Investigation on a method incorporating inhomogeneous environmental conditions into CFD analysis of outdoor thermal environment coupled with multifractional human thermoregulation model

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Abstract

In this paper, a new method that incorporates inhomogeneous environmental conditions into computational fluid dynamics (CFD) analysis coupled with multifractional human thermoregulation model has been described. This method can be used to investigate the distributions of absorbed solar and longwave radiations from around a human body in outdoor space; it is also used to evaluate the effects of airflow on heat transfer coefficient and clothing insulation on each segment of the human body. In future, we intend to evaluate the effects of applying this new method for carrying out practical analysis.

Key words: CFD analysis, Multifractional human thermoregulation model, Inhomogeneity of environmental condition

1. INTRODUCTION

In recent years, degradation of the outdoor thermal environment during the summer season in a city area of Japan has caused environmental problems including an increase in the risk of heatstroke. In order to estimate and evaluate the effects of countermeasures against environmental problems, the authors have proposed a new coupled simulation method based on computational fluid dynamics (CFD) for estimating thermal comfort in an outdoor space [1].

At present, the problem associated with a numerical analysis method is the incorporation of unsteady and inhomogeneous factors, which include physical environmental factors (instantaneous changes and local distributions of environmental conditions such as solar radiation and wind) and pedestrian’s activity factors (walking speed, rest time, activity level, and body posture), for the evaluation of outdoor thermal comfort.

In this paper, a new method that incorporates inhomogeneous environmental conditions into CFD analysis coupled with a multifractional human thermoregulation model has been described. This method can be used to investigate the distributions of absorbed solar and longwave radiations from around a human body in outdoor space; it can also be used to evaluate the effects of airflow on heat transfer coefficient and clothing insulation on each segment of the human body.

2. OUTLINE AND PROBLEM ASSOCIATED WITH NUMERICAL ANALYSIS METHOD

2.1. Outline of method for evaluating outdoor thermal environment

Figure 1 shows the outline of a computational method used for analysing the outdoor thermal environment [1]. Boundary conditions for the CFD analysis coupled with convection and radiation are determined using the input data, as shown in Fig. 1, i.e. meteorological and geometrical data and surface conditions. Spatial distributions of wind velocity, air temperature, radiation, and humidity are estimated using the CFD analysis imposed boundary conditions determined using the input data. Outdoor thermal comfort including unsteady and inhomogeneous factors is evaluated using the multifractional human thermoregulation model using the results of the CFD analysis.

2.2. Problems associated with imposing inhomogeneous conditions on thermal environment to multifractional human thermoregulation model

The human thermoregulation model enables us to predict a thermal physiological mechanism, which regulates heat production and heat loss through vasodilation, vasoconstriction, shivering, and sweating, in order to maintain the...
core temperature within normal limits. Recently, Tanabe et al. have developed three multifractional human thermoregulation models known as ‘65NM’, ‘COM’, and ‘JOS’ [3–5]. The objective of this study is to incorporate these thermoregulation models into the abovementioned method in order to evaluate various types of environmental designs in outdoor space such as relaxation space in a park and pedestrian space on a street. For this purpose, it is necessary to provide environmental conditions together with a relationship between disposition and direction of the thermoregulation model in a computational domain. The method for incorporating inhomogeneous environmental conditions of radiation and airflow for a pedestrian is described in the following section or later.

3. Method for analyzing inhomogeneous radiation in outdoor space

It is necessary to analyse incident solar and longwave radiations from all the directions around a pedestrian in order to include the effects of inhomogeneity on radiations. The method described in this paper is used to calculate the incident radiations on each segment of the thermoregulation model through the surface of a virtual sphere centring around the model.

3.1. Virtual spheres centring around a human body

Spatial distributions of solar and longwave radiations in the computational domain are calculated on each mesh for the CFD analysis of the outdoor thermal environment. On each mesh, we consider that a virtual sphere centres around a human body, whose surface is divided into 266 elements with 15° in both azimuth and altitude, as shown in Fig.2. Solar and longwave radiations and plane radiant temperature (PRT) on each surface element are calculated using the following method that is based on the Monte Carlo technique used for radiant analysis.

3.2. Calculations of configuration factor and irradiation ratio for radiant analysis

This section describes a method used for calculating the configuration factor and irradiation ratio on each surface element comprising the virtual sphere surface. For further information on the method based on the Monte Carlo method used for analysing radiation within the outdoor space, refer to the paper written by Omori et al. [6].

(1) Determination of dispositions of virtual sphere and the emitting point of radiant particle

The configuration factor determined by carrying out radiant analysis using the abovementioned method is derived from the proportion of radiant particles that reach each surface element, such as sky area, building area, and ground surface, to all radiant particles emitted from the surface element comprising the virtual sphere surface. Therefore, it is necessary to determine the emitted location of radiant particles. The central point of the virtual sphere, O(x, y, z), is represented by Equation (1) as follows:

\[ x = L_x(I - 1) + R_x L_x(I), \quad y = L_y(J - 1) + R_y L_y(J) \]  

where \( L_x(I - 1) \) is the distance between the origin and the rearward corner of the cell number \((I - 1)\) along the x direction, and \( L_y(J - 1) \) is the distance between the origin and the rearward corner of the mesh number \((J - 1)\) along the y direction. \( L_x(I) \) and \( L_y(J) \) denote the cell widths along the x and y directions, respectively. \( R_x \) and \( R_y \) are uniform random numbers from 0 to 1. Point z is set at a height of approximately 1.0 m.

The emitted point \( P \) of the radiant particle is randomly determined within the surface element \( i \) comprising the virtual sphere surface, as shown in Fig.3.

(2) Determination of direction along which the radiant particles are emitted

The method for determining the direction along which radiant particles are emitted differs from that used to calculate the configuration factor and that used to calculate the irradiation ratio.

(a) Condition under which the configuration factor is calculated

A large number of radiant particles are emitted from \( P \) along the direction determined by Lambert’s cosine law. The unit vector of a particle \( f \) is defined using equations 2, 3, and 4 as follows:

\[ f = (\sin \eta \cdot \cos \theta) e_1 + (\sin \eta \cdot \cos \theta) e_1 + \cos \eta e_3 \]  
\[ \eta = \sin^{-1}(R_y^{0.5}) \]  
\[ \theta = 2\pi R_x \]  

where \( \eta \) is the zenith angle, and \( \theta \) is the azimuth angle. \( R_x \) and \( R_y \) are uniform random numbers from 0 to 1. \( e \) is also the orthonormal basis.

However, the unit vector is not based on the standard orthonormal basis. Therefore, coordinate conversion is carried out in order to match the vector to the basis using equation 5 as follows:

\[ f' = T f \]  

\( T \) denotes coordinate conversion matrix from the orthonormal basis to the standard orthonormal basis.
(b) Condition under which the irradiation ratio is calculated
A large number of particles are emitted from the surface element \( i \) comprising the sphere surface toward the sun, in order to determine whether or not the sun’s rays reach the surface element. The direction of the unit vector toward the sun is determined by the solar altitude and azimuth. When equation 6 is satisfied, the sun’s rays reach \( i \) when there are no obstacles around the human model.
\[
e \cdot n = \cos \theta^* > 0
\]  
(6)

(3) Calculation of configuration factor and irradiation ratio
(a) Configuration factor
A particle that is emitted from \( i \) along the direction determined by Lambert’s cosine law is absorbed by a surface element in the computational domain, such as ground, building surface, and sky area. The configuration factor viewed from \( i \) to another surface element \( j \), \( F_{ij} \), and that to sky, \( F_{sky} \), are defined using equations 7 and 8, respectively, such that
\[
F_{ij} = N_{ij}/N_{total}
\]  
(7)
\[
F_{sky} = \sum_{j} N_{ij}/N_{total}
\]  
(8)

\( N_{total} \) denotes the total number of particles emitted from \( i \), and \( N_{ij} \) denotes the number of particles reaching \( j \) from \( i \). \( n_{sky} \) is the total number of surface elements comprising the sky area in the computational domain.

(b) Irradiation ratio
It is confirmed that the sun’s ray reaches \( i \) when a particle that emitted from \( i \) in the manner described in section 3.3(2)(b) reaches the sky area. This confirmation repeats a large number of times by randomly changing the emitting point within \( i \). Then, the irradiation ratio is calculated using equation 9 as follows:
\[
\gamma_i = N_i/N_{total}
\]  
(9)

where \( N_i \) is the number of particles reaching the sky area from \( i \).

3.3. Calculation of plane radiant temperature and solar irradiation
Plane radiant temperature on each surface element \( i \) comprising the virtual sphere surface, \( T_{prt,i} \), is calculated using equation 10 as follows:
\[
A_i \sigma T_{prt,i}^4 = \sum_{j=1}^{n} A_j B_{ij} \sigma T_{j}^4
\]  
(10)
\[
B_j = F_j
\]  
(11)

where \( A_i \) is the area of \( i \), \( \sigma \) is the Stephan-Boltzmann constant, \( B_{ij} \) is Gebhart’s absorption factor for longwave radiation, and \( T_j \) is the absolute temperature of \( j \) in the computational domain. In the equation 10, \( B_j \) is assumed to be equal to \( F_j \), as shown in equation 11, since the inter-reflection of longwave radiation is negligible.

On the other hand, solar radiation reaching \( i, S_i \), is calculated using equations 12, 13, 14, 15, and 16 as follows:
\[
A_i S_i = A_i S_{di} + \sum_{j=1}^{n} F_{ij} A_j S_{rij}
\]  
(12)
\[
S_{di} = \alpha_i (E_{di} + E_{si})
\]  
(13)
\[
S_{ri} = (1-\alpha_i) (E_{di} + E_{si})
\]  
(14)
\[
E_{di} = A_i \gamma_i / N \cos \theta^*
\]  
(15)
\[
E_{si} = A_i F_{test} / N_{test}
\]  
(16)

\( S_{di} \) denotes the direct and diffuse solar radiations directly absorbed on \( i \). \( S_{ri} \) denotes the radiation reflected on \( i \); therefore the second term on the right-hand side of equation 12 represents the solar radiation reaching \( i \) after the occurrence of the first reflection at a certain surface element \( j \).

3.4. Solar and longwave radiations, MRT in each segment of the thermoregulation model
Absorbed solar and longwave radiations, \( S_{seg} \) and \( R_{seg} \), and the mean radiant temperature (MRT), \( T_{seg} \), in each segment of the thermoregulation model are calculated using equations 17, 18, and 19 as follows:
\[
R_{seg} = \left( \sum_{j=1}^{n} \sigma T_{prt,j}^4 \right) / \sum_{j=1}^{n} f_j
\]  
(17)
\[
T_{seg} = R_{seg} / \sigma
\]  
(18)
\[
S_{seg} = \left( \sum_{j=1}^{n} (1-\alpha_{seg,j}) S_j \right) / \sum_{j=1}^{n} f_j
\]  
(19)
where \( f_p \) is the projected area factor between each segment of the model and \( i \) comprising the virtual sphere surface. \( f_p \) was measured by Oguro [7]. As an example, \( f_p \) on whole body is also shown in Fig. 4. Associating the disposition and direction of the virtual sphere centring the human thermoregulation model with the projected area factor enables us to consider the inhomogeneous condition including the effect of a pedestrian’s direction on a radiant environment.

4. Method for including inhomogeneous effect of air flow on thermal environment

The inhomogeneity of airflow affects convective heat transfer coefficients and clothing insulations on each segment of the human thermoregulation model.

The convective heat transfer coefficient on each segment of the thermoregulation model includes a relationship between the direction of pedestrian and that of air flow, as evaluated either upwind or downstream. The coefficient \( h_c \) is determined using equation 20 as follows:

\[
h_c = a (v)^b \tag{20}
\]

where \( v \) is the airflow, \( a \) and \( b \) are constants on each segment. These constants were determined by the results of Oguro’s measurement [9]. As an example, Table 1 summarises these constants for a standing pedestrian facing upwind.

Clothing insulations on each segment vary with the thickness of the air layer between the clothing and the skin. The relationship between the pedestrian’s facing direction and the air flow direction also affects the distributions of thickness of the air layer. Therefore, we use the following equation that includes the effect of the relationship on the clothing insulation on each segment such that

\[
l_p = a \ln(v) + b \tag{21}
\]

Table 2 lists the values of constants \( a \) and \( b \) for a standing pedestrian.

5. Conclusion

In this paper, a method for incorporating inhomogeneous conditions of a thermal environment in outdoor space into the evaluation method coupled with CFD analysis and a multifractional human thermoregulation model has been described. We intends to show an example of the application of the new calculation method for the practical evaluation of an outdoor thermal environment in the summer season, as reported in the paper written by Kishi et al [9].

**References**


