Solar Energy 158 (2017) 572–594

Contents lists available at ScienceDirect

Solar Energy

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

Overheating phenomena induced by fully-glazed facades: Investigation of a sick building in Italy and assessment of the benefits achieved via fuzzy control of the AC system

Giulia Ulpiani

Dipartimento di Ingegneria Industriale e Scienze Matematiche (DIISM), Facoltà di Ingegneria, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

ARTICLE INFO

Keywords:
Overheating
Large glazed façade
Indoor thermal comfort
Fuzzy control

ABSTRACT

This paper investigates the overheating due to overabundant solar gains through fully glazed façades, aligned on the heliothermal axis. An Italian sick building was selected as case study to quantify the level and the characteristics of discomfort and verify whether a smart control of the AC system could suffice in restoring satisfactory environmental conditions.

Fuzzy control logics were designed and implemented to regulate the speeds of the false-ceiling fan coil unit serving the office, selected as exemplary environment. Data were collected by an articulated sensor network mapping internal and external climate conditions as well as the thermal distribution on the internal side of the glazed façade and inside the fan coil ducts.

Each configuration was assessed on a representative sunny day in terms of global comfort (operative temperature, PMV), local discomfort (draught rate, vertical gradient) and energy consumption.

Serious overheating episodes were recorded throughout the year and in every configuration. Nevertheless, non-negligible improvements were achieved by including outdoor temperature and solar radiation in the control algorithm which allowed to narrow down the offset from to the set point (resulting in PMV < 1 for the 97.2% of the time) and limit the use of the full-power mode (with all associated energy benefits).

1. Introduction

Today, the general trend in the construction of offices and public buildings is to privilege large areas of glass façade, mostly for aesthetic reasons.

All around the world, the skyline of the major cities is dominated by glass towers, regardless of totally different outdoor temperature profiles and global horizontal irradiance levels. Yet the adoption of such architectural design appears to be the most vulnerable to climate variations (Altan et al., 2008).

Indeed, windows thermo-optical properties play a major role in the building energy balance both during the heating and the cooling season (Chiras, 2002; Gasparella et al., 2011; *Technical codes for energy conservation design of office buildings*, 2005; Ward, 2004). Thereby, when unproperly designed, they might lead to huge energy inefficiency, trigger thermal discomfort and act as a health and productivity drain (Lyons et al., 2000).

Sustainable building criteria underpin the need to conceive the windows as filters and climate moderators, keeping in daylight, useful solar gains and ventilation while discarding excess heat, draughts, noise and rain.

Accordingly, all the mechanisms though which solar radiation interrelates with the built environment need to be tackled. Solar energy enters the building in multiple ways:

- by conduction, thus increasing the temperature of the glazed interior surface which, in turn, causes the mean radiant temperature to rise;
- by direct radiation, which affects occupants' thermal balance at the same extent of an 11 °C rise in mean radiant temperature (Arens et al., 1986);
- by diffuse radiation - generated by molecules and particles in the atmosphere that scatter the sunlight - which represent the main contribution on overcast days;
- by absorption and emission from lit indoor surfaces.

Computation and analysis of such effects is a rather complex task. Extensive literature exists on the subject.

Oliveti et al. suggested a simplified, yet accurate model for the calculation of solar heat gain through glazed surfaces in air-conditioned buildings (Oliveti et al., 2011). La Gennusa et al. (2007, 2005) proposed a general approach to quantify the thermal radiant field induced by solar radiation over individuals. Zmeureanu et al. (2003) developed a practical tool to assess the impact of radiation from windows on occupants' thermal sensation. Lyons et al. (2000)) and Sullivan (1986) proposed a method to split the Predicted Mean Vote (PMV) into two

http://dx.doi.org/10.1016/j.solener.2017.10.024
Received 7 July 2017; Received in revised form 28 September 2017; Accepted 6 October 2017

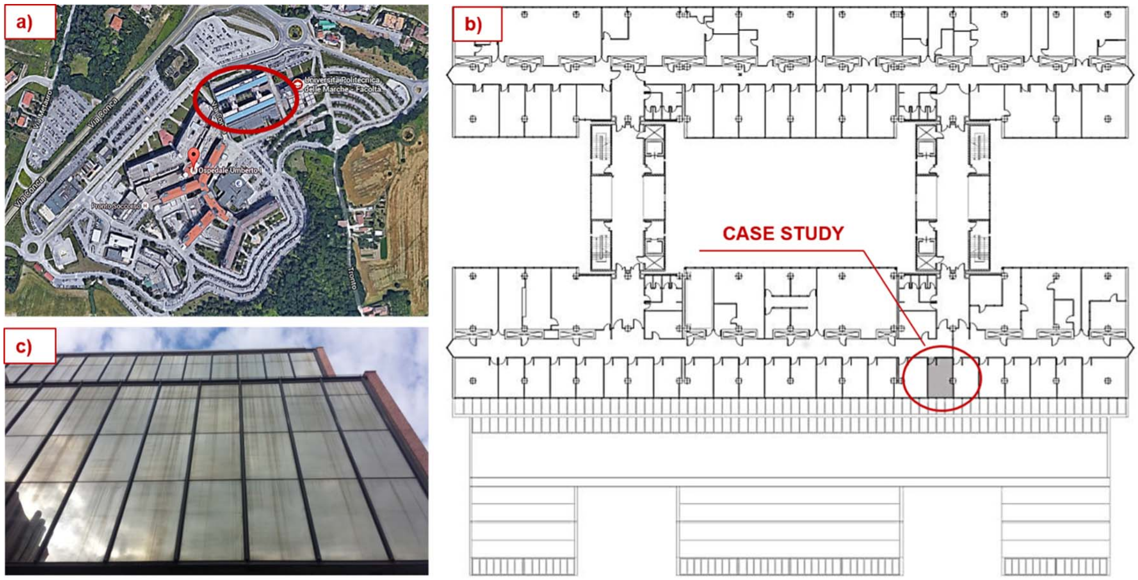

Fig. 1. Case study: (a) satellite localization, (b) plan view and identification of the office under investigation, (c) view of the fully-glazed façade.

components, one accounting for solar radiation and the other for surface temperature. Another modification of the PMV to refine solar radiation contribution was proposed by Ohnaka et al. (2005), based on test chamber experimental activities. Tzempelikos et al. (2010) developed a transient thermal comfort model to investigate in a separate and multi-criterion way the impact of different shades and glazing in offices with high window-to-wall ratio. Trombe et al. (1999) conceived and experimentally validated a zone thermal simulation model via TRNSYS of solar gain local characteristics. Marino et al. (2017) proposed a method to evaluate the radiant asymmetry caused by both direct and diffuse components of solar radiation. Cappelletti et al. (2014) simulated and analysed the energy performance of an open-space office with different window characteristics (glazing system, area, disposition and orientation) under controlled internal comfort conditions and according to different climates by including the effect of the diffuse and beam solar radiation. Although quite good thermal indoor conditions were generally satisfied, the detrimental effect of potentially excessive solar radiation was mirrored by time variable or locally inhomogeneous conditions.

A general remark is that radiant asymmetries (through the single room or zone as well as throughout the building) constitute a prominent issue:

- from the energy perspective, skew distributions of the irradiative sources are likely to jeopardise the manageability of the loads: on a wintry day, sun-exposed rooms might require a certain cooling load to counteract the heat irradiated by the hot surfaces of the lit façade, while those in the shade might need to be heated up;
- from the ergonomic perspective, radiant asymmetry represents a major trigger for local discomfort phenomena (ISO, 2006), notably when the occupants are in close proximity to highly-glazed façades (i.e. offices, classrooms, auditoriums, …): over long periods, the constant thermal stress is likely to affect the immunological system (Sick Building Syndrome – SBS) (Mølhave, 1989).

Table 1
Test office general data.

Location	
Address	*Polo* Did. *Eustachio* – School of Medicine; 10 A, Via Tronto; Ancona (Italy)
Latitude	43.60°
Longitude	13.46°
Elevation [a.s.l.]	31.13
Köppen-Geiger classification	Cfa
Characteristics	
Gross area [m × m]	3.70 × 5.64
Net area [m^2]	19.17
Indoor volume [m^3]	57.51
Surface/Volume Ratio [m^2/m^3]	0.33
Surface mass [kg/m^2]	171

Human body is particularly receptive to radiant heat, up to four time more than to any other form of heat (Fanger et al., 1970); accordingly, mild increases of radiant temperature might suffice in creating very uncomfortable microclimates. Even so, most of room temperature sensors driving the HVAC systems are not IR-based and neglect such component, even in presence of massive sources of radiation (like large glazed facades).

Several design parameters affect indoor mean radiant temperature and thereby compete in the occurrence of discomfort phenomena: window size and geometry, building layout and orientation, thermo-optical properties of opaque and transparent materials used, scale and surface properties of the surrounding buildings, outdoor weather conditions…

Various papers witness such complex interlacement.

Singh et al. tested 15 different glazing systems - from 3 mm single glazed clear glass to double glazed, low-e and solar control coatings – to quantify their impact on human thermal comfort (PMV-PPD method) (Singh et al., 2008). Chaiyapinunt et al. (2005) investigated the thermal behaviour of clear glass, tinted glass, reflective glass, double pane glass, and low-*e* glass: the former led to the strongest discomfort condition despite the low heat absorption. Hien et al. (2005) ran comparative simulations of single and double-glazed facades in terms of energy consumption, thermal comfort and condensation in Singapore's climate. In the same vein, Stegou-Sagia et al. (2007) and Ihm and Krarti (2012) examined the impact of glazing systems on energy and comfort in Greece and Tunisia respectively. Hwang and Shu (2011) ran parametric simulations of a highly-glazed façade (changing glazing types, areas and depths of overhang) to investigate occurrences and severity of overheating, based on the PMV-PPD model.

Existing low energy buildings rely on double/triple glazing, low-e and heat absorptive and/or reflective, provided with an external solar shading system (Bahaj et al., 2008; Dascalaki and Santamouris, 2002). Yet most of high window-to-wall-ratio buildings do not combine such