Evaluating Thermal Environments of Air Conditioned Rooms based on Equivalent Temperature by using a Thermal Manikin Simulation

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Abstract
As one of the primary controlling methods of energy saving for residential air conditioner (RAC), human-detecting sensors are applied. These sensors are widely applied to products and control the air flow direction to the occupants. This method can make the lower temperature about 2~3 ℃ around the human body than other area in the room and the increased speed of direct air flow, the occupants feel cooler than that of low speed which is attributed to the forced convection. This research is focusing on evaluating thermal environments of air conditioned rooms based on equivalent temperature and identifying the effect of this controlling method. Equivalent temperature $T_{eq}$ is expressed by one temperature value so, thermal environments can be more easily understood without many relevant factors. Equivalent temperature of thermal manikin simulation is calculated by the Realizable $k$-$\epsilon$ turbulence model with SIMPLE algorithm and second-order upwind convection differencing scheme and separated by 16 body segments to analyze the thermal effects on each body part. And confirm the correlation of equivalent temperature on manikin with wind direction and air speed difference of air conditioner’s outlet by controlling the boundary conditions in the simulation.

Keywords - computational fluid dynamics; equivalent temperature; thermal manikin; residential air conditioner; heat transfer coefficient;

1. Introduction

Thermal environment is evaluated by measuring some physical values like air temperature, radiant temperature, air velocity, humidity and so on. These values are useful to estimate human sensation. Thermal sensation is closely related to the heat exchange between human and their environments [1]. But unlike the uniform conditions of climate chamber, the indoor environment often occur vertical air temperature differences, local temperature differences, local air flows and non-uniform radiation. Therefore, predicting the thermal sensation in this condition is difficult and inaccurate.
For this reason, thermal manikins are developed and widely used for evaluating the local body heat fluxes in complex environments [2]. These manikins can directly measure the heat exchange between individual body segments and actual environments.

The equivalent temperature was first announced by Dufton [3] and developed by Madsen [4] and Nilsson [5]. Equivalent temperature is expressed by one value, so it is useful to identify the thermal environment of various climate conditions. It is defined as the temperature of a homogenous space, with mean radiant temperature equal to air temperature and zero air velocity, in which a person exchanges the same heat loss by convection and radiation as in the actual conditions under assessment [6].

The purpose of this paper is to report the correlation of equivalent temperature on the 16 body segments of manikin with changes of air flow directions and temperature differences of residential air conditioner’s outlet. And to evaluate the environments based on equivalent temperature of the thermal manikin due to air flow direction and air speed with computational fluid dynamics simulation. For the indoor environment prediction, the $\kappa$-$\epsilon$ turbulence model was used for many years to show the acceptable results in various cases [7-10].

2. Methods

2.1 Equivalent temperature

Calculating the equivalent temperature $t_{eq}$ of real environment, the total heat transfer coefficient $h_t$ should be derived from a uniform standard environment. The total heat transfer $q_t$ between skin temperature $t_s$ and environments can be expressed by convective $h_c$ and radiative $h_r$ heat transfer coefficient.

$$ q_t = h_r(t_s - t_r) + h_c(t_s - t_a) $$

(1)

The mean radiant temperature $t_r$ and ambient temperature $t_a$ is equal in a standard environment.

$$ q_t = h_t(t_s - t_o) $$

(2)

In this paper, the total heat transfer coefficient is calculated at 24°C and 0.05m/s wind velocity as a standard environment. Then in a real environment under the same heat transfer and same posture of manikin, equivalent temperature is expressed as

$$ t_{eq} = t_{s,r} - \frac{q_t}{h_t} $$

(3)

In a real condition, each part of the body’s skin temperature $t_{s,r}$ is calculated by simulation. The thermal manikin simulation is implemented with seated posture and controlled a constant heat flux (1 MET = 58 $W/m^2$, resting metabolic rate).
2.2 Thermal manikin simulation

To obtain the heat transfer coefficients of a thermal manikin in a standard environment, calculation should be done in specific conditions. The boundary conditions of a standard environment are indicated in Table 2. The emissivity of human body is supposed 0.95 and the thermal manikin model in Fig. 1 is composed of about 81,000 surface meshes and covered with 10 prism layers. The value of $y^+$ is lower than 1 all over the surface of the manikin, and calculated with two layer all $y^+$ wall treatment which is a hybrid approach that seeks to recover the behaviors of the other two wall treatments in the limit of fine or coarse meshes. Tetrahedral volume mesh areas are separated by structured and unstructured grid regions. The structured mesh is very flexible, and the unstructured mesh has higher quality and can reduce the total number of mesh cells. The unstructured mesh is applied around the body because the thermal manikin model is a complicated shape. And the other area has been applied by structured mesh method for better results and reducing calculation time. The Navier-Stokes equations are solved by using the Realizable $\kappa$-$\varepsilon$ turbulence model which performs better than other $\kappa$-$\varepsilon$ turbulence models [11].

![Surface mesh on thermal manikin model](image1)

![Section view of mesh and prism layer](image2)

**Table 1  Numerical methods**

<table>
<thead>
<tr>
<th>Turbulence model</th>
<th>Realizable $\kappa$-$\varepsilon$ turbulence model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical schemes</td>
<td>upwind second-order difference; SIMPLE algorithm</td>
</tr>
</tbody>
</table>

**Table 2  Boundary conditions**

<table>
<thead>
<tr>
<th>Room size</th>
<th>width $\times$ depth $\times$ height = 3.5m $\times$ 3.0m $\times$ 2.5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air supply</td>
<td>velocity inlet ($U_s = 0.05 \text{ m/s}$); $T_s = 24^\circ\text{C}$</td>
</tr>
<tr>
<td>Air exhaust</td>
<td>pressure outlet ($P_e = 0$)</td>
</tr>
<tr>
<td>Room wall</td>
<td>temperature ($T_{\text{w}} = 24^\circ\text{C}$)</td>
</tr>
<tr>
<td>Manikin body</td>
<td>heat flux ($h_t = 58 \text{ W/m}^2$); emissivity=0.95</td>
</tr>
</tbody>
</table>
2.3 Heat transfer coefficients in a standard environment

The difference in environment temperature and manikin surface temperature slightly decreases radiative heat transfer coefficients $h_r$ but increases convective heat transfer coefficients [12]. Heat transfer between body and environment is mainly divided into radiative and convective heat transfer. The total heat transfer coefficients $h_t$ which are composed of these values are not affected by the environment temperature [1]. But, when the posture (e.g. standing and sitting) is changed, the total heat transfer coefficients are also altered due to the changes of radiative heat transfer area and air flows. Therefore, the posture of manikin should be commented when calculating the equivalent temperature. In this paper, equivalent temperature is calculated with sitting posture manikin, and coefficients are calculated at 24°C uniform climate as a standard environment. Before evaluating a real indoor environment by equivalent temperature using a thermal manikin simulation, these results are verified with the previous thermal manikin test, studied by de Dear [13] and represented in Fig.4 (The data is average of anatomical segments of left and right body parts). The results of whole body convective and radiative heat transfer coefficients are 3.35 W/m²·K and 4.91 W/m²·K. But the radiative heat transfer coefficients of head and chest are 1.55 W/m²·K different in test result and simulation data because the thermal manikin’s posture is leaning back 10 degrees for relaxation. And the simulation results show that the heat transfer coefficients of hand and foot parts are larger than others because the convection heat transfer is higher than the other parts.

![Fig. 3 The 16 body segments modeling of thermal manikin.](image)

![Fig. 4 Radiative and convective coefficients of each parts in a standard environment.](image)
2.4 Air conditioned rooms

The simulation is done in a large indoor model to avoid the return air and identify the effects of direct air flows of the residential air conditioner. An examination by P.V. Nielsen shows that the average penetration $l_{re}/H$ is 4.0 to 4.5 for $h/H=0.056$. The penetration is independent of Reynolds numbers in the range examined from 2400 to 9300 [14]. Air flow speed becomes slow according to increase in distance from the inlet openings and the air speed rapidly decreases as it passed the penetration length. Therefore, the dimensionless ratio $L/H$ is considered 6 to reduce the effects of return air flows. The geometry of indoor air is described in Fig. 5. In Table 4, the Reynolds number is same as $Re=5740$ based on the inlet length $h$ for the 1 to 4 simulation cases.

![Fig. 5 Definition of indoor space geometry with coordinates and residential air conditioner.](image)

Table 3  Boundary conditions of real environment.

<table>
<thead>
<tr>
<th>Room size</th>
<th>$H \times L \times W = 2.5m \times 15.0m \times 11.75m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W/H$</td>
<td>$4.7$, $L/H = 6.0$</td>
</tr>
<tr>
<td>Air supply</td>
<td>velocity inlet ($U_s = 5.0 \text{ m/s}$), $T_s = 28^\circ\text{C}$, $h_s/H = 0.032$, $w_s/W = 0.063$</td>
</tr>
<tr>
<td>Air exhaust</td>
<td>pressure outlet ($P_e = 0$), $h_e/H = 0.068$, $w_e/W = 0.063$</td>
</tr>
<tr>
<td>Room wall</td>
<td>temperature ($T_w = 28^\circ\text{C}$)</td>
</tr>
<tr>
<td>Manikin body</td>
<td>heat flux ($h_t = 58 \text{ W/m}^2$), emissivity=0.95, $L_m/L = 0.66$</td>
</tr>
</tbody>
</table>

And to confirm the correlation of equivalent temperature on manikin with wind direction and air flow rate of residential air conditioner (RAC), control the air flow angle each 10 degrees of 0 to -30 and change the supply speed $U_s$ in case 5 and 6. Then the equivalent temperature can be calculated using the skin temperature of the thermal manikin for each of the following cases and the total heat transfer coefficients in a standard environment.

Table 4  Additional boundary conditions for each simulation case.

<table>
<thead>
<tr>
<th>Simulation cases</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air supply, $U_s$ [m/s]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Air flow angle, [degree]</td>
<td>0</td>
<td>-10</td>
<td>-20</td>
<td>-30</td>
<td>-20</td>
<td>-20</td>
</tr>
<tr>
<td>Air flow temperature, $T_s$ [°C]</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Room wall temperature, $[T_w]$</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>
3. Results

3.1 Effects of Air flow direction

The environment temperature is constant at 28°C in all cases. Therefore, the effect of radiative heat transfer remains the same and the convective heat transfer is the major cause of the differences. The indirect air flow effect in case 1 shows that the equivalent temperature of whole body decreases by 0.6°C and the segments of the head, chest and lower leg are affected than other parts. The air flow direction of case 2 is toward above the head, case 3 is the chest and case 4 is the pelvis. As the air jet reaches the body, it flows forward toward the head and downward to the thigh and the leg around the surface of the body in case 3 and 4.

![Fig. 6](image1) Distribution of $\frac{U}{U_s}$ on air flow direction changes in a section view of room center and body temperature on the surface of the manikin ($U_s=5\text{m/s}$).

![Fig. 7](image2) The velocity $\frac{U}{U_s}$ scale.

![Fig. 8](image3) Body temperature scale (°C).

The body temperature results also correspond with air flow directions in each case. The direct air flow method (case 2, 3 and 4) decreases the equivalent temperature of whole body about 0.7~3.6°C in comparison with the indirect method in case 1. The parts of the hands, lower legs and feet are not affected much by the flow method in case 3. And the most effective cooling condition is case 4 in Fig. 9.
3.2 Effects of Air flow rate

The equivalent temperatures of the whole body in case 3, 4 and 5 are 23.9, 25.6 and 28.0°C, respectively.

Fig. 9 The average equivalent temperature of each 16 segments on the thermal manikin body by the changes of air flow angle (L=left, R=right).

Fig. 10 Distribution of $\frac{U}{U_s}$ on air flow rate changes in a section view of room center and body temperature on the surface of the manikin ($U_s=5$ m/s in case 3, $U_s=3$ m/s in case 5, $U_s=1$ m/s in case 6).

The equivalent temperatures of the whole body in case 3, 4 and 5 are 23.9, 25.6 and 28.0°C, respectively.
27.0°C. As the air speed increases, each part of the body temperature is decreased because of the forced convective heat transfer. The air flow direction of these cases is toward the chest so the equivalent temperature of this part of the body is the lowest. And the temperature of the hands, thighs, lower legs and feet in case 6 are almost 28°C. That means there is no forced convective heat transfer on that parts because the velocity of supply is too low. Moreover, the equivalent temperature of the lower legs and feet in case 3 are 26.9 and 27.6°C but that parts of the body in case 5 and 6 are higher than indirect air flow in case 1.

![Graph showing the average equivalent temperature of each 16 segments on the thermal manikin body by the changes of air flow rate (L=left, R=right).]

**4. Discussion**

![Patterns of the streamline ($\frac{U}{U_s}$) of case 3]

The air flow direction of the case 3 is toward the chest of the body which is known
by the patterns of the streamline in Fig. 14. As the air flow touches the body it flows upward toward the head and downward to the thigh through the surface of the body. But the air flow is not moving around the lower legs and feet, so the equivalent temperatures are as same height as the indirect air flow in case 1.

5. Conclusions

This research identifies the effects of residential air conditioner’s controlling method to find more effective cooling ways with handling the air flow direction and the flow rate. The effect of the indirect air flow shows that the equivalent temperature of whole body decrease by 0.6℃ and the maximum of direct air flow was 4.1℃. And the equivalent temperature using a thermal manikin simulation was very useful to identify how much the parts of the body were influenced by the thermal environment.

References