Journal of Building Engineering 16 (2018) 118–128

Contents lists available at ScienceDirect

Journal of Building Engineering

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

The spatial evaluation of the radiative human body heat exchanges: An effective contribution for limiting energy consumption and achieving better indoor conditions in buildings

Concettina Marino[a,*], Antonino Nucara[a], Giorgia Peri[b], Gianfranco Rizzo[b], Gianluca Scaccianoce[b]

[a] Department of Civil, Energy, Environmental and Material Engineering (DICEAM), "Mediterranea" University of Reggio Calabria, Italy
[b] Department of Energy, Information Engineering, and Mathematical Models (DEIM), University of Palermo, Italy

ARTICLE INFO

Keywords:
Thermal comfort
Radiative exchange
Mean radiant temperature
Projected area factors
HVAC systems

ABSTRACT

Radiative heat exchanges inside buildings remarkably affect the thermal balance of the human body in confined spaces and the related thermal comfort sensations of people. The mean radiant temperature is an important component of this balance. Unfortunately, it is usually computed by means of too simplified relationships, which significantly influence the comfort evaluations. Such simplified approaches are also accountable for a less effective design of HVAC systems which, in turn, could result in high energy consumption in the climatization of buildings. However, an accurate evaluation of the mean radiant temperature, especially when high intensity sources are present in a given internal space, depends on the angle factors between human subjects and surrounding surfaces of the enclosure. Angle factors, in turn, are direct functions of the projected area factors of the human body. Presently, there is still a certain lack in the availability of simple and reliable methods for computing angle factors of people in assigned postures, particularly in case of complex geometry and presence of heat high intensity sources, like sun.

A comprehensive method is here introduced for evaluating the thermal comfort conditions of indoor spaces, avoiding the difficult singling out of several algorithms, dispersed in an inorganic way in the literature. A further contribution consists in the possibility of evaluating geometrically complex enclosures also in presence of direct solar radiation entering the room. Moreover, an analytical method for computing the projected area factors, based on experimental results, obtained by means of a photographic apparatus on purpose designed, is included in the methodology.

An application of the method to a typical building situation in presence of direct solar radiation is also proposed.

1. Introduction

Analytical modelling of heat exchanges involving the human body and the internal surfaces of buildings is a practice often utilized for the evaluation of thermal comfort conditions of people living or working inside the so-called thermal moderate environments. The ASHRAE 55 [1] and the ISO 7730 [2] standards, for example, take into account the predicted mean vote, that is a function of the thermal balance of the human body. In other methods, which exploit the new communication technologies, the subject becomes an active actor in the process of identifying and controlling the best indoor conditions and contributes to improve energy-efficient and environment-friendly management of buildings [3].

However, by and large, in the approach exploited by the most widespread models, the assessment of thermal comfort conditions often implies the solution of the human body thermal balance equation, which involves the various heat fluxes affecting the subject and whose terms depend on a set of subjective, physical and physiological independent parameters, that is: thermal insulation of clothing, metabolic rate, air temperature, air velocity, mean radiant temperature of the surrounding environment, water vapor partial pressure.

In this context, the radiative thermal exchanges are recognized to be one of the pivotal phenomena whose main variable is the mean radiant temperature, which can be expressed as a function of the angle factors between people and the surrounding surfaces.

Angle factors are currently computed by means of graphical and analytical methods included in the ISO 7726 [4] which, however, are referred to mutually orthogonal rectangular surfaces only. However, actually, buildings are often characterized by more complex shapes, where walls are not always mutual orthogonal. In these cases, the

* Corresponding author.

https://doi.org/10.1016/j.jobe.2017.12.015
Received 6 October 2017; Received in revised form 28 December 2017; Accepted 29 December 2017
Available online 31 December 2017
2352-7102/

computation of angle factors by means of the ISO standard is not directly feasible. The same limitation must be noticed for the algorithms currently present in the literature [5–8].

In other words, what is lacking is a comprehensive method for evaluating the thermal comfort conditions of indoor spaces, avoiding the difficult singling out of several algorithms dispersed in an inorganic way in the literature. Further, the possibility of evaluating geometrically complex enclosures also in presence of direct solar radiation entering the room should be on the availability of designers. The present work tries to provide a contribution towards the assessment of a global algorithm suitable for computing mean radiant temperature and the needed human body angle factors referred to generically shaped surfaces of a given building envelope, even in case of tilting and rotating bearings angles of these surfaces. The proposed algorithm is built up on the basis of data acquired during a field measurement campaign, in which a photograph device was utilized for gauging the projected area factors of seated or standing people [6].

The paper contains a brief explanation of this photograph apparatus and of the method for the experimental measurements. Hereafter, a description of the proposed generalized algorithm is presented, along with its application to a typical parallelepiped-building module.

The most innovative aspect of the proposed algorithm is that it permits a fairly realistic analysis of the indoor local changes of the thermal conditions of people occupying different zones of a given room and this leads to a more efficient design of building envelope structures, plant and control systems.

Contributing to extend the current methods for the automatic computation of thermal comfort and energy efficiency to more articulate and realistic configurations, its approach usefully allows a better and more reliable analysis of buildings performances, also leading to a more effective design of the HVAC systems, which are called to guarantee proper indoor physical conditions.

2. Radiative exchanges in confined environments

The net thermal losses by a subject placed in a given indoor environment, Q_S, are equal to the difference between the emitted flow, Q_{0S}, and the absorbed ratio of the thermal flow reaching the subject and coming from the surfaces of the environment, $Q_{A\to S}$:

$$Q_S = Q_{0S} - \alpha_S Q_{A\to S} \tag{1}$$

where α_s is the mean absorptance of the human body.

Eq. (1) may be placed in a more general form by taking into account the presence of high intensity radiative fluxes and solar radiation striking the human body: in such case, an increase of the absorbed share of the thermal flow reaching the subject should be considered.

Therefore, in presence of high-intensity radiative sources the expression will be:

$$Q_S = Q_{0S} - \alpha_S Q_{A\to S} - \alpha_{irr} Q_{irr\to S} \tag{2}$$

where Q_{irr} is the total amount of the radiation that, starting from the high-intensity radiative sources, hits the subject and α_{irr} is the absorbance of the outer surface of the subject at the actual mean wavelength of the radiation.

Instead, in presence of solar radiation, the previous balance becomes:

$$Q_S = Q_{0S} - \alpha_S Q_{A\to S} - \alpha_{irr}(Q_{d\to S} + Q_{b\to S}) \tag{3}$$

in which $Q_{d\to S}$ and $Q_{b\to S}$ are respectively the diffuse and the direct solar radiation entering the room through the glazed surfaces.

In the hypotheses that: a) the inner surface of the environment behaves as black surface; b) the diffuse radiation entering the room through the glazed surfaces follows the Lambert's law; c) the temperature of the human body is equal to the mean temperature of the clothed surface of the human body; d) the human body is considered as a small object with respect to the dimensions of the confined environment, the net thermal flow, $Q_{S\leftrightarrow A}$, exchanged by radiation between the subject and the black enclosure can be expressed as follows:

$$Q_{S\leftrightarrow A} = A_r \varepsilon_S \sigma (T_{cl}^4 - \overline{T}_r^4) \tag{4}$$

where A_r is the effective radiating area of the body, σ the Stefan-Boltzmann constant, ε_S the emittance of the person, T_{cl} the mean temperature of the clothed surface of the human body and $\overline{T}_r$ the mean radiant temperature.

Since the net flow leaving the human body is equal to the thermal flow exchanged by radiation between the subject and the environment, it is possible to write:

$$Q_S = Q_{S\leftrightarrow A} \tag{5}$$

from which it is possible to derive the equation of the mean radiant temperature [9]:

$$\overline{T}_r = \sqrt{\sum_{i=1}^{N} F_{S\to i} T_i^4 + \frac{\alpha_{irr,d} \sum_{j=1}^{M} F_{S\to j} I_{d,j}}{\varepsilon_S \sigma} + \frac{\alpha_{irr,b} f_p I_b}{\varepsilon_S \sigma}} \tag{6}$$

where $F_{S\to i}$ represents the angle factors between the subject and the opaque or transparent surfaces, T_i is the temperature of the i-th surface, I_d and I_b are respectively the intensity of the diffuse or direct component of the solar radiation and f_p is the projected area factor.

Due to the presence of the view factors and of the intensity of the solar radiation, the proposed expression allows the assessment of the time and spatial variability of the thermal condition, so that indoor areas where thermal comfort is achievable may be properly mapped [10]. This approach is also easily associable with local discomfort analysis, capable of considering the effect of solar radiation on the values of the radiant asymmetry [11,12].

On the other hand, in many actual cases, when the solar short wave radiation (wavelength < 2 μm) is considered, the hypothesis of black body behavior regarding the internal surfaces of the building, which is the basic hypothesis of Eq. (6), cannot suffice to assess the real conditions of the environment with the needed level of accuracy. In those cases Eq. (6) can be easily modified in order to take into account the reflected component of the short-wave radiation [13].

Conversely, in the simplest case of absence of solar radiation, the expression (6) becomes:

$$\overline{T}_r = \sqrt{\sum_{i=1}^{N} F_{S\to i} T_i^4} \tag{7}$$

However, with or without the presence of solar radiation, the calculation of the mean radiant temperature needs the knowledge of the angle factors between human body and surrounding surfaces. Actually, they represent the most important element in the assessment of the mean radiant temperature in the very frequent real situations occurring in complex geometry buildings.

3. Angle factors and projected area factors

The main objective of the paper originates from the consideration that the mean radiant temperature is a local definable parameter and that, in order of achieving an accurate evaluation of indoor thermal comfort conditions, it must be properly evaluated in its spatial change.

This local computation requires the punctual knowledge of the angle factors between the human body, in a given posture, and the surrounding surfaces of the building envelope. In turn, angle factors depend on the projected area factors, which is on the shape that the human body presents towards incoming radiation.

In the following sections, the existing methods for assessing angle factors and projected area factors are revised, along with the equations describing them. Actually, these equations can be usefully introduced in the comprehensive algorithms for computing the mean radiant temperature, as it is here proposed (Eqs. (6) and (7)).