Numerical Thermal Comfort Analysis Using Combined Computer-Simulated Person with Clothing and Multi-Node Thermoregulation Model

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Abstract. To analyse the interaction between the indoor environment and the human body, various computer-simulated persons (CSP) which can treat specific characteristics of the human body have been suggested as a “digital twin” for experimental thermal manikin. However, previous studies simplified or ignored the reproduction of the clothing function. In this study, a digital twin based on ANDI thermal manikin integrated with a multi-node thermoregulation model was developed in a naked and clothed state. In addition, to validate the prediction accuracy of numerical thermoregulatory analysis coupled with CSP-CFD simulation, the analysis results were compared with the experimental results using thermal manikin. The computational model was generated based on 3D scan data of ANDI manikin and clothe. Moreover, the user subroutine program for coupled simulation of CSP and Fiala thermoregulation model was developed and applied into CSP to estimate the heat generation by metabolism, heat transfer between layers and parts, and skin surface temperature. CFD analysis was performed using CSP under identical environmental condition with the experiment, by setting CFD boundary conditions based on the data measured in the experiment. Through a series of numerical analyses, we confirmed that the analysis result of CSP corresponds well with experimental results using thermal manikin.

1 Introduction

In urbanized society, people spend most of their time indoors, and indoor thermal environmental quality has a significant impact on human health and comfort. [1] With increased interest in Indoor environmental quality (IEQ), many experimental studies have been conducted targeting indoor environments and the surrounding environment of the human body. [2-4] However, there are many constraints such as time, scope, cost in the measurement-based experimental study. Against this background, many comprehensive evaluation methods for IEQ using numerical analysis such as Computational fluid dynamics (CFD) have been proposed. Also, the Computer-simulated person (CSP), which can treat specific characteristics of the human body, has been suggested as a “digital twin” for CFD simulation. In terms of the thermal environment, various CSPs have been developed and reported to analyse the interaction between the indoor environment and the human body. However, previous studies simplify or ignore clothing on CSP, heat and mass transfer around clothing. [5-7] Moreover, most of the previous studies have not reproduced narrow air gaps in the intermediate zone between clothing and the human body, which have an important role as a ventilation layer. Therefore, this study developed digital twin based on ANDI thermal manikin integrated with a multi-node thermoregulation model, which is in naked and clothed state. In addition, to validate the prediction accuracy of numerical thermoregulatory analysis coupled with CSP-CFD simulation, the analysis results were compared with the experimental results using thermal manikin.

2 Methodology

2.1 Application of multi-node thermoregulation model

This research focused on the ANDI thermal manikin as the target model. The ANDI thermal manikin functions by Fiala thermoregulation model which is an advanced, multi-node, and multi-segment thermoregulation model. [8] Skin temperature and thermal function of thermal manikin are controlled corresponding to the change of environmental conditions. This model incorporates two interacting systems of thermoregulation: the controlling, active system, and the controlled passive system. As shown in Fig 1, The body is divided into 15 parts, and typical body tissue layer construction, including bone, muscle, fat, and skin, were modeled in each part. Fiala model solves the governing equations for thermoregulation in the body. As shown in Eq. 1, the heat transfer mechanisms occurring in the body tissues have been formulated by Pennes in the so-called bioheat
Integrating the CSP model and CFD calculations and validation of the prediction accuracy of CSP are the main objectives of this study. Accordingly, different computing nodes obey these thermal equations, which considers heat conduction, blood circulation, and metabolism. Approximately 0.06 of skin wittedness was assumed in CSP for normal condition of latent heat loss with no regulatory sweating, as same as the experimental condition of thermal manikin. [10,11] To provide the skin surface boundary condition for CFD, this study considered actual physical properties of human body components, and a user subroutine program for ANSYS Fluent was used for coupled analysis of all governing equations in the Fiala model and CFD analysis [12].

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k \left( \frac{\partial^2 T}{\partial r^2} + \frac{\omega}{r} \frac{\partial T}{\partial r} \right) + q_m + \rho_b l w_{hi} c_{hi} (T_{pla} - T) = \rho c \frac{\partial T}{\partial t}
\]

2.2 Establishment of CSP’s geometry
To create a CSP based on the ANDI thermal manikin, a detailed 3D geometry was obtained from the thermal manikin using a high-performance 3D scanner (EinScan Pro 2X Plus by SHINING 3D). Fig. 2 shows the 3D geometry that reproduces real ANDI thermal manikin and cloth. And the geometry including air gap between human skin and cloth was reproduced in detail.

2.3 Numerical thermal comfort analyses using CSP
To validate the prediction accuracy of the CSP, a cuboid analytical domain corresponding to the experimental chamber was prepared, as shown in Fig. 3. Depending on the reproducing of clothing, the analytical grids around the CSP were arranged with approximately 2.6/7.2 million polyhedral cells. For accurate prediction of airflow and heat transfer in the viscous sublayer on CSP, five layers of boundary cells with a thickness of approximately 0.2 mm were applied on the surface of CSP and clothing. As a result, the dimensionless wall distance \((y^+\) was below 1.0 over the entire surface of the body and cloth.

The numerical and boundary conditions for CFD are summarized in Table.1. This study applied the SST \(k-\omega\) turbulent model that combines the advantages of the \(k-\varepsilon\) model and the \(k-\omega\) model. In addition to the convective heat transfer analysis based on CFD, a surface-to-surface (S2S) model with a view factor calculation was used for radiative heat transfer analysis. In the chamber experiment, the air volume of SA (Supply air) and RA (Return air) is 165 m\(^3\)/h. OA is outer air with a flow rate of 47 m\(^3\)/h. The exhaust air (EA) is set as an outflow condition. The supply air (SA) temperature was controlled to maintain the indoor air temperature. The temperature of RA is regarded as the set point of indoor temperature. However, there was a small fluctuation in the measured result of the return air (RA) temperature and relative humidity (RH) over time. Therefore, the temperature and humidity profile of SA, RA, and outdoor air (OA) over time were extracted and applied to the boundary conditions to precisely reproduce the experimental condition. This profile was wrote based on experimental measurement results. Finally, the skin temperature analysis result obtained by thermoregulatory analysis coupled with indoor CFD simulations was compared with the experimental result.
3 Results and Discussions

3.1 Verification of digital twin coupled with CFD

Fig. 5 is a comparison graph of the average skin surface temperature for 20 minutes in CFD and chamber experiments. The temperature difference between the thermal manikin and CSP in naked state was approximately 0.15, 0.38 was in clothed state, which is acceptable for thermal comfort assessment. As shown in the RA temperature trend in the graph A, the skin surface temperature slightly increased gradually as the ambient temperature increased. However, the temperature difference in Case 2 seems to be larger than that of case 1 because the insulation and permeability of the clothing were not applied in detail.

3.2 Distribution of velocity and temperature

Fig. 6 shows the analysis result of the scalar velocity distribution around the CSP (Case 2). As the inlet is located on the rear side of the CSP in the ceiling, the rear side of the CSP is expected to be relatively more affected by the air inflow. It was confirmed that the air flow velocity in the part with the air layer between the cloth and skin surface was significantly lower than that of the external environment of clothing. Fig. 7 shows the skin surface temperature distribution on the CSP (Case 2). Non-uniform and complex temperature distributions were identified around the CSP, and there was a clear thermal plume above the head of the CSP. In addition, a distinct difference of temperature level between inside the air gap and outside the cloth was observed by the thermal insulation of clothing.

Fig. 8 shows the skin surface temperature distribution of CSP (Case 2). The characteristics of temperature distribution in body parts shown in the thermal manikin were well reproduced in CSP analysis. Although the influence of the inflow air on the skin temperature control of CSP was reduced due to the clothing, the temperature distribution on the rear side of the CSP was relatively lower than on the front side. The temperature distribution was relatively lower in the parts such as hands and feet compared to other parts, which is a representative characteristic shown in the experiment.

4 Conclusion

In this study, the CSP was developed as a digital twin of the advanced, multi-node thermal manikin. This CSP was integrated with the CFD analysis to reproduce the chamber experiment using actual manikin. The
prediction accuracy of CSP was verified by comparing analysis results from thermal manikin and CSP under the same environmental conditions. In addition, the clothing was applied to the developed CSP and the ventilation layer (air gap between the skin and cloth) was well reproduced. The temperature difference between the thermal manikin and the CSP was in acceptable level for thermal comfort assessment. Therefore, it was confirmed that the CSP developed in this study has sufficient prediction accuracy as a digital twin of an actual thermal manikin with the multi-node thermoregulation model. In future studies, we will investigate more diverse characteristics of clothing such as thermal insulation and air permeability.

References


