CFD Simulation of Flame Manikin Test for Fire Proof Garment during Flash Fire Exposures and Cooling Phase

Zhao-Li Wang[1,2,3,a], Jun Li[1,2,3,b*], Miao Tian[1,2,c]

[1]Fashion institute, Donghua University, Shanghai, 200051, China

[2]Protective Clothing Research Center, Donghua University, Shanghai, 200051, China

[3]Key Laboratory of Clothing Design &Technology, Donghua University, Ministry of Education, Shanghai, 200051, China

[a]email: wangzhaoli39@163.com

[b*]Corresponding author's email: lijun@dhu.edu.cn

[c]email: ti.miao@hotmail.com

Keywords: Flame manikin test; CFD simulation; Fire proof garment; Thermal protective performance; Flash fire.

Abstract. Numerical simulation study of flame manikin test for fire proof garments has significance on better understanding transient heat transfer to human body under extreme environments. Skin burns can occur not only during a fire, but also after a fire ends. In this study, a full scale transient numerical simulation of naked flame manikin test during both flash fire exposure and cooling phase is conducted based on CFD techniques. The full-scale 3D geometrical model of the combustion chamber is built by means of non-contact 3D body scanner, Geomagic studio and Gambit software, The elaborate structures of 12 burners are rebuilt according to actual structures to improve accuray. The prediction results have been validated using data from naked manikin tests. The history of simulated heat flux is consistent with the measured heat flux history. The temperature filed inside the chamber and particularly in the close vicinity of the body at different times is obtained. It would be helpful for further study on modeling heat transfer in clothed manikin tests and for predicting skin damage accurately.

Introduction

The thermal protective performance of firefighter's clothing can be evaluated by using Flame manikin tests. However, the manikin test suffers from high-operation costs and environmental impacts [1]. The development of the numerical simulation helps us to do virtual fire disaster experiment and therefore is showing distinct advantage in predicting the performance of protective garments [2,3].

At present, numerical simulations of heat transfer through fabric in small-scale tests, for example TPP tests, have been widely reported. One-dimensional transient model developed by Torvi [4] demonstrated the heat transfer process through fabrics. Song [5] developed a one-dimensional finite volume model to study heat and moisture transfer in multiple layer firefighter's clothing during the contact flame TPP test. However, researches on the full-scale numerical simulations of flame manikin tests during flash fire and cooling phase [6] is limited. Wang [7] established a model of heat transfer of a calibration test with naked manikin during flash fire exposure by CFD. But the chamber was not the real size as the experiment room considering the restricted computational capacity, which was regarded as the main reason of local error of heat flux on the manikin surface.

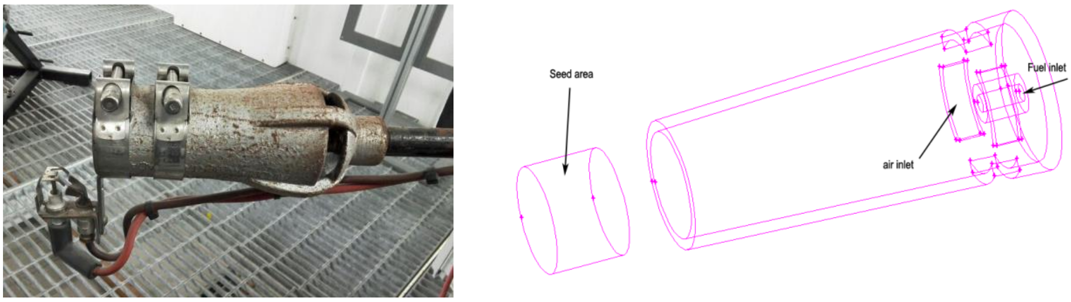
In this study, a full-scale 3D transient simulation of naked flame manikin test during flash fire exposure and cooling phase is achieved by means of CFD technique. Another feature of the present study is that the elaborate structures of 12 burners are rebuilt to be exact copies of actual structures.

© 2015. The authors - Published by Atlantis Press

Experimental

Donghua Flame Manikin protective clothing analysis system. Donghua Flame Manikin protective clothing analysis system [7, 8] which meets the requirements of both ASTM F1930 [9] and ISO 13506 [10] was used in this study. The burn chamber was equipped with one flame manikin body and six sets of two burners around the body, as shown in Fig.1. The naked manikin experiment is conducted with chamber initial temperature of 20 ± 3 ℃, initial humidity of 65 ± 5%. The average heat flux is controlled at 80-84 KW/m^2, with standard flux variance of 21 KW/m^2. The data-gathering period consists of 4s fire exposure and 20s cooling phase.

Figure. 1 Donghua Flame Manikin protective clothing analysis system



(a) (b)

Figure. 2 (a) The actual burner; (b) The structure of a burner in geometrical model.

3D Geometrical modeling of naked flame manikin test system. The three-dimensional shape information of the manikin body is measured by a 3-D non-contact human body scanner. The NURBS surfaces model of the naked manikin is rebuilt by using the reversing engineering software: Geomagic. The burner geometrical model established with the precise structure consists of 3 parts: nozzle, ejector and seed area, as shown in Fig. 2. The geometrical model of flame chamber was created in Gambit with a dimension of 5.01 by 5.01 by 3.36 m, which was exactly the size of the experimental room, as shown in Fig. 3. The whole grid model consists of about 5,858,000 tetrahedral unstructured grid cells.

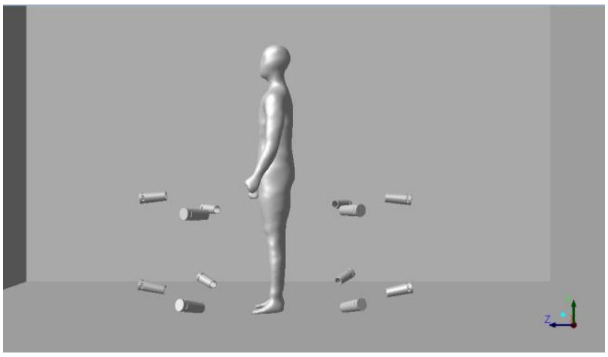


Figure. 3 The full-scale chamber.

CFD transient simulation of naked manikin test. It is well known that the naked manikin test is the crucial calibration experiment for dressed manikin tests [11]. In this study, Fluent software is used to model the three-dimensional transient flow and heat transfer in the naked manikin chamber during the combustion process of flash fire and cooling.

For better prediction of the spreading rate of round jets, realizable k-epsilon model is selected as the viscous model. The generalized eddy-dissipation model is used to analyze the propane-air combustion system. Considering the front wall of chamber made of heat-resistant glasses is semi-transparent, DO model (Discrete Ordinate) is used to solve the radiative transfer equation.The weighted-sum-of-gray-gases model (WSGGM) is used to specify the composition–dependent absorption coefficient of the combustion products.

Results and discussion

Validation of the accuracy of the transient CFD simulation. In order to validate the accuracy of the computed temperature and heat flux field, we drew a comparison of the mean heat flux history of naked manikin test CFD simulation with that of an actual calibration experiment during 4s flash fire exposure and 4s cooling phase.

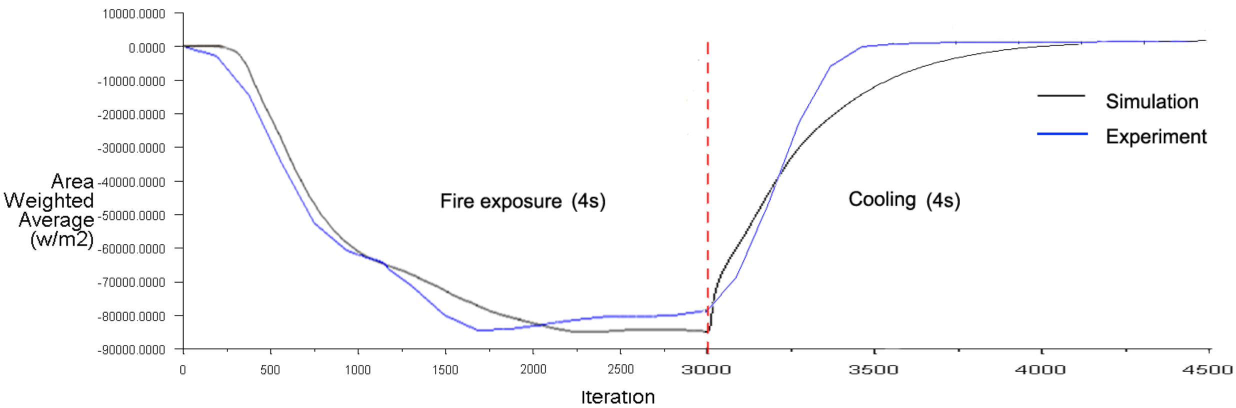


Figure. 4 The convergence history of total surface heat flux on the manikin surface by CFD simulation and experiments.

As shown in Fig.4, there is a steady region of heat flux and the average incident heat flux of the naked manikin surface is stable at $84kw/m^2$ at the end of fire exposure in CFD simulation. During cooling phase, the average heat flux drops rapidly and approaches zero at the time of about 3s' after exposure. And the standard deviation was less than $19.2kw/ m^2$. These are perfectly correspond to the

ASTM standard and the naked flame manikin tests, suggesting that the CFD simulation predicted the flowfield with a reasonable accuracy. Note that the heat fluxes in the iterative process are negative suggesting an endothermic process. Though the measured heat flux by sensors is changed to positive, we make these data negative and merge the two curves into one picture for better comparison.

Temperature results of transient CFD simulation. By means of CFD simulation, the temperature field in the whole combustion chamber can be obtained easily. Fig.5 shows the chamber temperature distribution of some sections at different times which conforms to the physical reality. Relative to a few of pointwise information provided by real manikin experiment, CFD results provide more sufficient information of temperature for the next step of skin burn prediction.

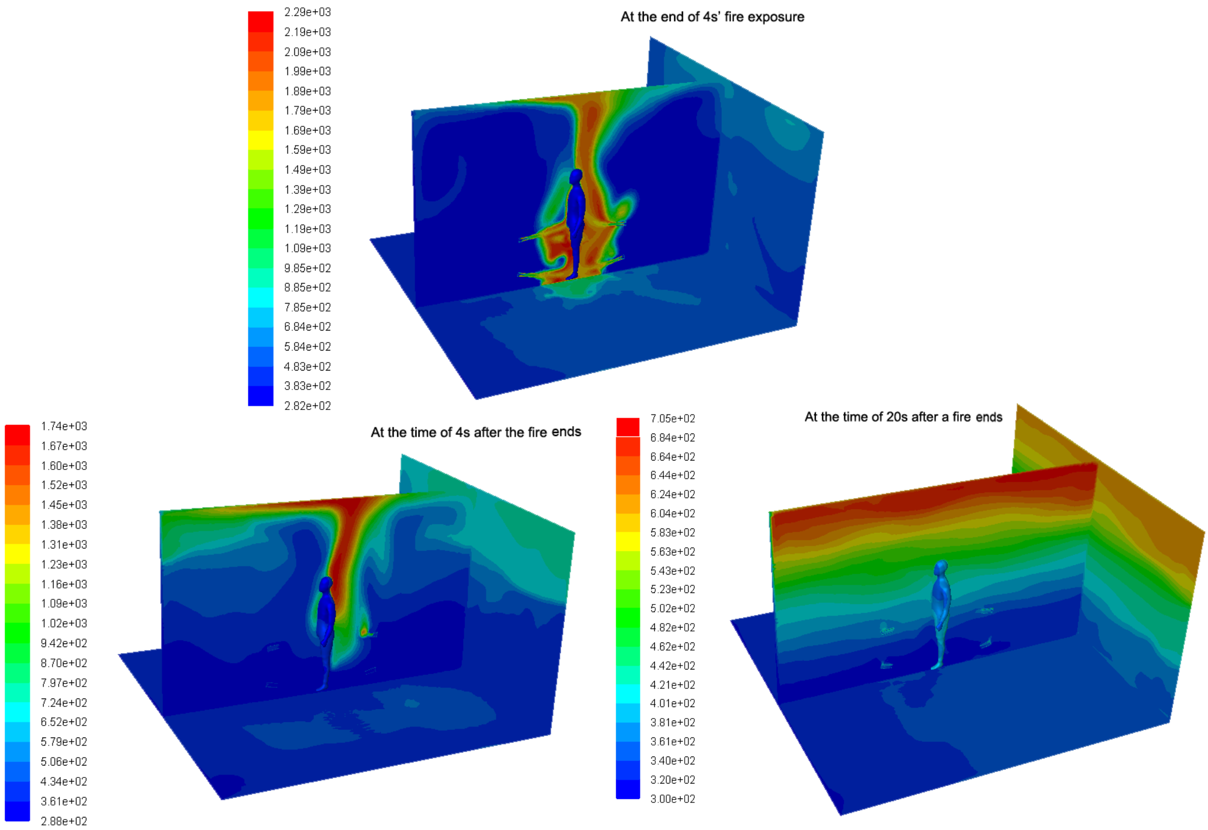


Figure. 5 The temperature field in the whole combustion by CFD simulation.

Conclusions

In this study, we have conducted a 3D transient simulation of naked flame manikin test during flash fire exposure and cooling phase by means of CFD technique. We developed a full-scale geometrical model of the combustion chamber with elaborate structured burners and improved simulation precision. The prediction results have been validated using data from naked manikin tests. The temperature field inside the chamber and particularly in the close vicinity of the body at different times is obtained, providing enough information for understanding the heat transfer of the manikin test system. Related experiments on the next step of skin burn prediction and the clothed manikin test simulation are currently being carried out in our laboratory. We anticipate further achievements will soon be produced.

Acknowledgements

This work was financially supported by the Fundamental Research Funds for the Central Universities in China.

References

[1]YuyanJiang, Eiji Yanai, Kazumi Nishimura, Huilai Zhang, Nobuyuki Abe, Masahiko Shinohara, and Kaoru Wakatsuki: An Integrated Numerical Simulator for Thermal Performance Assessments of Firefighters' Protective Clothing, Fire Safety Journal, 2010, Vol. 45 (2010) No.5, p. 314-326.

[2] Ahmed Ghazy, and Donald J Bergstrom: Numerical Simulation of the Influence of Fabric's Motion on Protective Clothing Performance during Flash Fire Exposure, Heat Mass Transfer, Vol. 49 (2013) No.6, p. 775-788.

[3]Guowen Song, Patirop Chitrphiromsri, and Dan Dinga: Numerical Simulation of Heat and Moisture Transport in Thermal Protective Clothing Under Flash Fire Conditions, International Journal of Occupational Safety and Ergonomics, Vol. 14 (2008) No.1, p. 89-106.

[4]Torvi D.A., and J.D. Dale: Heat transfer in thin fibrous materials under high heat flux, Fire Technology, 1999,Vol. 35 (1999) No.3, p. 210-231.

[5]Guowen Song, Patirop Chitrphiromsri, and Dan Dinga: Numerical Simulation of Heat and Moisture Transport in Thermal Protective Clothing Under Flash Fire Conditions, International Journal of Occupational Safety and Ergonomics, 2008, Vol. 14 (2008) No.1, p. 89-106.

[6] Torvi, D. A., and Threlfall, T. G.: Heat Transfer Model of Flame Resistant Fabrics During Cooling After Exposure to Fire, Fire Technol, Vol. 42 (2006), p. 27-48.

[7]Yunyi Wang, Zhaoli Wang, Xue Zhang, Min Wang, and Jun Li: CFD Simulation of Naked Flame Manikin Tests of Fire Proof Garments, Fire Safety Journal,Vol.71 (2015), p. 187-193.

[8]Min Wang, and Xiaohui Li: The World Leading Garment Flame Manikin System- Donghua Fireman- Was Built in China. China Personal Protective Equipment, Vol. 5 (2011), p. 54-55.

[9]ASTM F 1930-13: Test Method for Evaluation of Flame Resistant Clothing for Protection against Fire Simulations Using an Instrumented Manikin, American Society for Testing and Materials, West Conshohocken, PA, 2013.

[10]ISO13506:2008, Protective Clothing against Heat and Flame-Test Method for Complete Garments-Prediction of Burn Injury using An Instrumented Manikin. 2008.

[11]Guowen Song, Roger L. Barker, HechmiHamouda, Andrey V. Kuznetsov, PatiropChitrphiromsri, and Robert V. Grimes: Modeling the Thermal Protective Performance of Heat Resistant Garments in Flash Fire Exposures, Textile Research Journal, Vol. 74 (2004) No.12, p.1033-1040.