A Basic Evaluation of Non-Uniform Radiant Fields Using Computational Thermal Manikin

Ikumi Kishida[1], Koji Sakai[2], Hiroki Ono[3], Daiki Kobayashi[1]
[1]Graduate School of Science & Technology, Meiji University, Kanagawa, Japan
[2]School of Science & Technology, Meiji University, Kanagawa, Japan
[3]Central Research Institute of Electric Power Industry, Chiba, Japan

Abstract

It is important to predict thermal comfort, and several prediction methods were developed. One of the methods, Fanger's human thermoregulation model, is considered not to be proper to apply to all circumstances, in particular, non-uniform or unsteady fields. In this study, aiming to analyse with simple model of computational thermal manikin in CFD simulating non-uniform radiant field, we compared analyses to experiments and confirmed the model validity. It indicates that Fanger's model is maybe applicable to not only uniform and steady fields but also non-uniform radiant fields like an area near a window in summer.

Introduction

Glass buildings with enough daylighting and a fine prospect often deteriorate indoor thermal environments, and the windows in those building are easy to make non-uniform radiant fields, which are uncomfortable for human body. Therefore, to design more thermally comfortable buildings, it is important to predict evaluation of thermal comfort in the design phase. Generally, computational thermal manikin is regarded as important as an effective method, so it is used for analysing in many cases: studies and business practices.

There are various human thermoregulation models for computational thermal manikin, for example, Kobayashi and Tanabe (2013) developed JOS-2 model as an applicable to non-uniform or unsteady environment. The validity of this model was confirmed, but this model is controlled complexly and its calculation load is heavy. On the other hand, Fanger (1970) developed a simple model, but this model is said not to be suitable to apply to non-uniform or unsteady environment because this model is controlled uniformly on every body parts. However, there are few papers to evaluate it in such circumstances.

In this paper, aiming to evaluate non-uniform radiant fields simply and easily, we confirmed the validity of evaluating thermal comfort in a room with window blinds by using Fanger's model. At first, we considered an experiment by Tanabe and Hasebe (1993). We compared the first analysis simulating it to this experiment and confirmed the validity of this model. Then, we conducted an experiment under a non-uniform radiant field with window blinds in summer, and we compared the second analysis simulating our experiment

Table 1:Experiment conditions by Tanabe and Hasebe

Site	Climate chamber in Ochanomizu University
OT (=air temperature=MRT)	19.8℃ / 24.8℃ / 29.7℃
RH	Approx. 50%
Vel.	0.1m/s (still air)
Air Conditioning	Floor-supply displacement ventilation
Posture	Sitting
Cloth	Nude / Sweat / Normal
Manikin thermoregulation	$Ts = 36.4 - 0.054Qt$ (1) (Fanger's model)
Ts: skin temperature (℃)	Qt: sensible heat loss (W/m^2)

to our experiment. It turned out the model is maybe applicable to non-uniform radiant fields. Lastly, we analysed the first simulation by setting the wall facing human body higher temperature to grasp how non-uniform radiation affects human body. We confirmed how the distance of the window and the human body thermally affects the human body. All of these analyses were steady-state.

Validity under uniform and steady fields

Experiment by Tanabe and Hasebe

Tanabe and Hasebe conducted an experiment with a thermal manikin. The experiment was conducted in the climate chamber in Ochanomizu University in Japan. This chamber has a floor-supply displacement ventilation system and an air layer within the inner wall, which equalize mean radiant temperature (MRT) to the air temperature. The operative temperature (OT) was 19.8℃, 24.8℃, or 29.7℃ and air velocity was 0.1m/s. Clothing condition was nude, sweat, or normal. Measuring items were heat loss and skin temperature of the thermal manikin. The thermal manikin was thermally controlled by Fanger's model, the equation below.

$$Ts = 36.4 - 0.054Qt. \qquad (1)$$

Ts is a skin temperature, and Qt is a sensible heat loss. Table 1 shows the experiment conditions and the upper diagram of Figure 1 shows the experiment situation. The

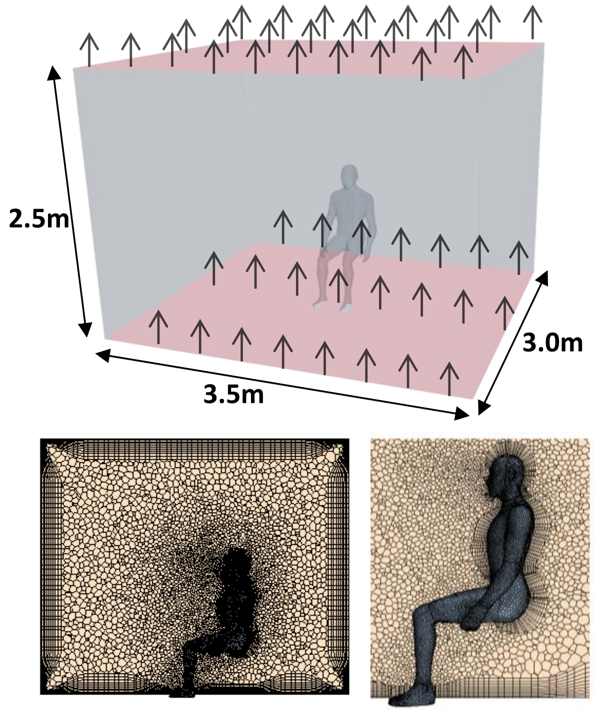

Figure 1: The first analysis region.

clothing thermal resistance of sweat was 1.27clo, and that of normal was 1.38clo. The thermal manikin wore a wig.

Analysis simulating the experiment by Tanabe and Hasebe: The first analysis

We simulated Tanabe's experiment using SST k-ω in a low-Re situation. The human body temperature was controlled by the same method as the experiment. Figure 1 shows the analysis region, and Table 2 shows the analysis conditions. Figure 2 shows the skin temperature results of weighted average in every body parts. We used the mesh data by Ito and Hotta (2006) as human body.

Although the heat loss from the waist was bigger than the experiment, the analysis results almost corresponded with the experimental results in each case. It shows that Fanger's model in CFD under uniform and steady environment is valid. Slightly, the analysis results were close to the experimental results when there was small difference of OT and core temperature of the human body. On sweat condition, there is difference between the analysis and the experimental results in left hand. It may be because they could not keep left-right symmetry in the experiment and the analysis kept symmetry.

Validity under non-uniform radiant fields

Experiment

We conducted a subjective experiment in seminor room in Meiji University in Japan from 1:00 to 6:00 PM 10th Sept, 2016 and 12th Sept, 2015. The chamber has a window with horizontal louvers on the west side. Figure 3 shows the installation position of the louvers. There are two cassettes of air conditioner and it was set 27℃ on 10th Sept, 2016. On 12th Sept, 2015, the air

Table 2: The first analysis conditions

CFD code	STAR-CCM+
Turbulence model	SST k-ω
Algorithm	SIMPLE
Scheme	Second-order accurate upwind
Mesh	Un-structured (Polyhedral)
Air conditioning	Floor-supply displacement (0.1m/s)
Human thermoregulation model	Fanger's model
Clothing	Nude / Sweat (OT=24.8℃)
OT	19.8℃ / 24.8℃ / 29.7℃

Clothing thermal resistances (m^2K/W)					
Parts	**Hair**	**Face・Hand**	**Chest**	**Back**	**Waist**
Nude	0.364	0.054	0.054	0.054	0.054
Sweat	0.364	0.054	0.209	0.209	0.209
Parts	**Upper arm**	**Lower arm**	**Upper leg**	**Lower leg**	**Foot**
Nude	0.054	0.054	0.054	0.054	0.054
Sweat	0.17	0.147	0.132	0.132	0.085

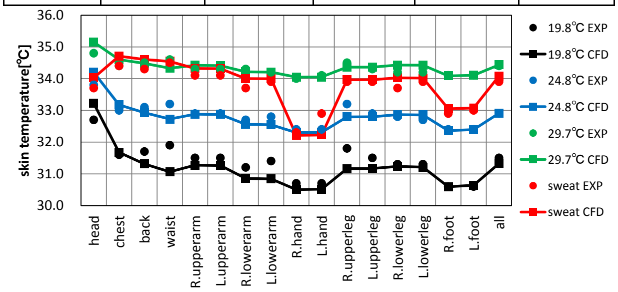

Figure 2: The first analysis results.

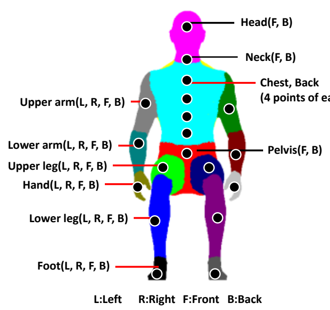

Figure 3: Louvers position. Figure 4: Measuring points.

conditioner was turned off. The human subject wore a gray short-sleeve T-shirt and a gray knee-length sweat pants. He was seated on a chair from 3:00 to 5:00 PM. We measured the temperatures of the air and his skin. To make the human subject be thermally neutral, he kept quiet in another room, which was kept 26℃, from2:30 to 3:00 PM. Figure 4 shows measuring points of the human subject.

On both days, the upper part of the blinds were heated, and the heat transferred to the air. It made heat pocket

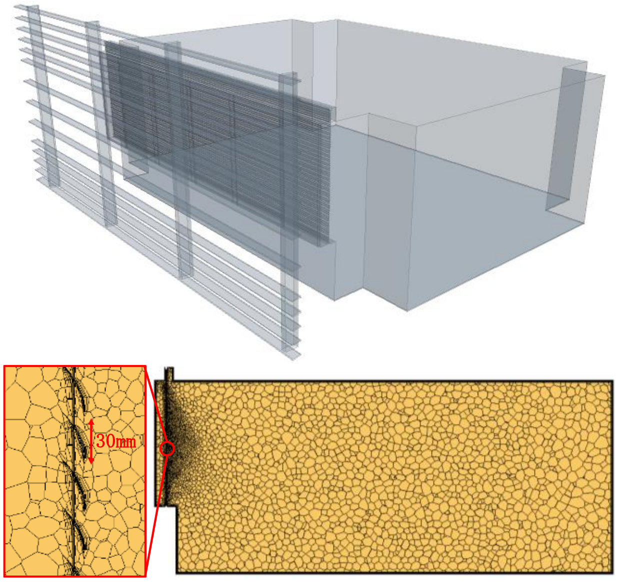

Figure 5: The environment analysis region.

between the window glasses and the blinds. Farthermore,the heated air was leaked into the room. On 12th Sept, 2015, the air was heated all over the chamber. In contrast, on 10th Sept. 2016, the air remained almost unchanged without the part between the blinds and the cassete owing to the air conditioner. The human skin facing the blinds was hotter than other parts of the skin. The difference was smaller on 10th Sept, 2016 than on 12th Sept, 2015.

Analysis simulating environment of our experiment

To reproduce the environment of the laboratory, we made louvers and blinds model in detail, and simulated without human body and air conditioner. Figure 5 shows the analysis region, Table 3 shows the analysis conditions, Figure 6 shows the air results in the chamber, and Figure 7 shows the profile of the air temperature results.

The analysis reproduced a heat pocket, and T=35℃ and v=0.2m/s breeze caused by a heat transfer from gaps of the top side of the blinds into the chamber. There was thermal stratification in the chamber in analysis, and there was the same phenomenon in the experimental results. Considering the profile, analysis results shows good agreement with the experimental results in air temperatures. This simulation is considered to reproduce the environment of the laboratory.

Analysis simulating human body of our experiment: The second analysis

We analysed our experiment using the same turbulence model and human thermoregulation model as the first analysis, simulating the experiment by Tanabe and Hasebe. Figure 8 shows the analysis region and Table 4 shows the analysis conditions. Taking into account the results of the analysis simulating environment of our experiment, we simplified the blind model and put it in this analysis. The simple blind model was consisted of top, bottom, and body. Top supplied T=35℃ and

Table 3: The environment analysis conditions

CFD code	STAR-CCM+
Turbulence model	Realizable k-ε 2 layer
Algorithm	SIMPLE
Scheme	Second-order accurate upwind
Mesh	Unstructured grid (Polyhedral)
Solar radiation	317W/m^2 (Direct), 79W/m^2 (Sky)

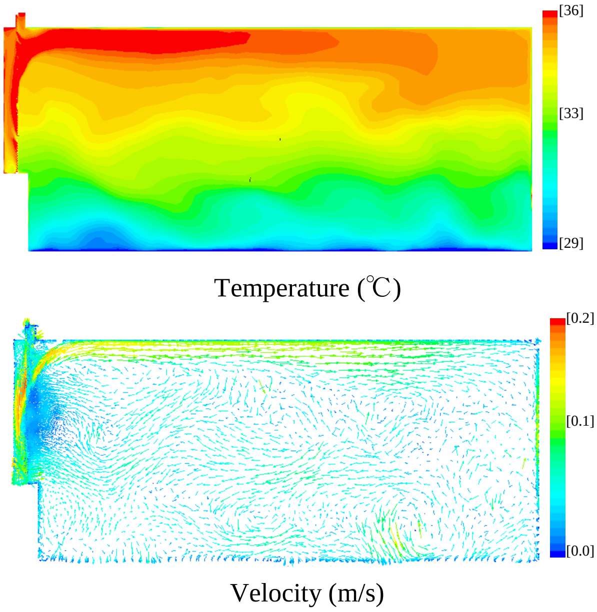

Figure 6: The environment analysis results.

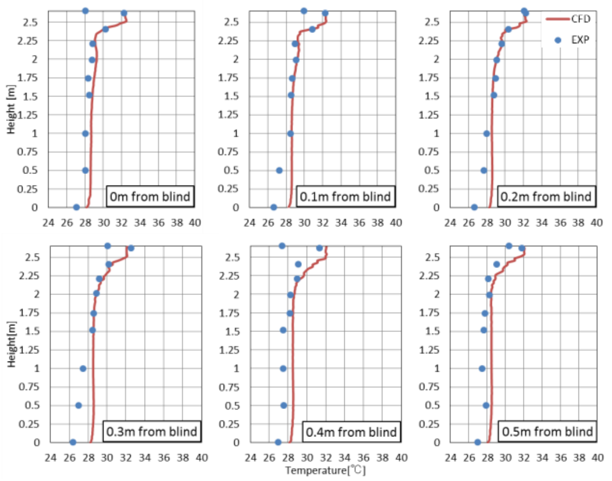

Figure 7: The profile of the environment analysis results.

v=0.2m/s velocity, and bottom was pressure outlet. A boundary setting of body is wall. Moreover, to lighten the calculation load, we set the temperatures of the walls be experimental results. Figure 9 shows the air results in the chamber, Figure 10 shows the skin temperature results of weighted average in every body parts, and Figure 11 shows the distribution of the human surface temperature results.

Regarding to Figure 9, This analysis is considered to reproduce the heat transfer from the gaps of the blind. We think that the conditioning air offseted thermal updraft and this is why the updraft was little.

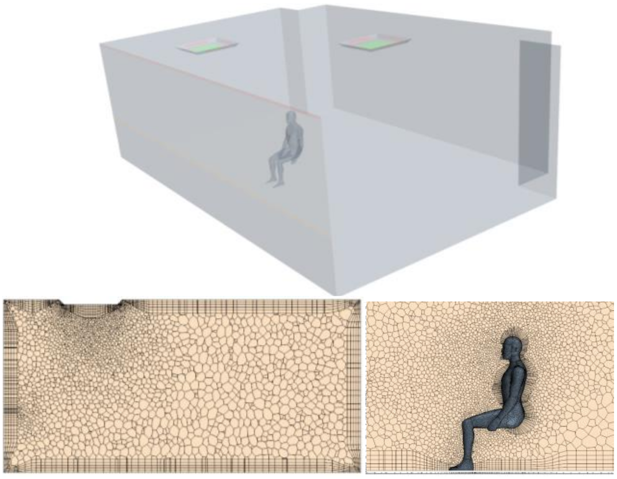

Figure 8: The second analysis region.

Table 4: The second analysis conditions

CFD code	STAR-CCM+
Turbulent model	SST k-ω
Algorithm	SIMPLE
Scheme	Second-order accurate upwind
Mesh	Unstructured grid (polyhedral)
Air conditioning	Cassette (4.4m/s, 24℃)
Human thermoregulation model	Fanger's model
Cloth	0.5clo
Breeze from the blind model	0.2m/s, 35℃

With regard to human skin temperature, Figure 10, though the results in the head, trunk and average were almost agreed, the analysis results in the limb did not agree with the experimental results. It possibly indicates that Fanger's model cound not reproduce human skin temperature well in a non-uniform radiant fields. However, non-clothed parts, where the analysis results were higher than the experimental results, were hotter than clothed parts in the experiment. It is unnatural. We estimate this is why the two results disagreed. We regard these errors came from experimental or individual differences.

Regarding to Figure 11, the analysis temperature results captured a rough characteristic in the human surface including the clothing. It shows the analysis results almost agreed with the experimental results in the human body.

In the chest and the back, the analysis results were slightly higher than the experimental results in Figure 10. It was probably because the clothing used for experiment was too thin to make an air layer which plays a big role as thermal resistance, and the air between the T-shirt and the skin was not remain and went through. It maybe higher accuracy when this model is used with thicker clothing.

Considering these results, the Fanger's model has

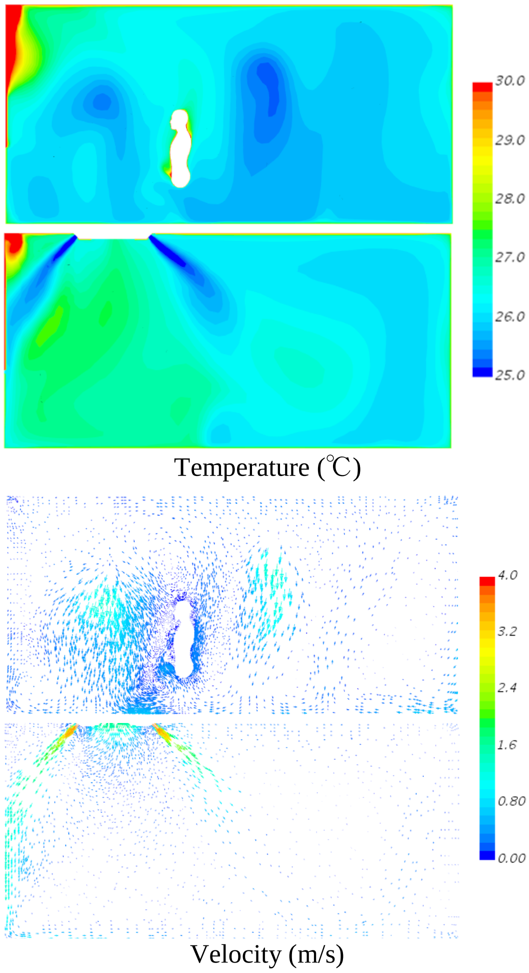

Figure 9: The second analysis results of the air.

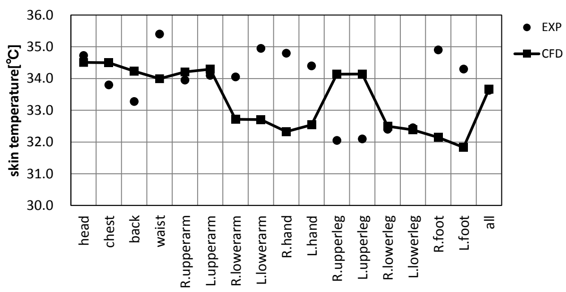

Figure 10: The second analysis results of the skin temperature averaged in each part.

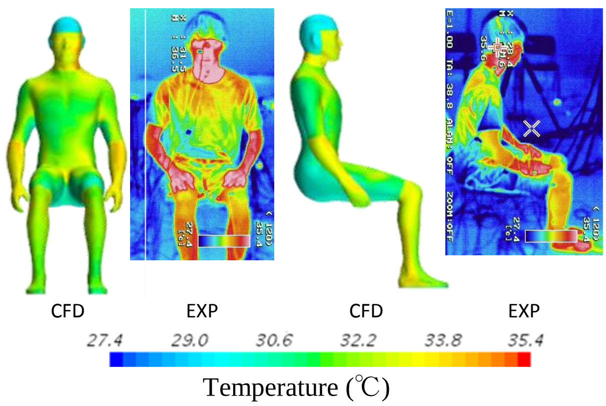

Figure 11: The second analysis results of the human surface temperature distribution.

potential to apply to non-uniform radiant fields like this situation: the environment around the blind or the window in summer.

Effects of non-uniform radiant fields on human body: The third analysis

To grasp the effect of non-uniform radiant fields on human body, we analysed the Tanabe's experiment simulation by setting the temperature of the wall facing the human body to 40℃, which is equivalent to blind temperature in summer sunny day, and simulated changing the distance of the wall and the human body. Figure 12 shows the skin temperature of a point of each part, and Figure 13 shows the distribution of the skin temperature. Paying attention to the skin facing the heated wall, in Figure 12, the skin temperature with the wall being 40℃ was higher 2℃ than that with the wall being 20℃. Moreover, the shorter the distance of the wall and the human body was, the hotter the skin was, and the difference was more than 1℃. These results show the blind effect on the human body thermally in summer, and it is greatly affected by the distance of the blind and the human body. With regard to Figure 13, the shorter the distance was, the more ununiformly the skin temperature was.

Conclusion

In this paper, aiming to evaluate non-uniform radiant fields simply and easily, we analysed several simulations by using Fanger's model. Firstly, comparing simulation results to the experimental results by Tanabe and Hasebe, we confirmed the validity of this model under an uniform and steady circumstance. Then, we conducted a subjective experiment around the window blind in summer and compared an analysis simulating it and the experiment. Consequently, we found possibility to apply this model to non-uniform radiant fields. Lastly, we grasped how non-uniformed radiation affects human body by the third analysis. We analysed the first experiment simulation with setting the wall facing the human body high temperature and simulating changing the distance of the heated wall and the human body.

There were experimental or individual errors in our experiment, so we are going to examine farther accurately. Then, we are going to analyse in greater detail to grasp what condition affects human body mostly and how the condition affects it.

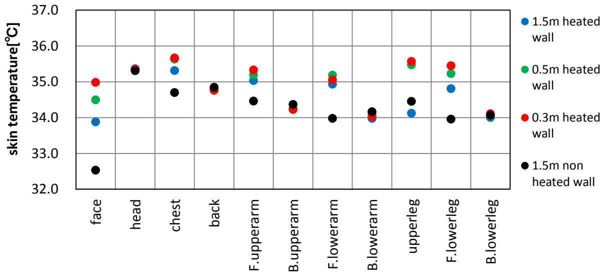

Figure 12: The third analysis results of the skin temperature.

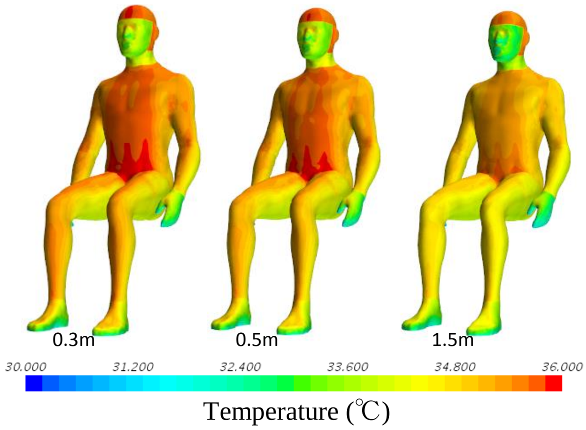

Figure 13: The third analysis results of the skin temperature distribution.

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