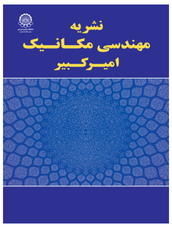

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A New Index for Evaluating Thermal Sensation Based on the Principles of Non-Fourier Heat Transfer

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ABSTRACT: In recent years, the modeling of human thermal sensation based on thermoreceptors response has attracted the attention of many researchers. However, biological tissues do not usually follow the principles of Fourier heat transfer. So, this study tries to develop a new predictive index for a thermal comfort model based on cutaneous thermoreceptors obtained by using non-Fourier heat transfer in biological tissues. The mentioned index is in conformity with the ASHRAE standard thermal sensation scale. The model used in this study considers the concept of non-Fourier heat transfer to describe heat transfer in biological tissues. Since biological tissues consist of complicated and nonhomogeneous structures, it is important to describe the process of heat transfer in these tissues by non-Fourier heat transfer equation. The new index has been verified by extensive comparisons with the experimental and analytical results under steady-state and transient conditions where a good agreement was found. Results show that the new index can predict the thermal sensation with mean absolute errors of 0.31 and 0.49 under steady-state and transient conditions, respectively. Since the new index is based on the concepts of non-Fourier heat transfer, it can provide an accurate prediction of thermal sensation in terms of sudden change in temperature.

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1- Introduction

Heat transfer in living tissues is associated with the production of metabolic heat and the rate of blood flow. In many cases, the Pennes heat transfer equation is used to describe heat transfer in living tissues [1]. The Pennes equation is one of the models of heat transfer based on the Fourier heat transfer law. This law indicates the unlimited speed of thermal signal propagation. Fourier heat transfer law is acceptable in many practical applications, but it leads to large errors in biomaterials with heterogeneous internal structures. In materials with a non-homogeneous structure, the heat transfer process requires sufficient time to occur, and in reality, the heat transfer rate is limited. This wave heat transfer behavior has been empirically observed by Mitra and Kumar [2]. After these observations, the heat wave model of the bioheat transfer was presented to investigate the physical mechanisms and the behavior of the heat wave propagation in biological tissues by Luo et al. [3]. Also, Cattaneo [4] developed a linear expansion of Fourier's law. By considering the effect of microstructure, Zhou and Puri [5] introduced two terms of phase lag for the gradient of temperature and heat flux. The model derived from the mentioned study was called the dual-phase lag model. Several studies have been carried out to investigate the temperature damage through non-Fourier heat transfer equations, especially the dual-phase lag model, and these studies are in good agreement with experimental results. Therefore, evaluation of heat transfer from biological tissue must be conducted by using the dual-phase lag model.

On the other hand, the prediction of the body's thermal sensation is one of the applications of bioheat transfer. In 1981, Hensel [6] found that the frequency response of the cutaneous thermoreceptors depends on both temperature and its derivative at the thermoreceptor's location. Subsequently, in 1991, Ring and Dear [7] presented the body's thermal response model based on Henel's studies on the transient response of cutaneous thermoreceptors. Zolfaghari and Maerefat [8] developed a Simplified Thermoregulatory Bioheat (STB) model by combining the well-known Pennes equations with Gagge's two-node model [9]. This model acquires the body's thermal response in transient environmental conditions. In the following, Bijari and Zolfaghari [10] developed a new thermoregulatory bioheat model using non-Fourier heat transfer concepts. They showed that this model is in good agreement with experimental results. However, the model does not provide an index for evaluating people's thermal sensation.

In the present study with regard to previous studies, a new thermal sensation index presents by using the non-Fourier thermoregulatory bioheat model [10].

2- Methodology

In the STB model, the temperature distribution acquires by using the Pennes equations and Gagge's two-node model in transient environmental conditions. In the non-Fourier thermoregulatory bioheat model, the temperature distribution computes by using the bioheat form of dual-phase lag model. By using the Ring and Dear body's thermal response model [7] the response of cutaneous thermoreceptors is determined. This model represents the human thermal response in Hz and it does

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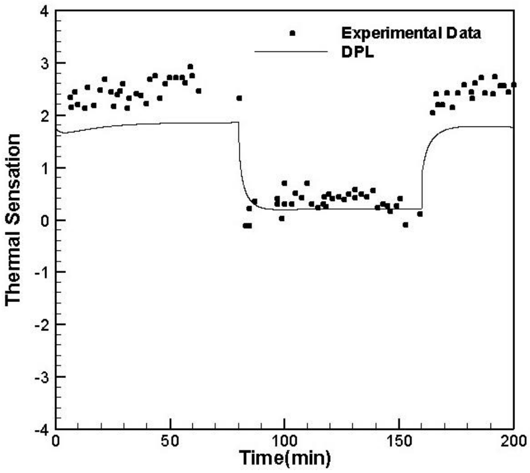

Fig. 1. Hybrid turbine model

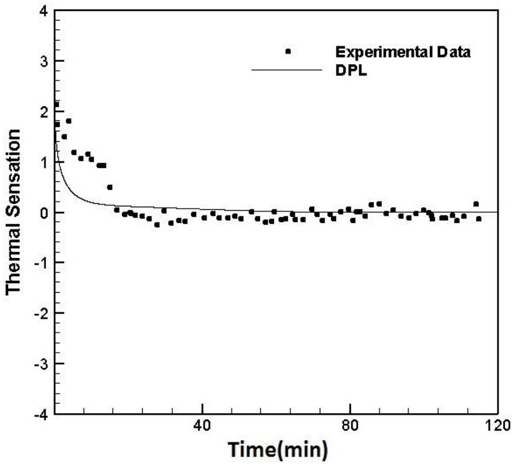

Fig. 2. The flow field and boundary conditions

not in conformity with the ASHRAE thermal sensation scale. The STB model presents a predictive index to express the human thermal response in the ASHRAE standard thermal sensation scale. We use this scale to evaluate the thermal sensation with concepts of non-Fourier heat transfer. The validation results for the index are presented in the next section.

3- Results and Discussion

The thermal response index has been validated in two sections: steady-state and transient. This index, according to the results, can provide a reliable prediction of the thermal sensation of people in both steady and transient conditions. The first comparison against the sudden changes in the air temperature from $34.3^{\circ}C$ to 26.4and from $26.6^{\circ}C$ to $33.7^{\circ}C$ was made with the experimental results of Arens et al. [11]. Fig. 1 shows a comparison between the thermal response index of the new model and the experimental results [11].

The second comparison is also with the experimental results of Arens et al. [11]. They suddenly exposed people with a metabolic rate of 1.1 met and warm initial condition to an environment with a relative humidity of 50% and a temperature of 29.6 ° C. In Fig. 2, the thermal sensation of individuals is experimentally compared with the thermal response index of the new model.

The mean error of the new thermal response index in the transient cases is 0.49, while the mean errors in the steady cases are less and equal to 0.31. This model does not consider the various properties such as age, gender, clothing, and physical characteristics. Hence, in some cases, the difference between the results of the new model and experimental data is observed.

4- Conclusions

In this study, non-Fourier heat transfer equations are used to predict the distribution of temperature at the location of thermoreceptors. Then, the thermal response index was presented and validated. The thermal sensitivity index of the new model was investigated in two steady and transient states. This index, according to the results, can provide a reliable prediction of the thermal sensation in a steady and transient condition. The major achievement of this study is to provide an index for assessing the body's thermal sensation using non-Fourier heat transfer equations. The presentation of a new thermal sensation index consistent with non-Fourier heat transfer can lead to the examination of the individual's thermal feelings under different conditions, including sudden changes in temperature and pulse changes such as draft. Of course, this will require further research in this area.

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