A STUDY OF THE EFFECTS OF SOLAR RADIATION ON THE INDOOR ENVIRONMENT

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ABSTRACT

This paper presents an experimental and numerical study that quantifies the effects of both direct and diffuse transmitted solar radiation on thermal comfort in terms of globe temperature, and shows the need for including this parameter in the comfort estimation for buildings with large solar gains. A linear model is used to predict the effect on the globe temperature of solar radiation transmitted through the window. The experimental and numerical results obtained are in good agreement with those given in the Chartered Institution of Building Services Engineers (CIBSE) Guide. *Furthermore, it is also shown that diffuse solar radiation can have a significant effect on the thermal comfort of occupants of buildings with large windows.*

INTRODUCTION

Thermal comfort in an indoor environment is influenced by many parameters, the most important ones being temperature, air velocity, humidity, and thermal radiation. The latter parameter has a significant influence on the thermal environment in rooms with significant solar gains. Solar radiation transmitted through fenestration has two effects on the indoor thermal environment: (1) immediate effects due to the incidence of direct and diffuse transmitted solar radiation on people and (2) indirect effects due to absorption of part of the solar radiation by the room interior surfaces and furnishings and subsequent reradiation (longwave) or convection from these surfaces.

The amount of direct solar radiation absorbed by a person depends on the position of the sun, the window properties, and his or her average solar absorptance. Gianccone and Gianfranco (1986) developed a computer program to calculate thermal comfort maps that show the influence of the internal distribution of hourly radiation on thermal comfort taking into account the presence of direct, diffuse, and reflected radiation falling on the occupant. Solar radiation was modeled with two different methods: (1) uniformly distributed on all room surfaces and (2) its internal distribution accurately calculated taking into account the hourly path of solar radiation and external as well as internal shadowing effects. The two methods showed great differences in their estimation of thermal comfort. The Predicted Mean Vote (PMV) model was applied to estimate the thermal comfort level (Fanger 1970).

The *CIBSE Guide* (1987) states that the only significant component of transmitted solar radiation (for thermal comfort calculations) is the direct component. It gives the effect of varying levels of direct solar radiation on effective mean radiant temperatures. For example, for a clothing/skin absorptance of 0.8 and incident solar radiation equal to 500 W/m^2, a rise of 14.4°C in the effective mean radiant temperature is reported (equivalent to 7.7°C in the dry resultant temperature, which is what would be approximately measured with a globe thermometer having the same absorptance). Similar results have been reported by Olesen et al. (1989).

This paper attempts through both experiments and simulation to further quantify the direct and indirect effects of solar radiation on thermal comfort. Measured data from three heating-season days will be reported and compared with simulations of the operative and room air temperatures. The simulation will assist in the analysis and interpretation of the measured data.

BACKGROUND

The energy balance for a globe thermometer in the center of a room that does not receive any solar radiation is (ASHRAE 1981)

$$\epsilon_g \sigma (T_g^4 - T_{mrt}^4) + h_c (T_g - T_{ai}) = 0 \qquad (1)$$

where T_{mrt} is the mean radiant temperature (K)—the uniform surface temperature of a black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual enclosure. The convective heat transfer coefficient is given by (ASHRAE 1987)

$$h_c = 6.32 D^{-0.4} v^{0.5} \qquad (1a)$$

where D is globe diameter (m) and v is air velocity (m/s). Equation 1 can be expressed as

$$T_{mrt}^4 = T_g^4 + C v^{0.5} (T_g - T_{ai})$$

where

$C = 6.32 D^{-0.4}/\epsilon_g \sigma$
($C = 2.47 \times 10^8$ for $D = .15$ m and $\epsilon_g = 0.96$).

Similarly, for a globe that receives solar radiation, we add the contribution of the diffuse (q_d) and beam (q_b) solar radiation absorbed by the globe (with solar absorptance α_g):

$$\epsilon_g \sigma (T_g^4 - T_{mrt}^4) + h_c (T_g - T_{ai}) = \alpha_g (q_d + \frac{q_b}{4}) \qquad (2)$$

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or

$$T_{mrt}^4 = T_g^4 + C v^{0.5}(T_g - T_{ai}) - \frac{\alpha_g}{\varepsilon_g \sigma}(q_d + \frac{q_b}{4}).$$

Note that the beam term is divided by four because the projected area of a sphere is one-fourth of its surface area. For convenient analysis, we may also linearize Equation 2 by expressing the longwave radiation term $\epsilon\sigma(T_g^4 - T_{mrt}^4)$ as $h_r(T_g - T_{mrt})$, where the radiative heat transfer coefficient is given by

$$h_r = 4\,\varepsilon_g\,\sigma\,T_m^3 \tag{3a}$$

and the mean temperature T_m is estimated as

$$T_m = (T_g + T_{mrt})/2.$$

The corresponding convective heat transfer coefficient for the globe is given by Equation 1a. The linearized form of Equation 2 is thus given by

$$h_r(T_g - T_{mrt}) + h_c(T_g - T_{ai}) = \alpha_g(q_d + q_b/4).$$

Therefore, the globe temperature may be explicitly determined as

$$T_g = [h_r T_{mrt} + h_c T_{ai} + \alpha_g(q_d + q_b/4)]/(h_r + h_c). \tag{4}$$

The operative temperature T_e is defined (ASHRAE 1981) as the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment:

$$T_e = (h_r T_{mr} + h_c T_{ai})/(h_r + h_c). \tag{5}$$

Comparison of Equations 4 and 5 reveals that if the heat transfer coefficients h_r and h_c are the same in the two cases, then the globe temperature will be equal to the operative temperature in the absence of solar gains.

TEST FACILITY AND EXPERIMENTAL PROCEDURE

An outdoor experimental test room with a large window and high solar gains was used for this study. The test room is of lightweight construction, has a double-glazed window facing 10 degrees east of south, and is equipped with both radiant and convective electric heating. It is fully instrumented for thermal measurements, which are typically recorded for periods of 15 minutes to one hour with a digital data acquisition and control system. Experimental measurements of globe temperature at two locations in the room and of surface and air temperatures have been performed for several sunny days. A schematic of the experimental setup is shown in Figure 1. As indicated in Figure 1, one globe (TGW) is near the window and the other (TGC) is in the center of the room. TGW receives beam radiation all day, while TGC receives beam radiation only part of the time; this setup permits determination of the relative impacts of diffuse and beam solar radiation on thermal comfort. The effect of diffuse solar radiation on globe temperature is equal to the difference between TGC and the operative temperature (provided the center globe receives no beam radiation). The room air temperature, as well as the transmitted solar radiation, was also measured using a shielded thermocouple. Room interior surface temperatures were also evaluated by means of an infrared radiometer.

The solar absorptances of the room interior surfaces were measured by means of a pyranometer, which detects total hemispheric solar radiation. The reflectance of a surface is equal to the reflected solar radiation (measured by pointing the pyranometer to the surface) divided by the incident solar radiation. The values of the solar absorptance measured were 0.75 for the floor and 0.24 for the off-white walls and ceiling.

The area-weighted level of diffuse radiation in the room, q_d, was determined for one day by pointing a pyranometer at each of the six directions (walls, floor, and ceiling) and taking a reading while being careful to shield it from direct sunlight. The measurements were taken from the point of observation of the globe thermometer TGC (i.e., the center of the room). Each reading was then multiplied by the area of the corresponding surface, added together, and finally divided by the sum of the areas, giving a reasonable approximation of the average indoor diffuse radiation as observed by the globe. For a typical winter sunny day the total amount of solar radiation transmitted into the room was about 600 W/m^2, of which approximately 100 W/m^2 was diffuse. The average level of diffuse solar radiation, q_d, around the globe was measured to be in the range of 40 to 60 W/m^2. As noted from Equations 2 and 4, the influence of diffuse radiation is four times that of beam radiation, that is, 50 W/m^2 of diffuse radiation has the same effect on globe temperature as 200 W/m^2 of beam radiation.

RESULTS AND DISCUSSION

Figure 2 shows the measured values of solar irradiation, globe temperatures TGW and TGC, room air temperature TAI, and outside temperature for November 11, 1990. At 8:30 p.m., the solar radiation transmitted into the room was 550 W/m^2 (approximately 70 W/m^2 diffuse) and only the globe near the window received

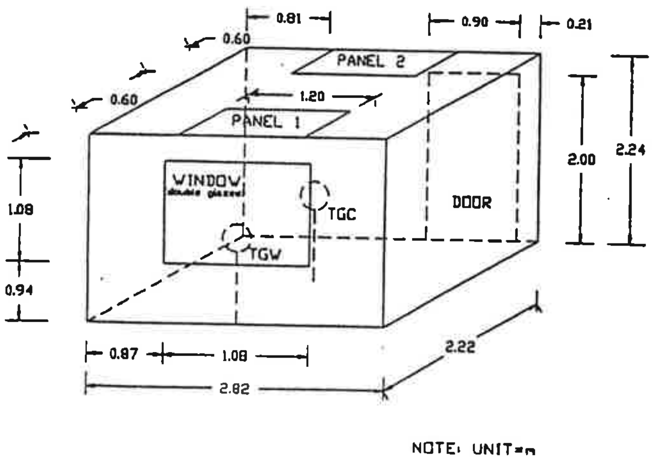

Figure 1 *Room schematic indicating location of two globes, TGW and TGC, in front of the window and in the center of the room.*

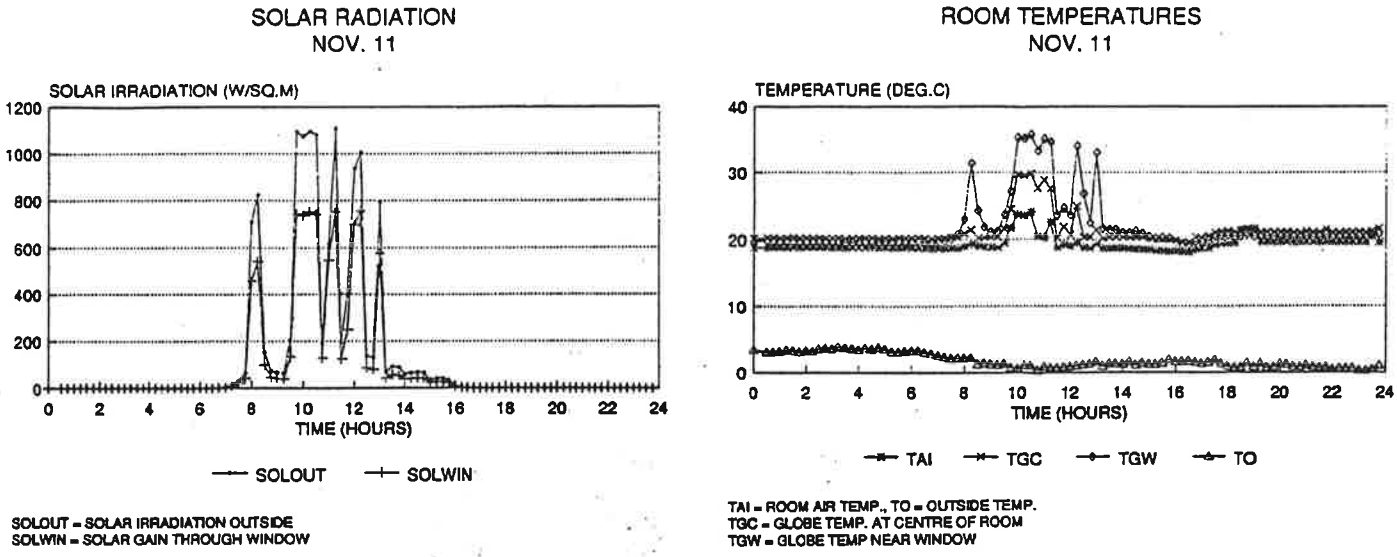

Figure 2 *(a) Measured solar radiation incident on and transmitted through window (b) measured temperatures (room air TAI, outside TO, globe 1—TGW, and globe 2—TGC) for November 11, 1990.*

beam radiation; the measured room air temperature TAI was 19.9°C, while TGC and TGW were 21.4°C and 31.4°C, respectively. Therefore, the effect of beam solar radiation, which is approximately equal to TGW − TGC, is 10°C. If the total heat transfer coefficient for the globe is estimated to be $h_c + h_r = 13$ W/m², then the predicted effect of beam solar radiation (from Equation 4) is equal to

$$\alpha_g q_b / 4(h_c + h_r) = 9°\text{C}.$$

Thus, measured and predicted values are in fairly good agreement. The effect of diffuse radiation is more difficult to estimate because of its small magnitude. The average level of diffuse solar radiation incident on the globe was 30 W/m² and its measured effect on TGC is on the order of 1 to 2°C (note that temperature measurement accuracy is typically 0.5°C). Its predicted effect, equal to

$$\alpha_g q_d / (h_c + h_r) = 2°\text{C},$$

is on the same order of magnitude.

Two more days of measured data are given in Figure 3. A lower room setpoint of 16°C was employed for part of the night, as indicated by the room air temperature TAI. All these days (November 13-15) were sunny and relatively mild. No heating was required during the daytime, allowing the effect of solar radiation to be

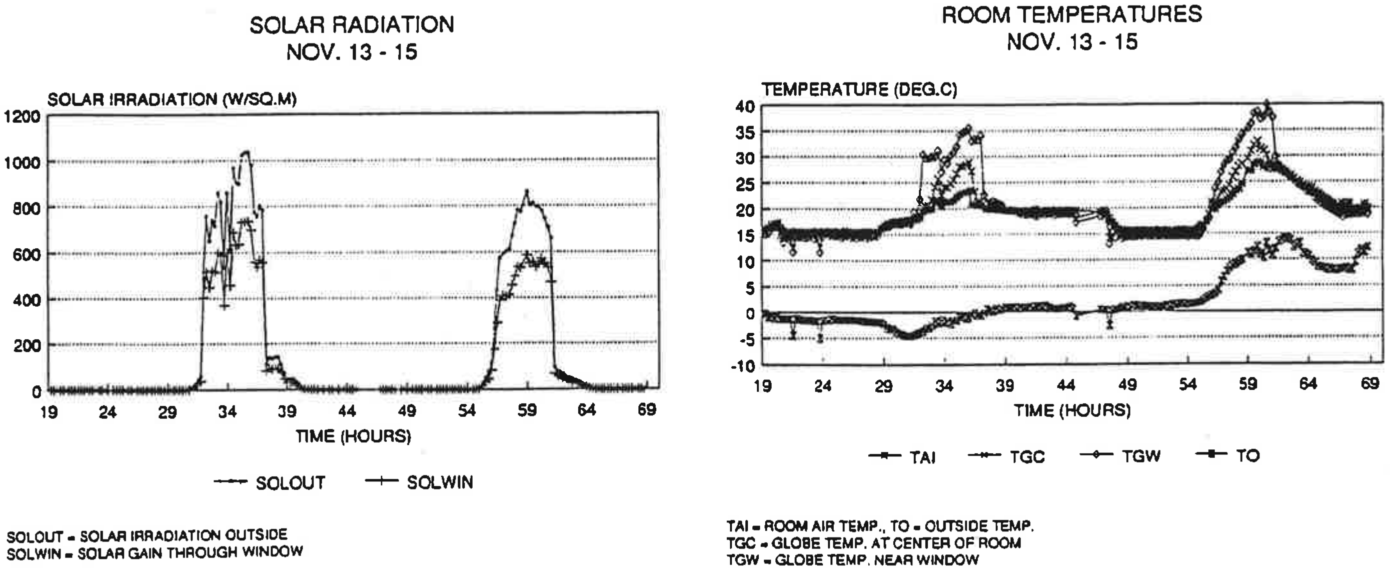

Figure 3 *(a) Measured solar radiation incident on and transmitted through window (b) measured temperatures (room air TAI, outside TO, globe 1—TGW, and globe 2—TGC) for November 13-15, 1990 (hour 24 is midnight of November 13).*

accurately studied. In order to study both the effects of diffuse solar radiation and mean radiant temperature on globe temperature, the mean radiant temperature must be measured. One way to do this is to measure surface temperatures and find their area-weighted average. The interior surface temperature distribution, as measured with an infrared radiometer, is shown in Figure 4 for the middle of the period considered, i.e., November 14 at approximately 10 a.m. This yields a mean radiant temperature (MRT) of 20.1°C. Other significant measured data at this time were

Transmitted solar radiation (beam component: 320 W/m^2)	= 430 W/m^2
TGC	= 24.0°C
TGW	= 28.3°C
TAI	= 21.1°C
Operative temperature = (TAI+MRT)/2	= 20.6°C.

The average air speed around the globe was also measured with a hot-wire anemometer and was found to be about 0.6 m/s. Only TGW was affected by beam radiation. The diffuse solar radiation around the globe was 50 W/m^2. The measured effect of beam solar radiation is equal to TGW − TGC = 4.3°C, which is close to the predicted effect $\alpha_g\, q_b/4(h_c + h_r) = 5$°C. The effect of diffuse solar radiation is equal to TGC − (TAI + MRT)/2 = 3.4°C and is close to the predicted effect $\alpha_g\, q_d/(h_c + h_r) = 4$°C.

The difference TGW − TAI consists of two combined effects: (1) the immediate effect of diffuse solar radiation and (2) the rise of the mean radiant temperature over the air temperature due to the absorption and storage of solar radiation in the room walls. The second effect, which is indirect, can be estimated from measurement of MRT, as explained above, or from simulations and is approximately equal to the difference between the predicted operative and room air temperatures.

The validated detailed building thermal analysis computer program BEEP (Athienitis 1988) was employed for simulations of the operative and room air temperatures for November 14. BEEP, which agrees closely with other detailed programs and with measured data (Haghighat and Athienitis 1989) models distributed elements, such as thermal storage mass in walls, as two-port elements without employing discretization and accurately represents room interior radiant exchanges and transmitted solar energy effects (Athienitis et al. 1987). The predicted profiles of TE and TAI are given in Figure 5. As can be seen, at night the operative temperature can be approximately 1°C lower than the room air temperature due to lower surface temperatures, while during the day the operative temperature TE is higher by about 0.5°C. The maximum air temperature is about 25°C, and this is close to the measured maximum of 24°C (see Figure 4).

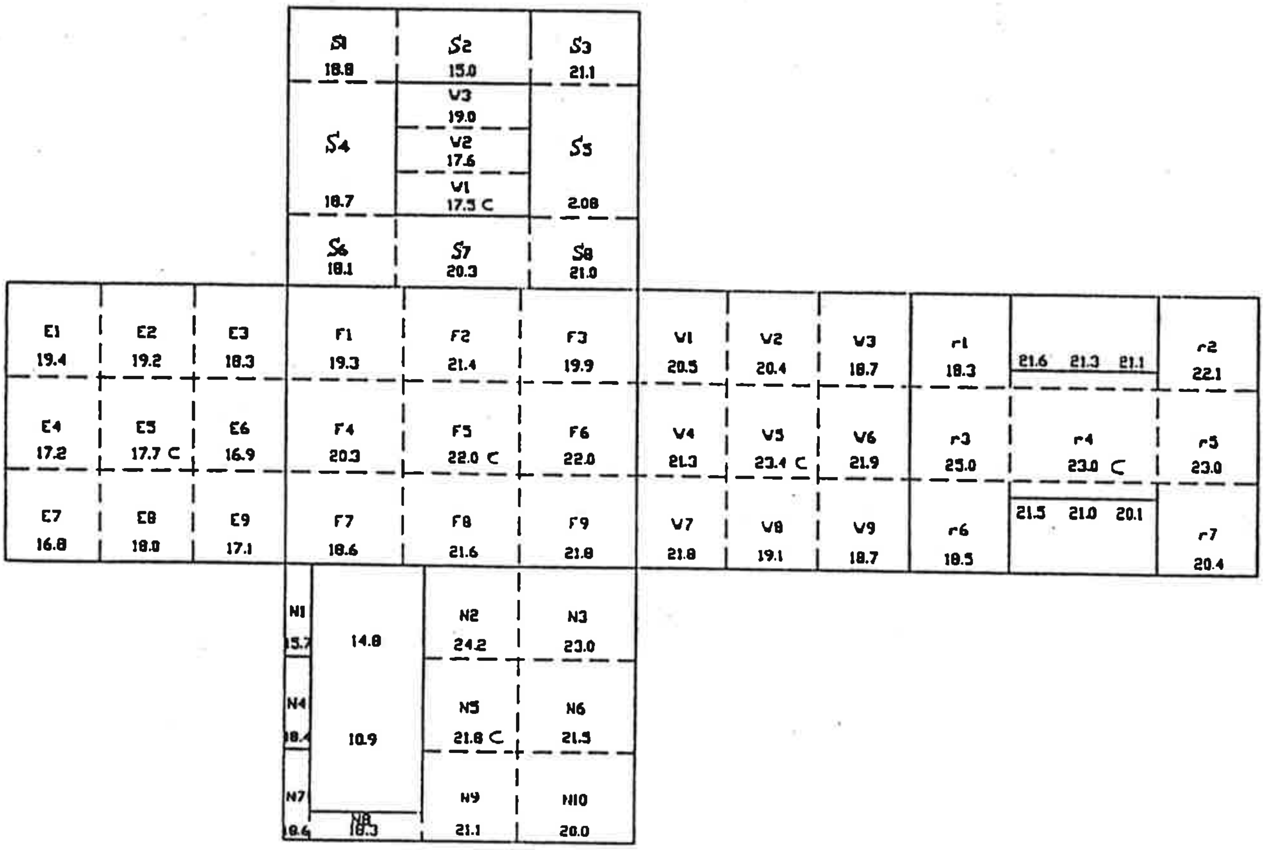

Figure 4 Measured temperature distribution of room interior surfaces on November 14 (at 10 a.m.).

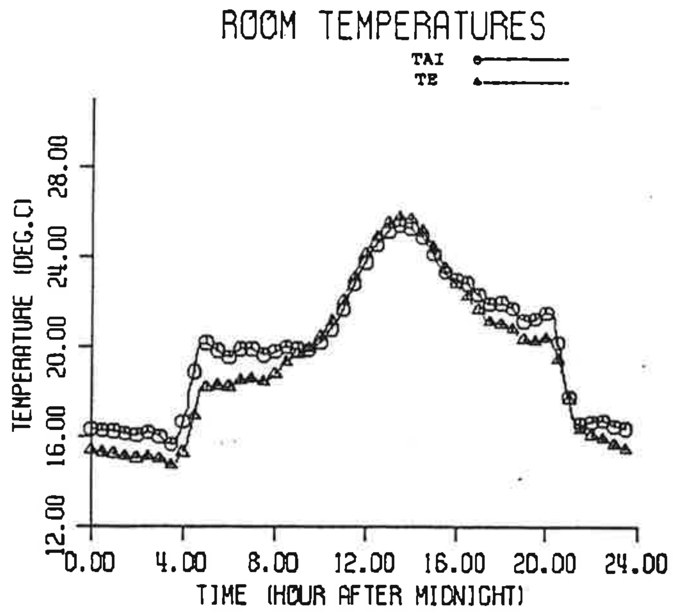

Figure 5 *Predicted operative temperature TE and room air temperature TAI for November 14, 1990.*

CONCLUSION

This paper described an experimental and numerical study that quantifies the effect of both direct and diffuse transmitted solar radiation on thermal comfort in terms of globe temperature and shows the need for including this important parameter in the comfort estimation for passive solar buildings. Both numerical simulations and experimental measurements of the solar effects were described.

It was concluded that the effects of solar radiation transmitted through windows may be reliably investigated by means of the linearized globe temperature (Equation 4).

The experimental and numerical results were in good agreement with the ones given in the *CIBSE Guide*, and it was also shown that the diffuse solar radiation incident on a person in a room may have a significant effect on his or her thermal comfort; diffuse solar radiation may result in an increase of more than 3°C in the globe temperature.

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