12**, we used four colors to denote the four patterns of the varying trends of heat flow rate and LF/HF value, each pattern denotes one thermal transition. The four patterns of thermal transition are explained as follows:

ⅰ. When the thermal transition is from feeling hot to feeling cozy, the heat flow rate should be increasing while the LF/HF value should be decreasing.

ⅱ. When the thermal transition is from feeling cozy to feeling cold, the heat flow rate should be increasing and the LF/HF value should be increasing, too.

ⅲ. When the thermal transition is from feeling cold to feeling cozy, the heat flow rate should be decreasing and the LF/HF value should be decreasing, too.

ⅳ. When the thermal transition is from feeling cozy to feeling hot, the heat flow rate should be decreasing while the LF/HF value should be increasing.

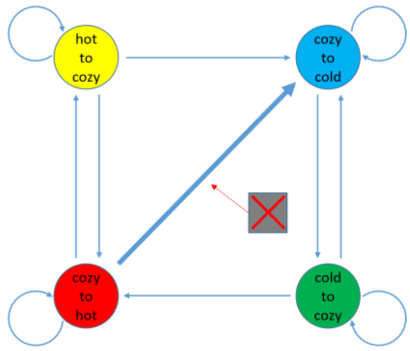

Figure 13 State transition diagram of the four states

Figure 13 demonstrates the state transition diagram of the four states in our hypothesis. In **Figure 13**, thin lines denote all possible state transitions, while the thick line denotes an example of impossible state transitions. Obviously, State “cozy to hot” cannot transit to “cozy to cold” directly.

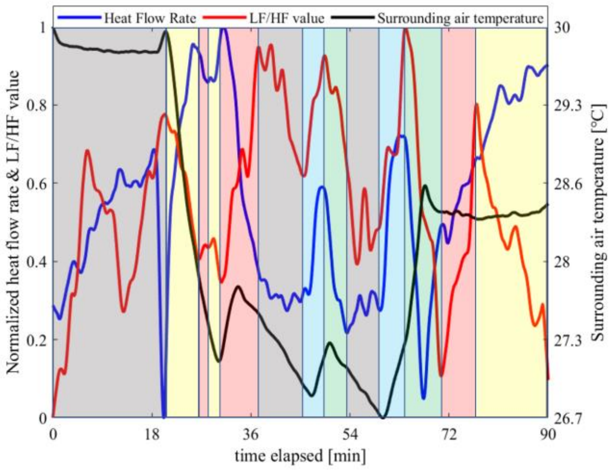

Figure 14 Analysis of using the rules stated above to distinguish the four different thermal feeling states

Red line: LF/HF value.

Blue line: Heat flow rate.

Black line: Surrounding air temperature.

Gray region: Difficult to interpret by using broad region correlation feature.

In **Figure 14**, by using the hypothesis we proposed to divide the time region into different thermal transition states, we can see that yellow color is next to red color while blue color is next to green color. And, in yellow & red regions the heat flow rate and the LF/HF value perform negative correlation while in green & blue regions the two curves perform positive correlation. This indicates that our hypothesis was right. What are notable are gray regions. In the first gray region there is no obvious correlation between the two curves, the reason is that during this region the subject just lied down (from motion state to stationary state) for a while, therefore the caused physiological effect made the graph difficult to interpret, no significant correlation observed. According to **Figure 14**, the second gray region cannot be interpreted well because human in "cozy to hot" thermal transition state cannot change to "cozy to cold" thermal transition state directly, due to common sense. In the third gray region, the curves perform as negative correlation, which is also difficult to interpret when observing the state transition diagram, further research is required.

5. Results

The LF/HF value does have correlations with the heat flow rate.

In this experiment, due to page limitations, we didn't show all the data. Due to the fact that the data of the other seven subjects did not contradict our hypothesis, thus we only showed the one subject's data in this paper.

Broad region correlation: In some regions two curves broadly positively/negatively correlate with each other. However, according to our experiment data, the broad region correlation feature between heat flow rate and LF/HF value is not always significant. On the other hand, the coziest point is not a constant value but fluctuates from time to time. However, the coziest point can be regarded as almost constant in a very small time interval. Therefore, our hypothesis on the correlation between heat flow rate and LF/HF value in small time intervals holds true. This is the intent of this paper.

Due to the broad region correlation feature, this experiment can thus provide physical evidence instead of subjective evidence to verify the fact that the fluctuation of LF/HF value can be caused by surrounding thermal changes (the fluctuation of the heat flow rate).

There might be a possibility to find the most thermal comfortable temperature by comparing the relative direction of the trends of LF/HF value and heat flow rate.

Due to the fact that human body has a heat capacity, sometimes the LF/HF value seems to have a time delay feature, only by using the LF/HF value's real-time feedback to control the air conditioner's temperature will cause bad user experience. It has a potential to use heat flow rate to assist the evaluation of thermal comfortability.

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