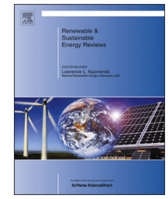
Renewable and Sustainable Energy Reviews 44 (2015) 304–318

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Thermal comfort models for indoor spaces and vehicles—Current capabilities and future perspectives

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ARTICLE INFO

Article history:
Received 14 August 2013
Received in revised form
10 September 2014
Accepted 31 October 2014

Keywords:
Thermal comfort models
Fanger's models
Adaptive thermal comfort models
Physiological thermal comfort models
Thermal comfort assessment

ABSTRACT

Throughout this paper, we reviewed the most popular thermal comfort models and methods of assessing thermal comfort in buildings and vehicular spaces. Most of them are limited to specific steady state, thermally homogenous environments and only a few of them address human responses to both non-uniform and transient conditions with a detailed thermo-regulation model. Some of them are defined by a series of international standards which stayed unchanged for more than a decade.

The article proposes a global approach, starting from the physiological reaction of the body in thermal stress conditions and ending with the model implementation. The physiological bases of thermal comfort are presented, followed by the main thermal comfort models and standards and finishing with the current methods of assessing thermal comfort in practice. Within the last part we will focus mainly on thermal manikin experimental studies, and on CFD (computational fluid dynamics) numerical approach, as in our opinion these methods will be mostly considered for future development in this field of research.

Contents

1. Introduction

Achieving thermal comfort for *occupants in buildings* in extreme conditioning requirements and irrespective of the environmental outside conditions has been the main focus for the heating

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http://dx.doi.org/10.1016/j.rser.2014.10.105
1364-0321/

ventilation and air conditioning (HVAC) design engineers and systems developers.

We observe, however, that contemporary techniques of air flow diffusion are not optimized simultaneously for these two inseparable goals: thermal comfort and energy savings. This observation can be applied to both buildings and vehicles fields. This paradox is due on one hand to bad diffusion of cold air, and on the other hand, to weakness of the conception of these systems. Behind this, the use of air flow models that are not fully adapted to conditions in the buildings and all other interior spaces can be found. In our opinion, this issue finds a theoretical response to the adaptation of existing theoretical models for different indoor (building or other enclosures) conditions, in terms of human thermal comfort.

On the other hand, the thermal comfort of *vehicular occupants* is gaining more and more importance due to the rising attention toward comfortable mobility, in addition to the growing time that people spend in vehicles (private or public transport). Furthermore, comfortable vehicular climate control in many cases not only help to reduce the driver stress but also guarantee good visibility by avoiding the fogging phenomenon, and contributing to a more secure driving. In addition, today's demand for better vehicular energy utilization and more efficient performance have led to an increased interest in investigating and analyzing the system and design requirements for good indoor and vehicle environments. For example, the need to reduce the heat loads that enter passenger compartments has become an important issue in the early stages of vehicle design. Moreover, achieving an improved thermal comfort system will lead to substantial cost reductions. A quantitative example given in the literature shows that in the United States alone approximately 26 billion liters of fuel are consumed annually for cooling vehicle passenger compartments [1]. This cost can be reduced by improving HVAC systems design.

A technical answer may come from the conception of the air diffusion devices which have to be optimized for improving mixing between supplied flows and their ambient in order to improve thermal comfort. Nevertheless, this technical direction of research has to be preceded by the theoretical advances in improving the existing comfort models which seem to be inappropriate in many situations [2–4]. Indeed, nowadays, we have the possibility of using advanced methods and devices both in terms of computing capabilities and experimental techniques. The existing thermal comfort models are all built with simplified assumptions, often limited because of available resources when they were conceived—over 30 years ago for the most used of them. We have today the opportunity to validate these models by taking into account the variation of several parameters, and to correct them and to propose new better models.

There were many attempts during the three past decades of proposing different objective evaluation methods of this subjective matter which is thermal comfort, though without very much success. Indeed, several models and indexes are available and standardized nowadays, proposing a quantification of the thermal comfort for buildings and other indoor spaces such as vehicular cabins or other [2–5]. In the same time, the majority of these models or indexes usually lead to wrong results and incorrect assessment of a thermal ambiance when the depending parameters are not close to the ones for which they were proposed [6–8]. Fanger's studies, for instance, are the basis for the two main standards [9,10] that are currently used for assessing thermal comfort in all types of enclosures occupied by humans even if they were originally conceived to be applied to buildings. Fanger's studies, as well as many of the experimental investigations conducted afterwards, are based on real human participants dressed in standardized clothing and doing completed standardized activities, exposed to laboratory thermal environments. These investigations established specifying environmental parameter ranges (i.e. comfort zones) in which a large percentage of occupants with given personal parameters will regard the environment as acceptable. However, it is currently recognized that even in buildings pure steady-state conditions are rarely encountered in practice, given the interactions between building structure, occupancy, climate and HVAC systems (especially for new systems like displacement or personal ventilation). For strongly non-uniform and transient environments like vehicular cabins the previous cited standards are even more not applicable for obtaining reliable results. Moreover, there are several parameters, usually affecting the human perception of thermal comfort, that are not even taken into account in these models. In the same time the models used so far can be either too generalist or either too difficult to implement and judge [11]. Experimental campaigns show high discrepancies between numerical results and in situ evaluation and furthermore even higher discrepancies between human subjects' response and experiments using other methods of evaluation [12,13].

Throughout this review we propose an attempt of answering to several questions, namely: *What are the limits of the mentioned above models in a CFD approach and which one gives the best results? Are these models adapted to nowadays indoor evaluation methods, since they have not been updated for decades? Which is the "best" thermal comfort model? Do we need extra evaluation or just a better implementation of existing models? What are the future perspectives for thermal comfort predicting?*

We decided to start our review by introducing the **physiological bases of thermal comfort**, followed by the **main thermal comfort models**, the discussion of the **main standards used for the thermal comfort assessment in occupied environments**, and finishing with the **current methods of assessing thermal comfort in practice**. Within the last part we will focus mainly on thermal manikin experimental studies, and on CFD numerical approach, as in our opinion these methods will be considered for future development.

2. Thermal comfort definition and physiological bases of thermal comfort

Thermal comfort is a subjective term defined by a plurality of sensations and is secured by all factors influencing the thermal condition experienced by the occupant, therefore is difficult to give a universal definition of this concept. Human thermal comfort is sometimes defined as all conditions for which a person would not prefer a different environment [14]. Another definition provided by American standard ASHRAE 55 [10] explains the thermal comfort as a subjective concept related to physical and psychological well-being in agreement with the environment. Because human beings are different, this term usually refers to a set of optimal parameters, for which the highest percentage possible of a group of people, feel comfortable about the environment [15].

Thermal comfort is assured by all the factors that influence the exchange of heat between the human body and its environment. This way we can differentiate between factors connected with the human organism like the age, gender, weight, metabolic rate, type of activity, etc., factors connected with the clothing like thermal resistance, material structure, number of layers, and factors connected with the environment like air temperature, velocity, humidity, pressure and turbulence intensity and frequency [9,15,17,18]. To achieve thermal equilibrium, the body continuously varies the ratio between the heat produced and transferred. Maintaining this balance is the first condition to achieve a feeling of thermal neutrality. Fanger [15] showed that "human thermoregulatory system is quite effective and tends first to make a heat