Journal of Fiber Bioengineering and Informatics 13:4 (2020) 221–240

Cite as: Z. Zhang et al.
doi:10.3993/jfbim00349

Modelling and Simulation of Heat and Moisture Transfer in Human-chemical Protective Clothing-environment System ⋆

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Abstract

A novel model of heat and moisture transfer in human-chemical protective clothing-environment is proposed to predict the human physiological regulatory response wearing chemical protective clothing (CPC). The human thermal model is developed by dividing the skin node into multiple segments based on the Gagge's 2 node model. The CPC is discretized into multiple control volumes and the control volume-time domain finite difference method is utilized to compute the temperature of the clothing. The CFD simulation method is employed to calculate the heat and moisture transfer of natural convection in the air gap between human and CPC. The air gap model is coupled with the human model and the CPC model by exchanging boundary conditions. The predictions of human heat stress obtained by the model agree well with the published experimental data. The results indicate that the condensation heat transfer mechanism in CPC changes with the thickness of air gap. When the thickness of the air gap is small, the condensation heat transfer is mainly based on diffusion. When the air gap is thicker, the condensation heat transfer is dominated by the 'heat pipe effect'. Compared with large changes in ambient temperature, the impact of ambient temperature on human temperature is not very great due to good air tightness and large thermal resistance of CPC, but that on sweating rate, moisture accumulated on the skin and moisture run off from the skin is great. Finally, based on the analysis of the results, the guidelines for the design of CPC are given.

Keywords: human thermoregulation model; CFD; chemical protective clothing; heat stress; heat and moisture transfer

⋆Project supported by the Key Laboratory of Aircraft Environment Control and Life Support (Nanjing University of Aeronautics & Astronautics), Ministry of Industry and Information Technology.

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Dec. 2020

1 Introduction

In December, 2019, a series of pneumonia cases which were caused by a novel betacoronavirus, the 2019 novel coronavirus (2019-nCoV) emerged in Wuhan, China. The virus is transmitted through close contact and respiratory droplets. Because there is no vaccine or treatment for 2019-nCoV, personal protective equipment is an essential way to combat the transmission of the virus. As the coronavirus disease outbreak continues to spread in the world, the research on chemical protective clothing becomes particularly urgent and important.

The chemical protective clothing (CPC) is designed to shield individuals from exposure to various hazards such as chemical, thermal, nuclear, radiation, and biological hazards [1]. In order to afford better protection against chemical agents present in the surroundings, CPC needs to be impermeable to air and water vapor. In addition, due to the low elasticity of the impermeable fabrics of CPC, it can't be made close-fitting. For the purpose of facilitating the activities of the wearer, CPC is made relatively loose. The impermeability of CPC makes it difficult to exchange heat between the human body and the environment, which often increases the physiological strain and decreases task efficiency. The clothing microclimates in the case of wearing CPC impair human heat dissipation through radiation, convection, conduction and evaporation of sweat which increase heat stress [2]. Consequently, the investigation of human physiological responses and heat strain burden associated with CPC is of great significance.

Experiments were conducted to analyze heat strain in subjects wearing CPC through indices such as core and skin temperature, tolerance time and intensity of sweating [3-6]. Nevertheless, these human trials were carried out under specific task, garment and environmental conditions and the results of the studies may not be suitable for individuals in other conditions. In addition, the human trials have certain risks, and the duration of the experiment should not be too long, otherwise the excessive heat burden may cause health problems. Thus, it's essential to develop a human-CPC-environment model in order to evaluate human physiological responses in different conditions and provide the instructions for the design of chemical protective clothing.

Several human thermoregulatory models have been developed and being used in physiological response prediction and thermal comfort assessment. Yang et al. [7] integrated a thermoregulatory model with a clothing model to simulate core and skin temperatures under different environmental conditions taking into account of the human-air gap-fabric-environment parameters. In their clothing model, empirical formulas are used to simulate the natural convective heat transfer in the air gap, which may cause certain errors. Fu et al. [8] proposed a new multi-segment UC Berkeley Thermophysiological (UCBT) model with an improvement in heat and moisture transfer through clothing to predict the heat strain of people working in hot environment. They used predicted equations developed from the measurements of the thermal insulation and evaporative resistance of clothing to calculate the thermal parameters of clothing. He and Ji [9] developed a multi-scale model incorporating models of three-dimensional bioheat transfer, systemic arterial thermo-fluid dynamics, a thermoregulatory system and clothing to predict body temperature and quantitatively evaluate human thermoregulatory responses. Lai and Chen [10] proposed a 12-segment model for transient and non-uniform surrounding conditions by considering two-dimensional heat transfer in each segment of a human body to assess the temperature of the body and a person's thermal comfort level. Hamdan et al. [11] developed a transient mathematical model of heat and mass transfer through clothing layers containing PCM packets and combined it with a segmental bio-heat model to predict core and mean skin temperatures. Wan and Fan [12] proposed a transient thermal model integrating the heat and moisture transfer through clothing as well as the