Journal of Engineering, Project, and Production Management
2015, 5(1), 26-35

Comparison of Thermal Comfort by Radiant Heating and Convective Heating

Shigeru Imai[1] and Shoichi Kojima[2]

[1]MSc Student, Department of Civil Engineering and Architecture, Saga University, 1 Honjo-machi, Saga-shi, Japan, E-mail: 13577006@edu.cc.saga-u.ac.jp (Corresponding author).

[2]Associate Professor, Department of Civil Engineering and Architecture, Saga University, 1 Honjo-machi, Saga-shi, Japan, E-mail: shokjm@cc.saga-u.ac.jp

Engineering Management
Received January 20, 2014; revision August 3, 2014; accepted on August 25, 2014
Available online November 9, 2014

Abstract: Currently, convective heating with a heat-pump system, which has high energy efficiency, is popular for room heating. However, it is possible that energy savings using convective heating can be further improved using heat pumps that service both occupied and unoccupied spaces. Moreover, convective heating increases vertical temperature gradients in a room; thus, it is hard to say whether occupants are being provided with sufficient thermal comfort. The purpose of this study is to compare the thermal comfort provided by both radiant and convective heating systems. In this study, a small office room was modeled, and then temperature and airflow distributions in the room were calculated by Computational Fluid Dynamics (CFD) simulations using ESP-r (Environmental research simulation software). Furthermore, distributions of Standard Effective Temperatures (SET^*) were calculated using the air temperature distributions obtained from the CFD simulations, which allows us to compare the thermal comfort provided by convective heating with that provided by radiant heating. The results show that radiant heating can provide satisfactory thermal comfort, even when the room air temperature is low. However, thermal comfort also depends on the temperature of blowing air, and blowing air must reach occupied regions; thus, only radiant heating cannot circulate sufficient air. In contrast, convective heating increases vertical temperature gradients in a room. Therefore, rather than using only radiant or convective heating, it may be more effective to combine them efficiently.

Keywords: Thermal comfort, radiant heating, convective heating, SET^*, CFD.

1. Introduction

Currently, there are two methods for warming interior spaces in winter. One method uses convective heating to warm the indoor air and the other uses radiant heating to warm the human body directly. Since ancient times, the Japanese, people have used localized heating systems such as kotatsu which is a Japanese style warming device and hearth for thermal comfort. Since 1960, heat-pump systems have been commercially available, which provide both heating and cooling; however, such systems were initially very expensive. Since the late 1970s, heat pumps have gradually come to be used in most households. According to a survey of consumption trends by the Cabinet Office, the diffusion rate of room air -conditioners in 2013 was as high as 90.5%. In contrast, the diffusion rate of oil stoves, which is one source of radiant heating, has continually decreased from 91.5% in 1981 to 54.1% in 2004. That is, the relative proportions of convective heating and radiant heating have reversed.

In recent years, saving energy has gained global attention, not only for economic reasons and for conserving natural resources but also for controlling global warming. A typical example of such international attention, is the Kyoto Protocol, which was adopted in 1997. Such treaties have motivated political and scientific efforts on “energy conservation.” Recently, it has been also discussed sustainability of the built environment in terms of energy saving. The Act on the Rational Use of Energy was enacted in 1979 under the influence of the oil shock in Japan, and so far, it has been amended three times. In addition, standards of energy conservation were established by introducing the Top Runner Program when it was amended in 1998.

Currently, these efforts have helped spread the use of convective heating with heat-pump systems because such systems have high efficiencies. However, convective heating warms spaces that are unoccupied by humans but are in the vicinity of occupied spaces. Therefore, it may be that additional energy savings can be achieved in room heating. In addition, convective heating may not be the most efficient in providing thermal comfort in occupied rooms because it increases vertical temperature gradients.

Previous studies have compared the energy savings attained by different heating methods applied to indoor thermal environments.

To verify the energy savings of floor heating in occupied housing, Sakaguchi et al. (2008) have performed actual measurements of the energy consumption by floor heating and warm-air heating. The results show that the total amount of heat generated by floor heating and warm-air heating (the amount of heating and internal heat generated in the target building) were almost the same. In addition, their Computational Fluid Dynamics (CFD) calculations for both heating methods provided the amounts of heat transmitted by each wall (i.e., walls, floors, ceilings, windows, etc.) and heat losses by drafts when SET* was set to be 22℃.

Omori and Tanabe (2008) and Ohira et al. (2010) focused on wall-mounted air conditioning and floor heating. They clarified differences in the thermal environments created by the two heating systems and compared the amounts of heat in a room for the same thermal sensation over an entire human body. Moreover, they compared the performance of thermal insulation in the building for five patterns under similar conditions at that time. In addition, they considered the relationship between heat dissipation by the human body and indoor heat dissipation due to the posture of the human body in combination with the particular heating system.

Kaji et al. (2007) studied the indoor thermal environment and ventilation efficiency of a room during heating. They used macro and micro analyses of CFD results for the age of air and the room air temperature distribution when the heating system, ventilation strategy, and positions of supply and exhaust ports were changed. Moreover, they considered the relationship between local air exchange efficiency of an occupied room and the thermal environment. Consequently, they determined that local air exchange efficiency was not affected by changes in the heating system.

In previous studies, evaluation of energy conservation and indoor thermal environment have been performed based on radiant heating such as floor heating and convective heating such as heat-pump systems. These investigations often included performance aspects of the building such as effectiveness of thermal insulation (hard) and combinations of ventilation method and heating method (soft). However, there has not been a study that includes the phenomenon of radiation itself such as the heat dissipation characteristics of radiation. The particular studies cited above are just a few of many, but other studies are similar. To reproduce actual phenomena more accurately, the directionality of radiant energy should be included because the directivity of radiation is known to contribute to the heat dissipation characteristics of actual phenomena.

So, one of the few studies is that by Yoshikawa (2013), who used a computational model of directional radiation by a radiant heater to calculate the Standard Effective Temperature (SET*) for an occupant in a room. By calculating the SET* using this computational model, the effective uses of a radiant heater were examined based on the thermal comfort of a human body.

In this study, we examine an indoor thermal environment heated by a radiant heater with strong directivity of radiation. Moreover, we determine the optimal heating method, convective or radiant, based on energy saving and thermal comfort. By using radiation heating which has directional radiation, it is possible task heating more effectively than when using only convection heating. It is also expected that maintaining the thermal comfort of residents and reducing energy consumption by using radiation heating. As a preliminary step, in this study we compare the influences of radiant and convective heating on the thermal comfort of occupants from SET* distributions, which are calculated from the heated environment.

2. Simulation Method

2.1. Analysis Method

Fig. 1 shows the flow of our simulations. The purpose of this study is to determine the optimal heating method by focusing on the directivity of radiation. In the calculation process, directivity was reproduced by estimating radiant emittance and effective directional emissivity, but the course of the solid line are calculated the process without the course of dotted line in this report. Our next paper will describe the process of considering the directivity.

A cross-sectional view of the model analysis room and its floor plan are shown in Figs. 2, 3, and 4. The model represents an ordinary small office with dimensions of 3800 mm(X) × 6000 mm(Y) × 2600 mm(Z) and a total floor area of 22.8 m2. A glass window was placed on the south wall with a height of 1300 mm and width of 2800 mm; a door was placed on the north wall with a height of 2100 mm and a width of 900 mm. Adjacent rooms were assumed to exist against all walls except the south and north walls. The south wall faced outdoors and the north wall faced a corridor. The analysis space was divided into 19(X) × 30(Y) × 13(Z), for a total of 7410 meshes; the standard k-ε model was adopted for the turbulence model. Detailed specifications for the room model and the numerical calculations are shown in Tables 1 and 2, respectively.

The simulation period was 168 h. The calculation results were examined for the duration when temperature was stable. The heating surface temperature for radiant heating was set to 30℃. The temperatures of other surfaces were calculated under the same conditions for both convection and radiant heating. The outlet air temperature from convective heating was set to 40℃. By using EES (Engineering Equation Solver), which is an equation-solving program, the distribution of SET* was calculated based on distributions of air temperatures and airflow vectors obtained from the CFD calculations. Further CFD calculations were performed using ESP-r (Environmental research simulation software).

2.2. Calculation of Surface Temperatures

To determine indoor surface temperatures as boundary conditions for the CFD calculations, the initial room temperature was determined by assuming that the outdoor temperature was 5℃ and substituting the coefficient of heat loss and internal heat generation into equation (1). The value of the design documentation assembly was used for the internal heat generation amount in equation (1). The value used for the heat loss coefficient was that stipulated for Region IV according to the geo-climatic regional division of Energy Conservation 1999 in Japan.

Therefore, the initial room temperature was set at 15℃ when the outside air temperature was 5℃.

$$\Delta T = Q_i \div Q \tag{1}$$

where ΔT is the temperature difference between indoor and outdoor air (℃), Q_i is the amount of heat generated (27.158 W/m^2), and Q is the heat loss coefficient (2.7 W/(m^2·K)).

Assuming steady state at the walls, the heat flux between indoor and outdoor air through a wall is equal to the heat flux from a wall surface to the air. Subsequently, the following equation was used to determine the indoor surface temperature. The heat transfer coefficients of walls are shown in Table 3, and the surface temperatures of walls are shown in Table 4.

$$T_{si} = T_i - \frac{U}{h}\left(T_i - T_o\right) \tag{2}$$

where, Tsi is the indoor surface temperature (℃), Ti is the initial indoor air temperature (℃), U is the heat transfer coefficient (W/(m^2·K)), h is the indoor heat transfer coefficient (W/(m^2·K)), and To is the outside air temperature (℃).

To represent a human body in the thermal environment, a sphere with a diameter of 10 mm was placed 700 mm above the floor. A form factor for a point on the radiation panel and a point on the building was calculated by a built-in function of EES. Calculation of the mean radiant temperature (MRT) is explained in Section 4.

2.3. Placement of Heating Equipment

Figure 5 shows the hot-air outlet position of convective heating, and Fig. 6 shows the position of floor heating. The hot-air outlet area of convection heating was set to 0.06m^2, the hot-air outlet position of convective heating was placed above the floor at 500mm and center of frontage direction as shown in the figure. The entire floor was heating surface in floor heating.

3. CFD Analysis Results and Discussion

In this paper, differences in the indoor thermal environment between radiant heating and convective heating are discussed by comparing analysis results for floor heating with results for the hot-air outlet below the window on the south wall. Application range of the analysis results shows in this study. Calculation results are different by a combination of the conditions such as outlet air temperature and outlet area in the case of convective heating. However, it is considered not change so much the tendency of air temperature distribution. In addition, air temperature distributions are different by the difference in the surface temperature of heating surface in the case of floor heating. However, it is also considered not change so much the tendency.

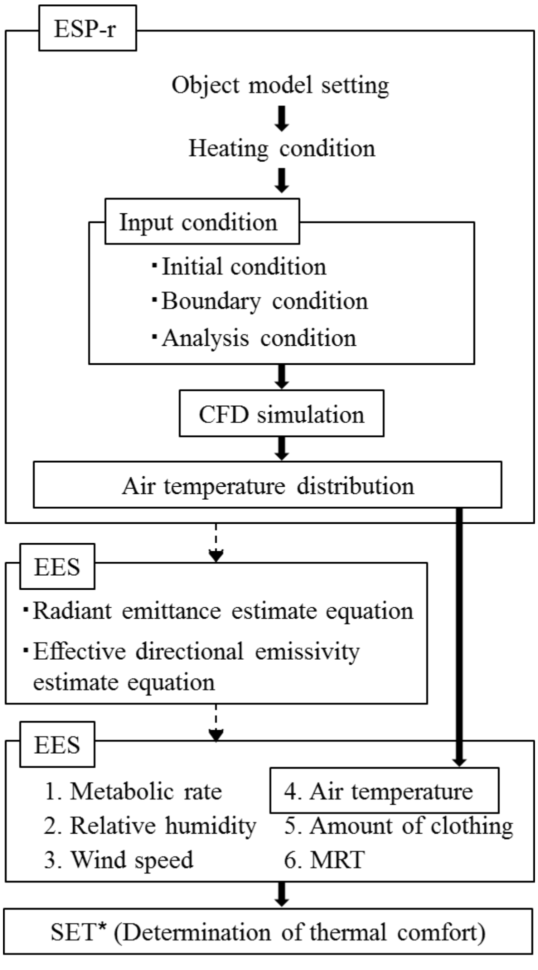

Fig. 1. Flow of simulation

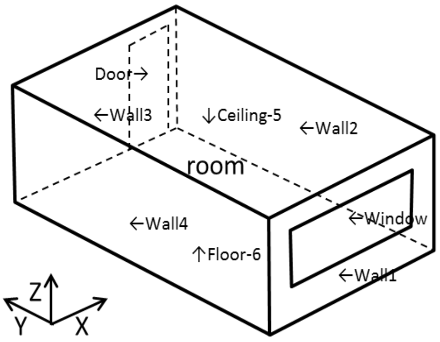

Fig. 2. Analysis object model

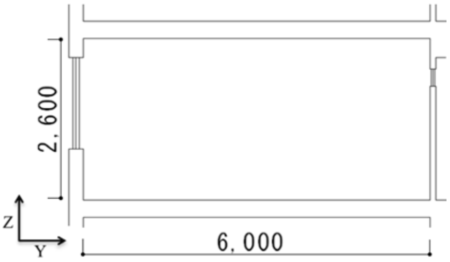

Fig. 3. Cross-sectional view of the model (Unit: mm)

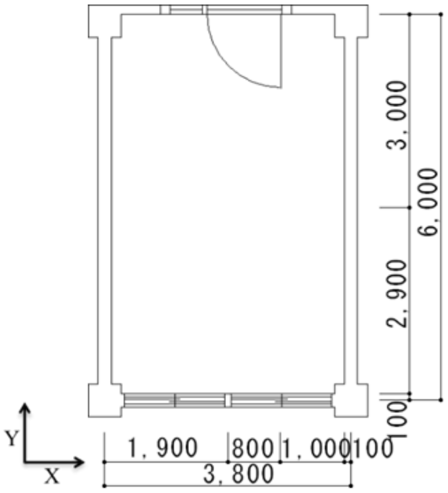

Fig. 4. Floor plan of the model (Unit: mm)

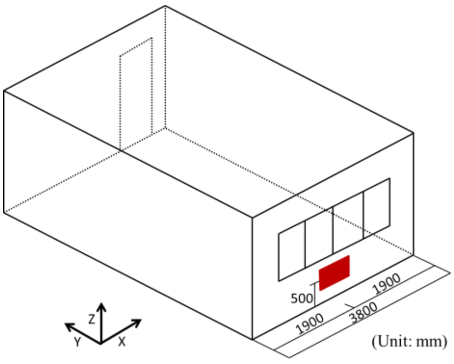

Fig. 5. Position of convective heating outlet

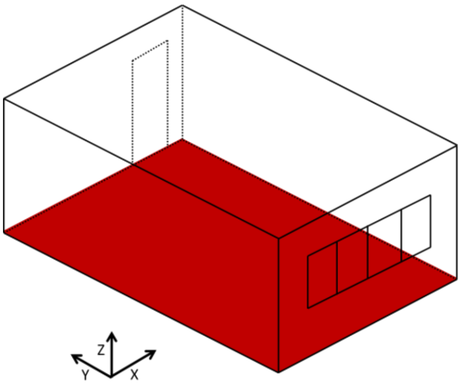

Fig. 6. Position of floor heating

Table 1. Specification of room

Overview of the object model		Object model conditions
Building dimension (mm)		3800 (X) × 6000 (Y) × 2600 (Z)
Aperture	Dimension (mm)	2800 (Width) × 1300 (Height)
	Specification	Double-glazing
	Window bottom height (mm)	800
North side door (mm)		900 (Width) × 2100 (Height)
Building orientation		South

Table 2. Numerical conditions

Analysis condition		Calculation condition
Mesh division		19 (X) × 30 (Y) × 13 (Z) 7410mesh
Turbulence model		Standard k-ε model
Difference scheme		Hybrid method
Solution		SIMPLE method
Outflow condition	Air outlet area (mm)	200(X) × 300(Y)
	Mass flow rate (kg/s)	0.0714
	Turbulence energy	0.005
	Turbulent dissipation rate	0.005
	Air outlet temperature (℃)	40
Inflow condition	Absorption area (mm)	300(Y) × 200(Z)

Table 3. Heat transfer coefficients of walls

Position	Heat transfer coefficient (W/(m^2·K))
Ceiling	0.3122
Floor	1.2170
External wall	0.3896
Partition	1.0390
Window	3.0090

Table 4. Surface temperatures of Walls

Position (Surroundings)	Temperature (℃)
South wall (Outside)	14.6
East wall (Adjacent room)	15.0
North wall (Corridor)	15.0
West wall (Adjacent room)	15.0
Ceiling (Adjacent room)	15.0
Floor (Adjacent room)	15.0
Window (Outside)	11.7
Door (Corridor)	15.0

3.1. Hot-Air Outlet below the Window on the South Wall

3.1.1. Air temperature distributions in vertical cross sections

Fig. 7 shows the temperature distribution of the Y-Z cross section when the hot-air outlet was below the window on the south wall. Hot air, which was blown out horizontally from the floor at 500 mm, reaches the ceiling surface and rises sharply. Subsequently, its momentum is weakened by collisions with the ceiling, and the hot air spreads in the Y direction along the ceiling. Moreover, the air circulates around a point at a distance of ~1000 mm in the Y direction from the north wall. Although the hot air blown from the outlet maintains a height of 2000 mm in the horizontal direction, the space below the air outlet does not get warm.

Fig. 8 shows the temperature distribution for the X-Z cross section when the hot-air outlet is below the window on the south wall. Warm air evenly circulates in the left and right direction from the ceiling surface, and the warm air moves from the ceiling to the wall surfaces. However, air movement cannot be confirmed except for the temperature distribution near 1200 mm from the floor.

3.1.2. Air temperature distributions of horizontal cross sections

Fig. 9 shows the temperature distribution in the X-Y cross section when the hot-air outlet is below the window on the south wall. The hot air reaches the seating position above the floor at 700 mm because the air outlet is at a lower position above the floor at 500 mm. For other heating methods, the air temperature decreases toward the south wall from the north wall. However, in Fig. 9, air around the south wall is warm because hot air is blown from the air outlet.

3.2. Floor Heating

3.2.1. Air temperature distributions in vertical cross sections

Fig. 10 shows the temperature distribution on the Y-Z cross section for floor heating. Warm air rises from the floor; however, that warm air is held down by the downdraft of ambient air. In the figure, the temperature range is only 0.5℃. The figure shows that increases in air temperature are difficult using only radiant heating.

Fig. 11 shows the temperature distribution in the X-Z cross section for floor heating. The air temperature fluctuation is lesser compared to the initial temperature (15℃). Floor heating provides little warming of indoor air, and thermal comfort of the human body is limited to direct contact with the floor.

3.2.2. Air temperature distributions of horizontal sections

Fig. 12 shows the temperature distribution of the X-Y cross section for floor heating. The temperature range in the figure is 0.5℃; however, the air temperature remains low and no changes in temperature appear at the human seating position, which is 700 mm above the floor; thus, thermal comfort is not improved. For floor heating, thermal comfort is greatly affected by the contact area between the human body and the floor.

4. Calculations of SET*

Values for SET* were calculated using the results for temperature distributions. The calculated area was a horizontal X-Y cross section with the X-coordinate from 0 to 3800 mm, the Y-coordinate from 0 to 6000 mm, and the height to 700 mm above the floor, which included the human seating position. The conditions used in the SET* calculation are shown in Table 5. Humidity, wind speed, metabolic rate, and amount of clothing were set to fixed values.

The MRT was calculated by,

$$MRT = \left\{ \sum_{\varphi 1i} \left(\theta_g - 273.15 \right)^4 \right\}^{0.25} - 273.15 \tag{3}$$

where Ti is the temperature of surface i (℃) and li is a form factor as seen from a point on surface l to surface i.

The thermal comfort range of SET* is assumed to be from 22 to 26℃.

5. SET* Calculation Results and Discussion

5.1. Hot-Air Outlet Below the Window on the South Wall

Fig. 13 shows results for SET* when the hot-air outlet was below the window on the south wall. Near the outlet, the values of SET* are consistent with thermal comfort; however, in other areas they are not. Therefore, regions of thermal comfort are limited to areas where a warm airflow is blowing directly. The air temperature on the south wall near the outlet is the same as the air temperature along the X-axis around 2–3 m; however, the air temperature near the south wall is lowest in terms of SET*. With all these factors, as a practical significance, it is difficult that controlling thermal comfort and air temperature distribution because it is heated by warmed air when convection heating is used. In addition, there is a possibility that the amount of energy required becomes excessive to obtain sufficient thermal comfort in the occupied zone.

5.2. Floor Heating

Fig. 14 shows results for SET* when floor heating is used. The air-temperature distribution was nearly uniform about 15℃, the value of SET* was about 22℃ in the center of the room to a depth of 4000 mm and a width of 2000 mm. In other areas of the room, SET* remained about 21℃. Thus, thermal comfort was easy to maintain with a floor heating system. With all these factors, as a practical significance, it can be confirmed that obtain sufficient thermal comfort as a whole when radiant heating is used. It is possible to accurately control the heating range and to perform the task heating effectively by using heating surface warmed, unlike convective heating.

6. Conclusions

In this study, we used CFD simulations to compare thermal comfort provided by radiant heating with that provided by convection heating. We used ESP-r CFD to calculate temperature distributions in a room, and then we used those temperature distributions to determine thermal comfort in terms of SET*. The results show that, with convection heating, temperature stratification possibly appears in the vertical direction; thus, for heating efficiency of convective heating, we should consider both air temperature and air circulation patterns and velocities. With radiant heating, temperature differences are small and air circulation is limited to natural convective flows. When convection heating only warms the air itself, a temperature difference occurs in the vertical temperature distribution. Air circulation in a room is important and should be imposed without sacrificing thermal comfort by varying air speed and direction. Calculated values for SET* were relatively high for radiant floor heating, although the air temperature was low. Similarly, values for SET* were relatively low for convection heating, although the air temperature was high.

Consequently, radiant heating can provide adequate thermal comfort even if the air temperature is low. However, generating flows of warm air is difficult when radiant heating is used. In contrast, the thermal comfort provided by convective heating depends on the temperature of air entering the room from the heating system and on the temperature range of airflows reaching human occupants. However, convective heating increases vertical temperature gradients in a room. As a practical significance, it is difficult that controlling thermal comfort and air temperature distribution because it is heated by warmed air when convection heating is used. In addition, there is a possibility that the amount of energy required becomes excessive to obtain sufficient thermal comfort in the occupied zone. In contrast, it can be confirmed that obtain sufficient thermal comfort as a whole when radiant heating is used. It is possible to accurately control the heating range and to perform the task heating effectively by using heating surface warmed, unlike convective heating. Based on these results, heating system is found that satisfies the energy efficiency and thermal comfort of occupants by analyzing the indoor thermal environment under a combination in future studies.

Table 5. SET* calculation conditions

Condition	Input value
Room temperature (℃)	Calculated value of CFD
Relative humidity (%)	30
Wind speed (m/s)	0.1
Metabolic rate (Met)	1.1
Amount of clothing (clo)	1.1
Mean radiant temperature	Calculated MRT according to equation (3)

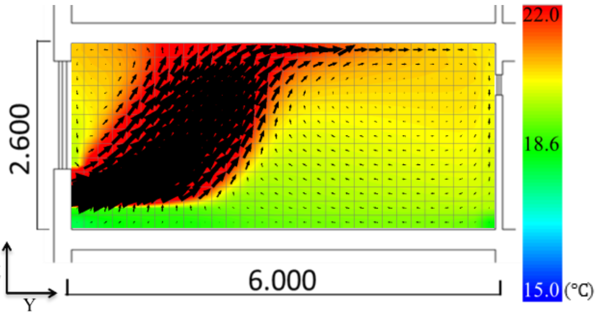

Fig. 7. Temperature distribution on the Y-Z cross section at X = 1900 mm (Unit: mm)

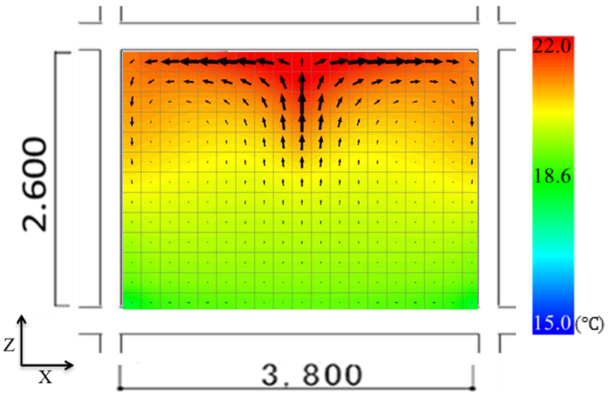

Fig. 8. Temperature distribution on the X-Z cross section at Y = 3000 mm (Unit: mm)

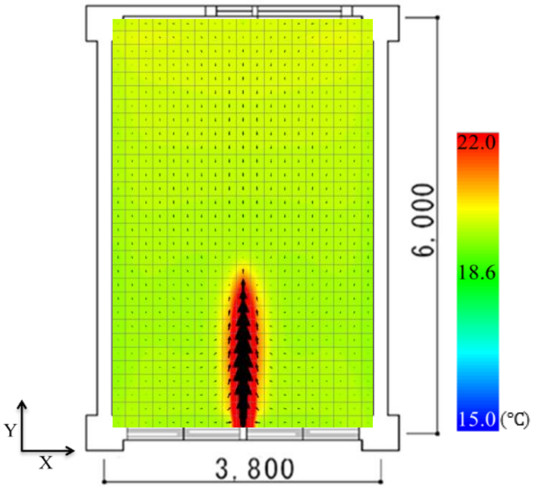

Fig. 9. Temperature distribution on the X-Y cross section at the floor (700 mm) (Unit: mm)

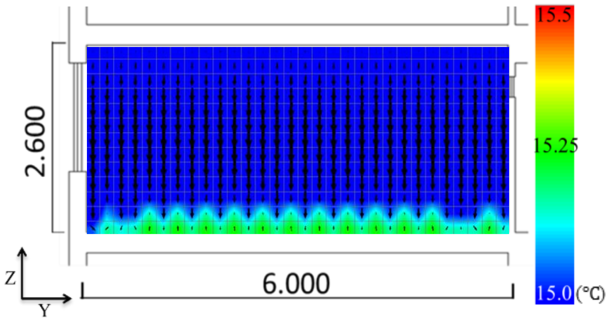

Fig. 10. Temperature distribution on the Y-Z cross section at X = 1900 mm (Unit: mm)

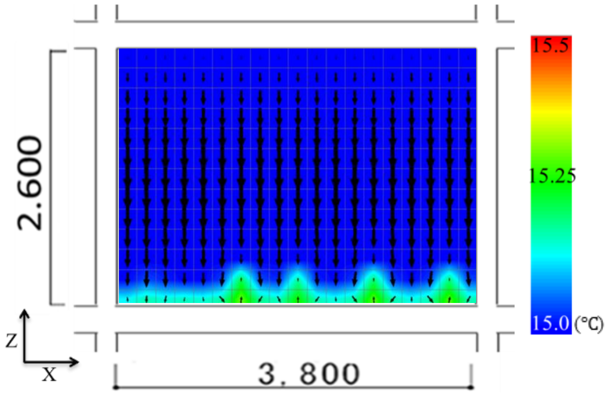

Fig. 11. Temperature distribution on the X-Z cross section at Y = 3000 mm (Unit: mm)

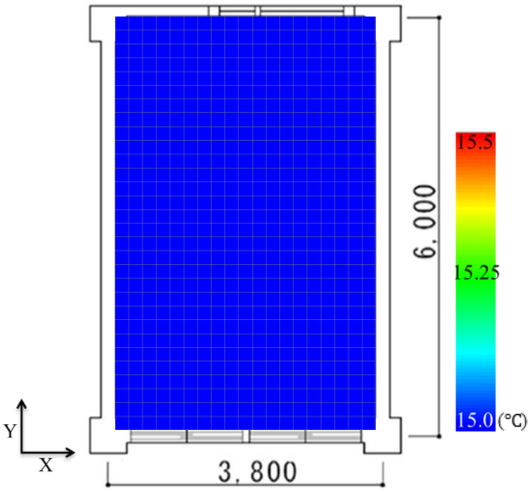

Fig. 12. Temperature distribution on the X-Y cross section at the floor (700 mm) (Unit: mm)

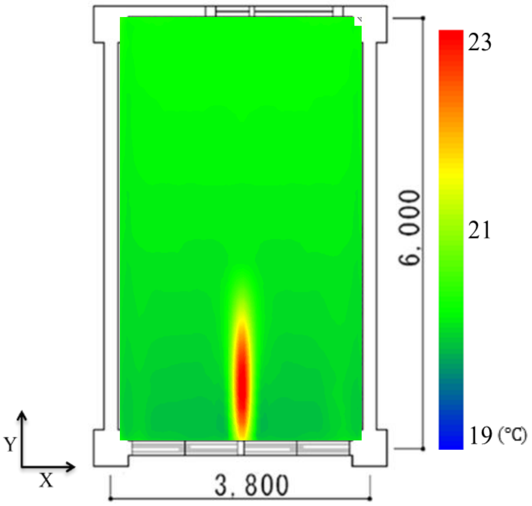

Fig. 13. SET* distribution on the X-Y cross section at 700 mm above the floor for convective heating (Unit: mm)

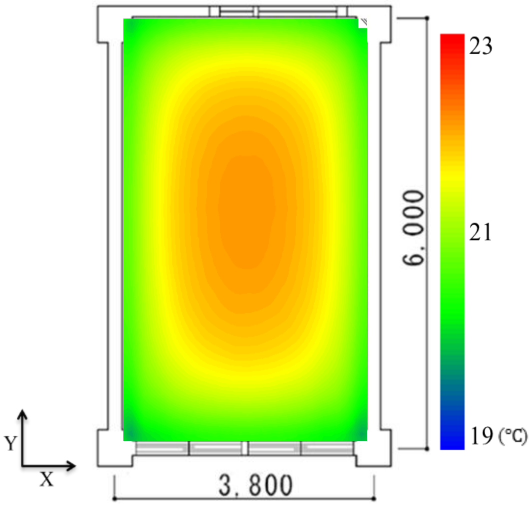

Fig. 14. SET* distribution on the X-Y cross section at 700 mm above the floor for radiant heating (Unit: mm)

References

Economic and Social Research Institute, Cabinet Office, Government of Japan. (2013). Diffusion rate of major consumer durables (Households). Retrieved from http://www.esri.cao.go.jp/jp/stat/shouhi/shouhi.html#kako on December 7, 2013.

Gagge, A. P. (1971). An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Transactions*, 77, 247-262.

Gagge, A. P. (1986). A standard predictive index of human response to the thermal environment. *ASHRAE Transactions*, 92, 709-731.

Kaji, H., Akabayashi, S., and Sakaguchi, J. (2007). Research on air-conditioning and ventilation system in house: part 2 the comparison of indoor environment in the case of air-conditioning and floor heating by CFD analysis. *Architectural Institute of Japan Hokuriku Chapter Research Report Collection*, 50, 225-228.

Matsumoto, T., Noda, M., and Matsui, I. (2009). History of heating technology and transition of thermal environment evaluation-index: research on realization of comfortable habitation space. *Summaries of academic conference of college of Industrial Technology, Nihon University*, 42, 121-124.

Ohira, N., Omori, T., Itagaki, M., and Tanabe, S. (2010). Evaluation of indoor thermal environment by coupled simulation of convection and radiation: part 11 influence of building insulation and heating systems on energy performance. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*, D-2, 655-656.

Omori, T. and Tanabe, S. (2008). Evaluation of indoor thermal environment by coupled simulation of convection and radiation: part 7 influence of body posture and heating systems on heat balance of human body. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*, D-2, 367-368.

Omori, T., Ohira, N., Itagaki, M., and Tanabe, S. (2010). Evaluation of indoor thermal environment by coupled simulation of convection and radiation: Part 10 analysis of thermal environment and energy performance taking account of building insulation and healing systems. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan*, D-2, 653-654.

Sakaguchi, J., Akabayashi, S., Hasegawa, H., and Asama, H. (2008). Study on the heat loss of the detached house when heated by both floor heating and air-conditioning. *Journal of Environmental Engineering (Transactions of AIJ)*, 73, 735-742. doi: 10.3130/aije.73.735

Tulika, G., Sabah, M., and Robert, N. (2014). Intelligent Buildings: Key to Achieving Total Sustainability in the Built Environment. *Journal of Engineering, Project, and Production Management*, 4(1), 2-16.

Yoshikawa, K. (2013). Study of efficient use of radiation heating equipment based on heat dissipation characteristics thermal comfort. *Saga University*, 53-90.

Shigeru Imai is a MSc student, Department of Civil Engineering and Architecture at Saga University, Japan. He received bachelor's degree at Saga University, Japan. His research is the analysis of indoor thermal environment of a building using computational fluid dynamics.

Shoichi Kojima is an associate professor, Department of Civil Engineering and Architecture at Saga University, Japan. He received PhD at Kyushu University, Japan. He is a member of the Architectural Institute of Japan (AIJ), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). His research interests include indoor thermal environment and heating, ventilating and Air-Conditioning (HVAC).