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Thermal environment characterisation of a glass-covered semi-outdoor space subjected to natural climate mitigation

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ABSTRACT

The human thermal sensation inside a semi-outdoor space enclosed by a semi-transparent pitched roof, located in Parma, north of Italy, is compared with the outdoor sensation under the same climate conditions. The assessment of the semi-outdoor setting was performed using the Physiological Effective Temperature (PET) thermal sensation index. With the aim of mitigating the semi-outdoor climate, some natural means were considered at the design stage, namely, the solar radiation absorptivity of the glass sheet roof, natural airflow, space thermal capacity and roof evaporative cooling. The dynamic thermal simulation of the semi-outdoor space was performed for three representative weeks of the months of January, March and July by accounting for the actual climate of the location. The results show that the semi-transparent roof can improve the human thermal sensation inside the semi-outdoor space with respect to that of the outdoor space. The results also demonstrate the effect of each design parameter on the PET index.

1. Introduction

Many outdoor microclimates previously regarded as beyond control can now be mitigated by man-made structures that produce semi-outdoor, partially controlled spaces. In a semi-outdoor setting, the human subject, characterised by physiology, activity and clothing, interacts with his thermal environment, which combines air temperature and humidity, wind speed and infrared and solar radiation. The semi-outdoor setting results in a very complex and heterogeneous thermal condition, which may approach health limits. Consequently, thermal comfort in semi-outdoor settings, i.e., in the field of outdoor location modification to moderate the full impact of the outdoor environment, has recently received much research consideration. Thermal comfort assessments of semi-outdoor environments have been recently applied to sports stadia [1,2], leisure/rest spaces [3,4] and bus shelters [5]. These research works have shown that, in semi-enclosed spaces, the main cause of thermal discomfort may be due to the solar radiation, both direct and as transmitted through a semi-transparent roof or wall.

Recently, Pagliarini and Rainieri [6] considered a space semi-enclosed by a glass roof either dry or subject to evaporative cooling, but they did not examine the thermal comfort aspect of the problem. Glass roofing may produce a semi-outdoor setting that attenuates extreme environmental conditions without excessive penalties in terms of natural lighting requirements. However, in the hot season, the solar radiation both absorbed in the glass sheet and transmitted through it can overheat the semi-outdoor space to temperatures that are incompatible with an acceptable thermal environment. To mitigate the effect of excessive solar radiation, a natural cooling technique may be suitable, i.e., a technique based on natural heat and mass transfer phenomena. The roof inclination angle over the horizontal plane promotes air changes due to buoyancy effects, thus attenuating excessively high air temperature. The thermal capacity of the structures included in the space can mitigate the thermal environment by both amplitude attenuation and phase shifting of the solar heat load. The glass roof absorptivity and reflectivity can reduce the solar radiation transmitted to the space underneath. Evaporative cooling can remove the heat absorbed by the roof before it enters the controlled space.

An effective, physiologically significant method to assess the global effect of all climatic solicitations on the human body is to compute the body energy balance. In this procedure, the definition of an equivalent temperature is used to quantify all thermal inputs of a particular outdoor or semi-outdoor environment and summarise them as a single ambient indoor temperature that would induce the same thermal environment as it is felt by an average person.

In this paper, the thermal environment underneath the glass roof analysed in [6] is considered from the point of view of human

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Nomenclature

a	glass sheet solar radiation absorptivity
A	glass sheet solar radiation overall absorptivity
C	thermal capacity per unit floor area (J/m^2 K)
d_g	glass sheet thickness (m)
D	width of the semi-outdoor space (m)
F	view factor
f_p	rotationally averaged projected area factor
h_c	convective heat transfer coefficient (W/m^2 K)
h_r	radiation heat transfer coefficient (W/m^2 K)
H	roof high (m)
L	length of the semi-outdoor space (m)
L_r	roof length (m)
PET	physiological effective temperature (°C)
q	heat flow rate (W/m^2)
q_e	evaporative heat flow rate (W/m^2)
q_g	absorbed solar radiation per unit surface area (W/m^2)
R	short wave radiation (W/m^2)
t	glass sheet solar radiation transmissivity
T	temperature (K, °C)
T_{mr}	mean radiant temperature (K, °C)
U	air velocity (m/s)
V	volume flow rate (m^3/s)
W	wind speed at the meteorological level (m/s)
x	coordinate normal to glass sheet surface (m)
z	elevation above ground (m)

Greek symbols

α	human body absorption coefficient for solar radiation
ε	human body thermal radiation emissivity
θ	roof inclination angle (°)
λ	thermal conductivity (W/mK)
σ_0	Stefan–Boltzmann constant (W/m^2 K^4)
τ	time (s)

Subscripts

a	air
av	mean value
b	direct
d	diffuse
g	glass
i	inside
m	basement
o	outside
r	roof
sky	apparent sky
w	wind

thermal sensation. In addition to the Roof Evaporative Cooling (REC) system, the thermal mitigation effects of glass sheet roof solar radiation absorptivity, roof inclination angle and space thermal capacity were investigated. To evaluate the effectiveness of these techniques, the Physiological Effective Temperature (PET) thermal sensation index was adopted in conjunction with the thermophysiological Munich Energy Balance Model for Individuals (MEMI) [7]. This index can provide insights into the ability of the different design options to mitigate thermal sensations in a semi-outdoor space setting.

2. Analysis

The semi-outdoor space under investigation is schematically shown in Fig. 1a. It is located in an urban zone of the town of Parma, north of Italy, and it consists of an air layer underneath a plane glass roofing facing south, with an inclination angle θ with respect to the horizontal plane. The space length is L = 36 m, and the minimum roofing height is $H_{\min}$ = 4.5 m. The space is completely open to the outer environment at both sides, and its width, D, in the direction normal to the figure, is considered unlimited, so that the thermal problem can be approached with reference to a unit space width. The space includes a mass thermal capacity, which is assumed to be uniformly distributed at the floor level.

On sunny days, the solar radiation impinging the roof is partially reflected, partially absorbed in the glass sheet, and partially transmitted to the inner space, where it is absorbed by the space thermal capacity, which is lumped in the semi-outdoor space basement. The heat absorbed by both the basement and the roof is, at least in part, transferred to the inside air by thermal convection. The consequent heating effect drives a natural airflow through the open ends of the semi-outdoor space, which is higher for higher roof slopes. This air circulation combines with the forced airflow due to wind, which is assumed to act in an assisting mode.

Without the action of a proper HVAC system, the thermal environment in the semi-outdoor space cannot be set to a required comfort value. In this condition, its assessment may be performed by comparison with the thermal environment that would be established outdoors under the same climate conditions (Fig. 1b).

Pagliarini and Rainieri [6] have presented a detailed analysis of the thermal problem, which is shown schematically in Fig. 1a. They formulated the unsteady energy balance for both the interior air volume and the basement by a lumped parameter approach while considering the actual temperature variation across the glass sheet.

The energy balance equations are listed below, and [6] gives the computational details.

The energy balance of the roof, per unit of roof area, is expressed by the Fourier equation:

$$C_g \frac{L}{L_r} \frac{\partial T_r}{\partial \tau} = \lambda_g d_g \frac{\partial^2 T_r}{\partial x^2} + q_{g,r}$$

where the heat generating term, $q_{g,r}$, includes the solar radiation absorbed by the glass sheet, whose thickness is d_g.

At the roof to ambient interface, the heat fluxes are given as follows for the lower and upper side of the roof, respectively:

$$q_i = h_{ci}(T_{r,i} - T_i) + h_{ri}(T_{r,i} - T_m)$$

$$q_o = h_{co}(T_{r,o} - T_o) + h_{ro}(T_{r,o} - T_{sky}) + q_e$$

where q_e is the evaporative heat flux.

The energy balance equation of the air layer included between the roof and basement is, per unit of floor area,

$$C_{a,av} \frac{dT_i}{d\tau} = h_{ci} \frac{L_r}{L}(T_{r,i} - T_i) + h_{cm}(T_m - T_i) + \frac{C_{a,av}}{LDH_{av}}(V_a + V_w)(T_o - T_i) \quad (2)$$

V_a is the ventilation flow rate driven by the indoor to outdoor air temperature difference and V_w is the ventilation flow rate due to wind.

The energy balance equation of the basement, per unit floor surface area, is

$$C_m \frac{dT_m}{d\tau} = h_{cm}(T_i - T_m) + h_{ri}(T_{r,i} - T_m) + q_{g,m} \quad (3)$$

where the heat generating term, $q_{g,m}$, accounts for the solar radiation absorbed by the basement.

For the outdoor location (Fig. 1b), instead, the energy balance is expressed by Eq. (3) alone.