Coupled simulation of CFD and human thermoregulation model in outdoor wind environment

Haobin Liang[1*], *Shin-ichi* Tanabe[2], and *Jianlei* Niu[1]

[1]Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong
[2]Department of Architecture, Waseda University, Tokyo, 169-8555, Japan

Abstract. Understanding of dynamic and transient wind environment is crucial to evaluating the outdoor thermal comfort of pedestrians. The thermophysiological responses of the human body depend on both the interaction with the climate and internal thermoregulation. The coupled simulation of CFD and thermoregulation model provides a pathway to predict human responses under non-uniform conditions where local effects may dominate thermal comfort. In this work, we explore the potential of coupled simulation under outdoor environmental conditions. The thermoregulation model JOS-3, which consists of 85 nodes and 17 body segments, is used to simulate the physiological responses and the obtained mean skin temperature is fed into CFD as the boundary condition of the thermal manikin. The thermal interactions between the human and surrounding environment in the wind tunnel, represented by convective and radiant heat transfer coefficient, are calculated by CFD and serve as inputs for the JOS-3 thermoregulation model. The results exhibit that under the wind velocity of 1 m/s and turbulent intensity of 11.6%, the coupling can converge within two iterations. This is because the convective heat transfer coefficient is not significantly affected by the body skin temperature under the assigned outdoor airflow velocity, which is higher than the value in an indoor environment. The study demonstrates the workflow of coupled simulation in an outdoor wind environment and could be a useful tool for evaluating outdoor thermal comfort under different conditions in the future.

1 Introduction

The perceived outdoor thermal environments can be highly asymmetrical in practice. On the one hand, spatially non-uniform conditions such as wind environment and solar radiation, may have significant influences on local heat transfer, which could dominate overall thermal comfort. On the other hand, the rapid variation of outdoor environments would exert great impacts on physiological variations of local body parts. Hence, transient thermal characteristics of local body parts are crucial to accurately predict the thermal sensation of the human body in outdoor environments.

Thermophysiological models are important to capture local thermal sensation as predicting human responses with high resolution by experiments is challenging [1]. The thermal sensation and perception in the human body are related to the thermal state, for example, core and skin temperature, which are the most important indicators of thermophysiological responses. The thermophysiological model provides a mathematical description of physiological responses to thermal environments [2]. Mathematical modelling of the human body can simulate thermophysiological responses under various environmental conditions, which allows us to further evaluate human thermal comfort. Multi-node thermoregulation models have been explored by researchers. Multi-node thermoregulation models have been explored by researchers to predict thermophysiological responses given environmental parameters, human activity intensity and clothing properties. Many thermoregulation models including JOS-3 [3] used in this work, are based on Stolwijk's model [4], which consists of a sphere representing the head and cylinders representing other body segments. CFD (Computational Fluid Dynamics) provides a simple way to derive detailed environmental conditions and heat transfer coefficients in a wide range of environmental conditions.

Coupling CFD with the thermoregulation model can describe both the internal thermoregulation of the human body and interaction with the local climate. Attempts have been made to explore the potential of coupled simulation in indoor environments. Skin temperatures obtained from thermoregulation models are commonly fed back to CFD as boundary conditions and used as the convergence criteria. Besides heat flux or heat transfer coefficient [2, 5-8], environmental parameters including air temperature and velocity [2, 6, 9] and moisture [5] were obtained from CFD and transferred into the thermoregulation model as the input. The coupling method was examined by comparing the simulated skin temperatures with published measurements [8] and further applied to predict thermal sensation [2]. The coupled simulation covers a wide

* Corresponding author: haobin-patrick.liang@polyu.edu.hk

range of applications in indoor environments, including natural ventilation [5], personal ventilation [9], radiant cooling/heating [6] and passenger thermal comfort in the car cabin [7]. In this work, the thermoregulation model JOS-3 was coupled with CFD simulation to predict the physiological responses in an outdoor environment with a wind velocity of 1 m/s. The workflow of coupling is demonstrated and would be useful to be further applied to predict thermal perception in complex outdoor environmental conditions.

2 Methodology

The human body can acclimatise and maintain a constant level of core temperature to a wide range of ambient conditions through physiological adaptations. Thermophysiological models include the active and passive systems. The active system refers to the thermoregulation including vasoconstriction, vasodilatation, shivering and sweating. Controlled by the central nervous system, the active system would affect metabolism, blood perfusion rate, sweat production, etc. if the body deviates from thermal neutrality. This can be simulated by warm and cold signals by calculating the temperature difference between nodes and set-points [8]. The passive system describes the heat transfer within the human body and the one between the body and the environment. The model decomposes the human body into multiple body segments and several layers, including bone, muscle, fat and skin. With Penne's bioheat equation, the passive system can predict heat transfer by blood circulation and radial conduction to the body surface. The body would exchange heat with the environment via convective and radiative heat transfer, evaporation, and respiration. In this work, the JOS-3 model [3] was used to calculate physiological responses and body temperatures in transient and non-uniform thermal environments, which consists of 85 nodes and 17 segments as shown in Fig. 1 (a). The computational thermal manikin was downloaded from the website of Kyushu University (http://www.phe-kyudai.jp/research_01.html), and the manikin is divided into 20 body parts with a height of 1.6 m. To ensure that the body parts are consistent in coupled simulation, face, left/right nose, mouth, and neck were considered as head for the manikin, while head and neck were viewed together as head in JOS-3.

To simulate the outdoor wind conditions, the manikin shown in Fig. 1 (b) was placed at the centre of a wind tunnel with a length of 7 m and both width and height of 1.8 m, which is based on the experimental study of Ono et. al [10]. The air temperature, wall temperature and skin temperature were 30°C, 28°C and 33.7°C, respectively. At the inlet the airflow velocity was 1 m/s with a turbulence intensity of 11.6%, turbulence length scale of 0.126 m and temperature of 30°C. No-slip boundary conditions were applied to surrounding walls, ceiling and ground, and outflow was applied at the outlet. Shear Stress Transport (SST) k-ω model in ANSYS FLUENT was used as the turbulence model for steady-state RANS simulation in this study, which showed good performance in predicting convective heat transfer of the human body in previous studies. The surface-to-surface model was chosen to calculate the radiative heat transfer and the emissivity of the manikin surface and surrounding walls were set as 0.95. The SIMPLE scheme was used for pressure-velocity coupling. First order upwind was applied for turbulent kinetic energy and specific dissipation rate, while second order upwind was applied for the discretization of momentum and energy. Residuals of continuity, velocity, energy, k and ω were all set as 1e-4.

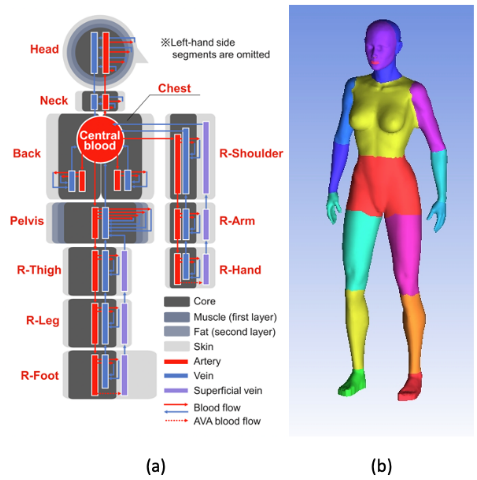
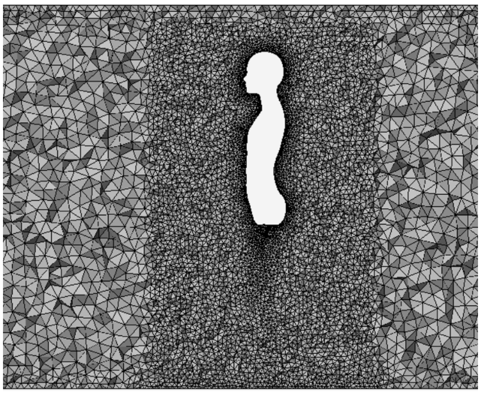


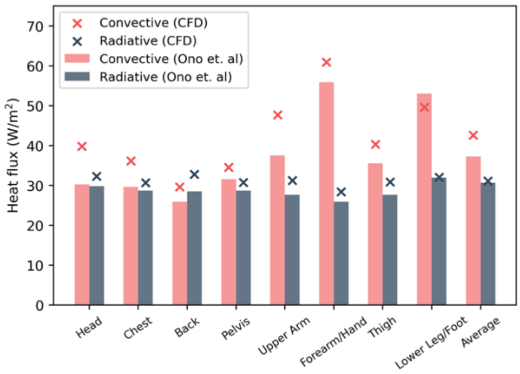
Fig. 1. (a) JOS-3 model; (b) computational thermal manikin.

Fig. 2 (a) shows the unstructured grids generated in ICEM to predict the complex flow fields around the manikin. The global mesh size of tetrahedra was set as 6 cm and the value near the manikin was reduced to 3 cm to ensure more accurate results of convective heat transfer between the manikin and the surrounding environment. The surface mesh size of manikin was set as 8 mm. Prism layer mesh was applied at the skin surface with a height ratio of 1.1 and a total height of 1 mm. The height of the first layer was set as 0.15 mm to make sure that the y+ value is around 1. The total mesh number is around 2.8 million. The mesh independence was checked, and the numerical results were validated against the experimental data of Ono et. al [10], as shown in Fig. 2 (b). The radiative heat flux for all body segments agrees well with the results from Ono et. al with small discrepancies. As for the convective heat flux, the variations at different body segments of numerical results show similar trends as the experimental data in general. The largest discrepancy mainly occurs at the upper body, including head, chest, and upper arm. Even though the difference in average convective heat flux between simulation and experiment is around 14%, considering the difficulties in accurately predicting the complex flow characteristics around the manikin [9], the numerical results are acceptable.

 https://doi.org/10.1051/e3sconf/202339605008



(a)



(b)

Fig. 2. CFD modelling: (a) grid design; (b) validation results.

The total sensible heat flux and radiative heat flux were calculated by CFD simulation, and the convective heat flux can be determined by subtracting the radiative heat flux from the total sensible heat flux. As shown in equation (1) and (2), the convective and radiative heat transfer coefficient can be calculated as the corresponding heat flux over the temperature, in which T_{sk} , T_a , T_w are skin, air and wall temperature respectively.

$$h_c = \frac{Q_c}{T_{sk} - T_{sk}} \quad (1)$$

$$h_r = \frac{Q_r}{T_{sk} - T_w} \quad (2)$$

In this study, the coupled simulation is used to study the interaction between the human body and the outdoor wind environment under steady state conditions. It means that the steady-state body skin temperature would be fed back to the steady CFD model as boundary conditions, even though the JOS-3 thermoregulation model is transient. The iterative loop continues until convergence is reached. The convergence criterion is when the difference in mean skin temperature between two consecutive iterations is lower than the threshold value, which is set as 0.1°C in this study since it has no significant influence on further calculations of thermal sensation and comfort [6].

The flow chart of the coupled simulation is shown in Fig. 3, which consists of the following steps:

1. Set up the JOS-3 model by specifying environmental conditions including air velocity and operative temperature. Keep other conditions the same as default settings.
2. Use the initial mean skin temperature of 33.7°C as the boundary condition for all human body segments in CFD.
3. Initialize the CFD model and simulate until the convergence is reached. Obtain the convective and radiant heat transfer coefficients for all body segments.
4. Update the heat transfer coefficients in the JOS-3 model and run the simulation. Record the mean skin temperature at the steady state, which is two hours in this study.
5. Update the mean skin temperature for all body segments in the CFD model.
6. Repeat step 3-5 until the convergence is reached.

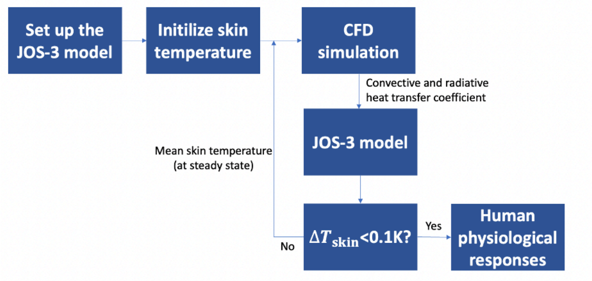
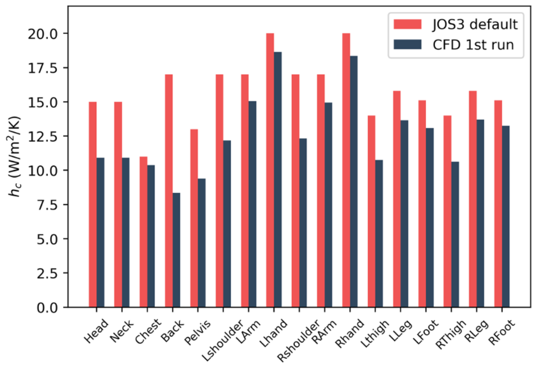


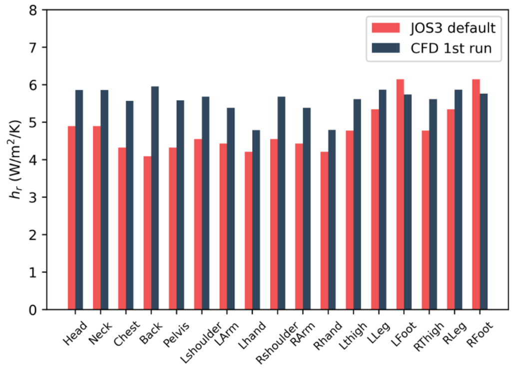
Fig. 3. The flow chart of coupled simulation.

3 Results

In the JOS-3 thermoregulation model, the convective heat transfer coefficients are calculated by the correlation $h_c = a{v_a}^b$, in which v_a is air velocity and a, b are constants of each body segment. The radiative heat transfer coefficients h_r are constants, which are plotted together with h_c in Fig. 4. The figure shows the numerical results of heat transfer coefficients from the first run of the CFD model against the default values in the JOS-3 model for comparative purposes. Under the specified outdoor environment settings, the JOS-3 model would overestimate the convective heat transfer for all body parts, if the values of h_c are not updated in the program. h_c at the back in JOS-3 code was over two times larger than the one obtained from CFD, which may significantly underestimate the skin temperature at the back. The discrepancy could be because the environmental settings to obtain the correlations of h_c is different from the wind tunnel test used in this work. For example, as shown In Fig. 2, the manikin faces towards the wind in the current wind environment settings, which might not be the case that was used to obtain the correlations. This shows the importance of updating convective heat transfer coefficients from CFD simulations as they can be representative of specific outdoor wind conditions. Besides, underestimations of radiant heat transfer can be observed for most body parts in the JOS-3 model. Predicting heat transfer coefficients with CFD would be crucial to obtain more accurate human physiological responses.



(a)



(b)

Fig. 4. The comparison of heat transfer coefficients between JOS-3 default values and calculated results from 1st run of the CFD model: (a) convective; (b) radiative.

After updating heat transfer coefficients in the JOS-3 model, the skin temperatures of body segments at the steady state for a two-hour simulation are exhibited in Fig. 5, in comparison with the results of using the default values of heat transfer coefficients. Discrepancies can be observed for most body parts, though the difference in mean skin temperature is negligible. The temperature difference at back was over 0.5°C and was the largest in all body segments. The JOS-3 model without updating h_c, h_r overestimated the skin temperature at chest, arms, feet and legs, and underestimated the skin temperature at head, neck, back, pelvis and thighs. This is mainly due to the different values of convective heat transfer coefficients shown in Fig. 4 (a), while the thermoregulatory process also had an impact on the responses. Hence, without proper estimations of heat transfer, local thermal sensation and comfort might be misrepresented.

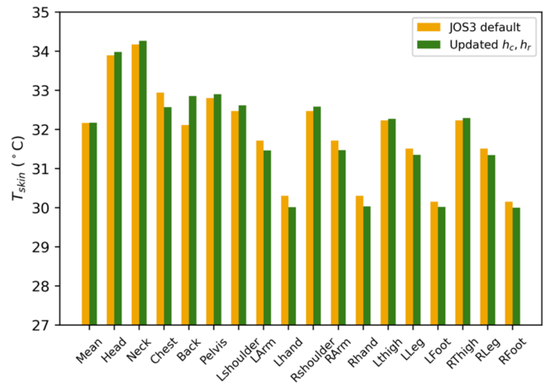
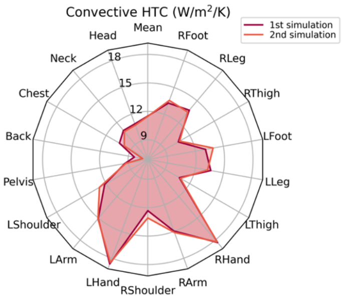


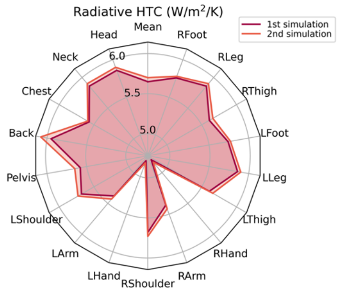
Fig. 5. The skin temperatures of body segments at the steady state with and without updating heat transfer coefficients.

The iterative results of the coupled simulation at different body segments are shown in Fig. 6. The mean skin temperature of the first (second) run in Fig. 6 (c) was obtained after updating h_c, h_r from the first (second) CFD simulation shown in Fig. 6 (a), (b). Fig. 6 (c) shows that after the human body reached the steady state in the specified outdoor environment, the skin temperature is distributed unevenly in the body. Feet and hands dropped to the air temperature at around 30°C owing to forced convection, while the skin temperature at head and neck increased to around 34°C because of the thermoregulation process. The mean skin temperature of 32.17°C was transferred back as the boundary conditions for all body segments in the 2nd CFD simulation. The radiative heat transfer coefficients increased as the temperature difference between skin and wall increased. The largest discrepancy of convective heat transfer coefficients between the 1st and 2nd CFD simulation occurred at the back, where the value decreased by 0.88 W/(m^2·K). Except for shoulder, foot and chest, the convective heat transfer coefficient did not show obvious change at other body segments. As a result, no significant differences in local skin temperatures can be observed between the 2nd run and 1st run of the JOS-3 model. The mean skin temperature remained the same at 32.17°C, indicating that the coupled simulation converged. The results revealed when the wind velocity is 1 m/s in an outdoor environment, the coupled simulation can converge faster than the one in indoor environments, which required 3-4 iteration loops [6]. When the wind velocity is higher, its influence on the convective heat transfer becomes more dominant. Therefore, the skin temperature of the human body shows less impact on the heat exchange with the local environment.

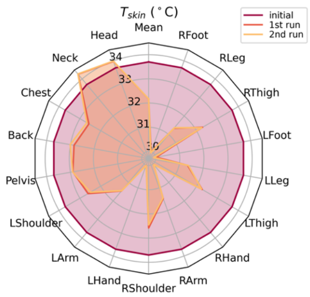
 https://doi.org/10.1051/e3sconf/202339605008



(a)



(b)



(c)

Fig. 6. Iterative results of coupled simulation at body segments: (a) convective heat transfer coefficient; (b) radiative heat transfer coefficient; (c) skin temperature.

4 Conclusions

This study presents the workflow for the coupled simulation of the CFD and JOS-3 thermoregulation model. The CFD model was used to calculate heat transfer coefficients of the outdoor wind environment represented by settings in a wind tunnel. The convective and radiative coefficients were updated in JOS-3 and calculated the mean skin temperature, which was transferred back to the CFD model in iterative loops. The results showed that CFD solutions are insensitive to the change of skin temperature under an outdoor wind speed of 1 m/s. In indoor environments, both wind velocity and the temperature difference between the human body and the surrounding environment would affect the convective heat transfer. However, the role of wind velocity is dominant in determining the convective heat transfer coefficient and thus the coupled simulation can converge faster in two iterative loops under outdoor wind conditions.

It should be noted that CFD simulation was initialized every time before running in this study. However, running the CFD model without initialization is an alternative as changing boundary conditions only exerts a temporary influence on convergence [5]. It would take a smaller number of iterations to stabilize CFD simulation and make transient coupled simulation possible. In addition, CFD was run at the start to provide heat transfer coefficients for the thermoregulation model in this work, while running the thermoregulation model first may help stabilize the solution in indoor environments [5, 8]. The effects of the running sequence in outdoor environments can be explored in the future.

Overall, the potential of assessing human thermal comfort by using CFD in combination with the thermal regulation model in outdoor environments is demonstrated. It is anticipated that the methodology can be applied to predict thermal sensation and thermal comfort in outdoor environments in future studies.

The work was supported by Research Talent Hub, the Innovation and Technology Commission, and the RGC TRS project (No. T22-504/21-R).

References

1. C. van Treeck, J. Frisch, M. Pfaffinger, E. Rank, S. Paulke, I. Schweinfurth, R. Schwab, R. Hellwig, A. Holm, J. Build. Perform. Simul. **2**(4), 233-250 (2009)
2. L. Schellen, M. G. L. C. Loomans, B. R. M. Kingma, M. H. de Wit, A. J. H. Frijns, W. D. van Marken Lichtenbelt, Build Environ. **59**, 10-22 (2013)
3. Y. Takahashi, A. Nomoto, S. Yoda, R. Hisayama, M. Ogata, Y. Ozeki, S.-i. Tanabe, Energy Build. **231**, 110575 (2021)
4. J. A. Stolwijk, NASA, (1971)
5. P. C. Cropper, T. Yang, M. Cook, D. Fiala, R. Yousaf, J. Build. Perform. Simul. **3**(3), 233-243 (2010)
6. C. Voelker, H. Alsaad, Indoor Air **28**(3), 415-425 (2018)
7. T. J, K. S, K. R, N. Kornev, Flow Turbul. Combust. **97**(4), 1281-1296 (2016)
8. J. Yang, S. Ni, W. Weng, Int. J. Therm. Sci. **120**, 437-445 (2017)
9. N. Gao, J. Niu, H. Zhang, HVAC&R Res. **12**(3), 497-518 (2006)
10. T. Ono, S. Murakami, R. Ooka, T. Omori, J. Wind Eng. Ind. Aerodyn. **96**(10), 1719-1732 (2008)