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The effect of the short wave radiation and its reflected components on the mean radiant temperature: modelling and preliminary experimental results

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ABSTRACT

In outdoor as well as indoor environments, human thermal sensation strongly depends on the direct component of solar radiation incident on the body. Nevertheless, even though the direct component exerts the major contribute on this issue, especially in indoor environments and confined spaces, the diffuse and reflected components of the solar radiation also affects the thermal sensations of people. Despite this evidence, simple and reliable methods designed to take into account the effect of solar radiation on the indoor radiant field enveloping the human being in indoor environments are hardly available.

This article aims to provide a contribute on this topic, proposing a model for the computation of the mean radiant temperature (MRT) in indoor environments in presence of solar radiation. The most innovative facet of the proposed model regards the computation of the effects of the radiation components reflected by the internal surfaces.

Moreover, in order to try a preliminary validation of the model, an experimental campaign was also carried out and MRT values were measured in positions either directly irradiated by the sun or shielded from direct irradiation. The purpose of the measurements was to preliminarily analyze the extent of the accuracy with which the model might predict the rise of MRT due to solar direct irradiation.

1. Introduction

In both outdoor and indoor environments, human thermal comfort is influenced by various factors (climate conditions, physiological and subjective issues, etc.), which have combined and diversified effects on human energy balance. Comfort and energy demand in buildings are strongly interconnected and the achievement of high quality standards involves an energy cost, which must be taken into account [1–3]. The maintenance of the required environmental quality levels, as a matter of fact, implies that a series of environmental variables should be controlled within recommended values [4]; nevertheless, this approach could not suffice in many actual cases, when comfort indexes [5], parameters and variables should be accurately evaluated [6,7].

Among all these factors, radiative heat exchanges play a pivotal role: in confined environments they contributes as far as 30% of the whole thermal exchanges involving the subject [8], but in case of direct solar radiation they can become the most significant cause of heat gain and discomfort [9].

The mean radiant temperature, MRT, is one of the main factor used to quantify the effect of the radiant field on human thermal response [10]. This quantity plays a crucial role in both outdoor and indoor situations and several studies have stressed the influence of this variable on thermal comfort in urban settings [11], researching and comparing reliable and feasible methods for its assessment [12–14] or its measurement [15–18]. All these studies, moreover, consider solar radiation as a key factor in the assessment of the mean radiant temperature on the grounds that thermal comfort is highly dependent on both long wave and short wave radiation fluxes from the surroundings.

In indoor environments, the influence of the mean radiant temperature on thermal comfort is also well documented [19–23]. Moreover, in this case, MRT also influences the energy consumption to a certain extent. The issue has been investigated, analyzing the energy saving potential in a PMV-controlled space [24]. The results suggested that energy consumption, in a thermal comfort-controlled space, is strongly affected by a change in the mean radiant temperature and that the thermal comfort control can be considered as a reasonable strategy for both thermal comfort and energy saving purposes which, in turn, are to become one of the main objective of the building industry all over the world [25–28].

On balance, the accurate assessment of radiant field and MRT is the key to achieving both comfort optimization and energy efficiency.

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Nomenclature

A_i	area of the *i*th surface of the envelope [m^2]
A_E	whole area of the surface of the envelope [m^2]
A_p	projected area of the subject onto a plain normal to the direction of the solar beam [m^2]
A_S	effective area of the human body exposed to radiation [m^2]
D	globe-thermometer diameter [m]
$\Delta\overline{T}_{rb}$	contribution to the mean radiant temperature due to the direct component of the solar radiation [K]
f_p	projected area factor
$F_{j\to i}$	angle factor between the *j*th glazed surface and the *i*th surface of the envelope
$F_{S\to j}$	angle factor between the subject and the *j*th glazed surface of the envelope
h_{cg}	convective heat transfer coefficient [W m^{-2} K^{-1}]
I_b	direct solar radiation that strikes the subject [W m^{-2}]
I_{bh}	direct solar radiation on the horizontal plane [W m^{-2}]
I_{dj}	diffuse sky radiation entering the room through the *j*th glazed surface [W m^{-2}]
I_h	global solar radiation on the horizontal plane [W m^{-2}]
Q_{0S}	emitted flow [W]
$Q_{A\to S}$	radiative flux emitted by the surfaces of the environment [W]
$Q_{B\to S}$	short wave solar radiant flux on the body surface, entering the room through the glazed surface and due to the direct radiation [W]
$Q_{D\to S}$	short wave solar radiant flux on the body surface, entering the room through the glazed surface and due to the diffuse sky radiation [W]
$Q_{E\leftrightarrow S}$	flux exchanged for radiation among the human body and the surfaces of the environment [W]
Q_S	net flux leaving the human body [W]
$Q_{S,abs}$	absorbed share of the thermal flow that reaches the subject [W]
T_a, t_a	air temperature [K, °C]
T_{cl}	mean temperature of clothed surface [K]
T_g, t_g	globe-thermometer temperature [K, °C]
T_{gd}, t_{gd}	globe temperature, in not directly irradiated position [K, °C]
T_{gb}, t_{gb}	globe temperature, in irradiated position [K, °C]
T_i	temperature of the *i*th surface of the envelope [K]
$\overline{T}_r$, $\overline{t}_r$	mean radiant temperature [K, °C]
$\overline{T}_{rb,C}$, $\overline{t}_{rb,C}$	calculated mean radiant temperature, in the presence of the direct component of the solar radiation [K, °C]
$\overline{T}_{rb,M}$, $\overline{t}_{rb,M}$	measured mean radiant temperature, considering the effect of the direct component of the solar radiation [K, °C]
$\overline{T}_{r,C}$, $\overline{t}_{r,C}$	calculated mean radiant temperature [K, °C]
$\overline{T}_{rd}$	mean radiant temperature, without considering the direct component of the solar radiation [K]
$\overline{T}_{rd,M}$	measured mean radiant temperature, without considering the effect of direct component of the solar radiation [K]
$\overline{T}_{r,M}$	measured mean radiant temperature [K]
v_a	air velocity [m s^{-1}]

Greek symbols

α	solar altitude [°]
α_{LW}	long wave absorbance of the human body
α_{SW}	short wave absorbance of the human body
ε_g	emissivity of the globe-thermometer
ε_s	emissivity of the human body
ε_E	emissivity of the surfaces of the environment
ρ_i	reflectance of the *i*th surface of the envelope
ρ_{floor}	reflectance of the pavement
σ	Stefan–Boltzmann constant (5,67×10^{-8} W m^{-2} K^{-4})

However, also in indoor environments, both radiant field and MRT are strongly affected by short wave and long wave radiation fluxes and several experimental analysis have demonstrated that solar radiation is a significant cause of discomfort to people [29].

Despite this evidence, there are few models [8,30,31] which allow analytical assessment of MRT taking into account solar radiation.

This article aims to provide a contribute on this topic, proposing a model for the computation of mean radiant temperature values, in thermal moderate indoor environments, in the presence of solar radiation. The most innovative facet of the proposed model regards the computation of the effects of the radiation components reflected by the indoor surfaces. Indeed, considering the various surfaces which, by and large, the building envelope is composed of, these components might have a considerable influence on MRT.

In order to further investigate on this subject, an experimental campaign was also carried out using the globe-thermometer method and MRT values were measured in positions directly irradiated by the sun or shielded from direct irradiation.

2. The calculation of the mean radiant temperature of a subject exposed to solar radiation: the proposed model

The proposed model is aimed at the calculation of the mean radiant temperature ($\overline{T}_r$) inside an indoor environment when the human subject is exposed to direct, diffuse and reflected solar radiation.

It considers the human body totally surrounded by an enclosed environment, so that, in this condition, if only radiative thermal exchange are taken into account, the net flux leaving the human body (Q_S) is equal to the flux exchanged for radiation among the human body and the surfaces of the environment ($Q_{E\leftrightarrow S}$) which the subject is in. That is [8,32]:

$$Q_{E\leftrightarrow S}=Q_S \tag{1}$$

According to the MRT definition (which is the uniform temperature of an enclosure where the radiative flux on the subject, is the same as in the actual environment [33]), it is now assumed that the environment is an enclosure with an uniform temperature $\overline{T}_r$; it is also assumed that the temperature of the human body is equal to the mean temperature of its clothed surface, T_{cl}. In this case, the thermal radiative flow exchanged between a subject and the surrounding surfaces of the enclosed environment is given by [8,32]:

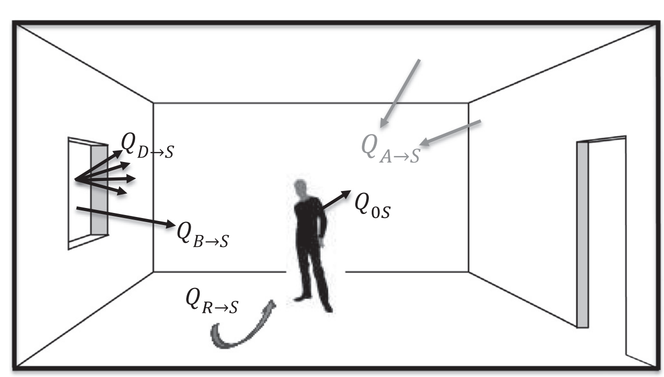

Fig. 1. Radiative exchanges between the environment and the human body.