Thermal perception in a room with radiant cooling panels coupled to a roof pond

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ABSTRACT: Roof ponds (RP) can promote comfortable thermal conditions, particularly in single-storey buildings. They allow structural cooling or heating and stabilization of surface and air temperatures. When coupled to radiant panels cooled by the exposed pond, they can further improve their thermal performance. However, there is a lack of research on RPs focusing on the thermal perception of users indoors. The main objective of this study was to evaluate empirically under hot dry summer conditions the thermal perceptions of volunteer participants in an indoor environment conditioned by a system composed of radiant panels coupled to a RP. We also sought to assess the applicability of the PMV model and the passive building models of ASHRAE Standard 55 and EN-15251 under these conditions, through comparison with subjective thermal votes reported by the study participants. In a test building at Ben-Gurion University of Negev, Israel, a sample of 46 participants found a room cooled only by a RP. Thermal votes showed more agreement with the PMV and EN-15251 models than with the ASHRAE model.
KEYWORDS: Roof pond; Radiant cooling; Passive cooling; Thermal comfort models.

1. INTRODUCTION

Roof ponds (RP) can promote comfortable thermal conditions in some locations, particularly in single-storey buildings. They allow structural cooling or heating and stabilization of surface and air temperatures. Radiant cooling using ponds on metallic ceilings instead of concrete ones may be more effective, because the temperature difference between the reservoir water and indoor air below due to their higher thermal conductivity [1]. To compensate for this, the performance of concrete ponds may be improved by coupling them with water-based radiant cooling systems suspended below the celling. There is evidence that radiant cooling systems can provide equal or better comfort conditions compared to conventional air conditioning systems [2]. Tests in an experimental building equipped with radiant cooling panels showed that two thirds of the summer cooling occurred by radiation and only one third by convection [3]. Studies on radiant cooling and evaporative cooling still focus mainly on the optimization and performance of systems [4], and there have relatively few field studies involving occupants reporting feedback [5].

The main objectives of this study were: First, to verify empirically in warm summer conditions whether volunteers would evaluate as comfortable a thermal environment conditioned by radiant panels coupled to a RP. Secondly, to identify which thermal comfort model best agrees with the votes registered by the study participants.

2. METHODOLOGY

The experiment was performed in a room cooled with radiant panels suspended from the ceiling coupled with a roof pond. Volunteers were requested to assess the thermal conditions in the room by means of questionnaires, and their responses were compared with comfort indices calculated from environmental data recorded in the test room. The performance of the roof pond was assessed through comparison with conditions measured before installing the evaporative cooling system coupled to the radiant panels.

2.1 Test facility

The rooms are part of a test facility located at the Sde-Boqer Campus of Ben-Gurion University of the Negev, in Israel. The climate (Köppen Climate Classification subtype "Bsh") is characterized by large diurnal and seasonal thermal fluctuations, dry air and clear sky with intense solar radiation. Summer weather is extremely stable: temperature differences from day to day are minimal, with a typical maximum of 32-33°C and minimum of 18-19°C. The average wet bulb temperature in July is 16.8°C [6].

The facility incorporates three similar test rooms (9.45 m²) with a white-painted interior. The room on the right in Figure 1 had a roof pond installed on it, while the center room served as a control.

The setup in the RP room (Fig. 2) comprised 1) a 2 mm-thick white PVC roof, installed 1.5 m above the slab; 2) a spray system; 3) a water pump; 4) a floating layer of EPS; 5) 755 l of water; 6) two radiant aluminum panels with coils, placed inside the test environment; 7) a dummy conditioner unit working only as a fan.

The control configuration (CC) consisted of a 10 cm thick concrete slab roof with 10cm thick polystyrene thermal insulation covered with a light-coloured gravel ballast. The room was equipped with a split AC unit.

Figure 1: South façade of test building.

External environmental data were obtained from the campus weather station. Internal conditions monitored included air temperature (T_a), air velocity (V_a), relative humidity (RH), water temperature (T_w) and the temperature of all surfaces (T_s). The mean radiant temperature (T_{mrt}) was calculated from T_s, using the procedure in ISO 7726 [7], which then allowed the calculation of operative temperature (T_o).

Useful monitoring started on July 31 and ended on September 21 2017, covering 22 days.

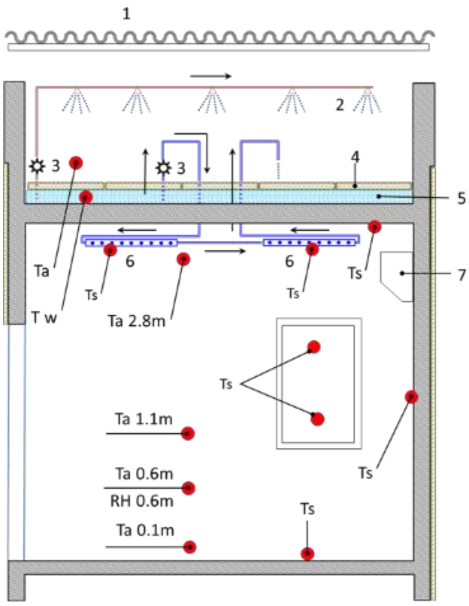

Figure 2 – RP section showing sensor locations.

2.2 Questionnaire and participants

Volunteers were recruited from members of the university community (students, staff and family members). The questionnaire was designed according to the guidelines of ISO 10551 [8], and included in addition questions about personal data and clothing.

Thermal perception was recorded by three metrics: thermal sensation (TS), thermal comfort (TC) and thermal preference (TP), as indicated below:

1 What is your general thermal sensation right now?

( )	( )	( )	( )	( )	( )	( )
-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

2 How do you feel about the thermal environment?

( )	( )	( )	( )	( )
0	1	2	3	4
Very uncomfortable	Uncomfortable	Neutral	Comfortable	Very comfortable

3 At this moment, would you prefer to be?

( )	( )	( )	( )	( )	( )	( )
-3	-2	-1	0	+1	+2	+3
Much cooler	Cooler	Slightly cooler	Without change	Slightly warmer	Warmer	Much Warmer

2.3 Determination of thermal conditions in the experimental environment

The thermal conditions in the RP room were assessed 30 minutes before volunteers arrived to establish a reference condition, and again 5, 30 and 35 minutes after their arrival, using the Predicted Mean Vote (PMV). The PMV was calculated according to ISO 7730 [9] using WinComf [10] and the CBE calculation tool (http://comfort.cbe.berkeley.edu), assuming a 'standard' male person, aged 35, 1.75 m tall, weighing 75 kg [11], wearing light clothing (0.3 clo) and in sedentary activity (70 W). The data shown in the following analysis refer to conditions recorded between 30 and 35 minutes after the arrival of volunteers in the test room.

According to ISO 7726 [7], T_{mrt}, which is required to calculate PMV, can be estimated from the temperatures of the internal surfaces and their respective angle factors (F) using Equation 1:

$$T_{mrt} = \sum(F_i T_s) \qquad (1)$$

Where T_s is the temperature of a surface and F_i is its angle factor from a given point of interest, so that the temperature of the surfaces is weighted according to their solid angles (Ω) in relation to the chosen point [12]. The angle factor (F) (Equation 2) corresponds to the relative solid angle around a point.

$$F_i = \frac{\Omega_i}{4\pi} \qquad (2)$$

The angle factor can be approximated by the projection of the surface or object on a sphere whose center is the point of interest. It measures the apparent size of the object seen from that point, such that the sum of the solid angles of the surfaces that delimit it will be equal to the area of a sphere given in steradians (4π or 12.566). Taking the point of interest as the vertex and a surface (wall, for example) as the base of a pyramid, one can estimate the solid angle given by that surface with Equation 3 [13].

$$\Omega = 4tan^{-1}\left(\frac{ab}{2d(4d^2+a^2+b^2)^{0,5}}\right) \qquad (3)$$

Where:

Ω is the solid angle given by the surface in relation to the point of interest.

a is the length of the base of the pyramid (length of the wall).

b is the width of the base of the pyramid (height of the wall).

d is the distance between the center of the base and the top of the pyramid.

2.4 Evaluating thermal perception

The thermal perceptions reported by the volunteers were assessed using the following models: a) the predicted mean vote (PMV), and the predicted percentage of dissatisfied (PPD) derived from it, calculated according to ISO 7730 [9]; b) the comfort range for passive buildings defined by ASHRAE Standard 55 [14]; c) and the comfort range for passive buildings defined by standard EN-15251 [15].

Thermally dissatisfied persons were classified as those who voted 'very hot', 'hot', 'cold' or 'very cold' (-2, -1, +1 and +2) on the seven-point thermal sensitivity scale suggested by ISO 7730 [9].

Thermal comfort models for passive buildings given by ANSI/ASHRAE Standard 55 [14] and EN-15251 [15] provide for the use of operative temperature (T_o) to derive neutral temperatures and comfort ranges in rooms with no air conditioning. T_o can be taken as the average between T_{mrt} and T_a [8, 16], if air speed in the environment (v_a) is less than 0.2 m/s (as was the case even when the dummy AC fan was turned on).

Standard EN15251 [15] establishes a comfort band for buildings with no mechanical cooling that is derived from the average daily outdoor temperature. The comfort band is defined around a neutral operative temperature ($T_{o\,comf}$) according to equation 5:

$$T_{o\;comf} = 0{,}33T_{ex\;\mathrm{ewa}} + 18{,}8 \qquad (5)$$

Where, $T_{o\,comf}$ is the neutral operative temperature and $T_{ex\,ewa}$ is the exponentially weighted running mean of the daily external air temperature.

$T_{ex\,ewa}$ can be calculated using Equation 6:

$$T_{ex\;\mathrm{ewa}} = (1-\beta) \times T_{ex\;m\,-1} + \beta \times T_{ex\;\mathrm{ewa}\,-1} \qquad (6)$$

In which:

β is a constant, equal to 0.8 [15];

$T_{ex\,m-1}$ is the mean air temperature of the previous day (°C);

$T_{ex\,ewa-1}$ is the exponentially weighted average external air temperature, calculated for the previous day.

The comfort range for "new construction and renovations with normal expectation" has a width of 6°C [15, 17].

ANSI/ASHRAE Standard 55 [14] also establishes a comfort band that is variable and is based on the average of external temperatures. The procedure is applicable only when the average monthly temperatures are greater than or equal to 10 °C and less than or equal to 33.5 °C [14]. The neutral operative temperature according to this standard may be derived using Equation 7 [14]:

$$T_{o\;comf} = 0{,}31T_{ex\;ma} + 17{,}8 \qquad (7)$$

Where $T_{ex\,ma}$ is the moving average of external temperatures (°C).

It is observed that $T_{ex\,ma}$ is a moving arithmetic mean, differing from the variable used by EN-15251 [15], which uses a weighted average. It must be based on no less than 7 and no more than 30 consecutive days before the day in question [14]. Around the neutral temperature, the range of thermal acceptability with 7 °C in width was adopted, to serve 80 % of the population [14].

2.5 Test sample

The test sample comprised 46 participants: 19 men (average age 33.9 years) and 27 women (average age 31.7 years). 91.3 % of subjects were aged from 16 to 40 years old, making the majority of the sample composed of young adults. Participants were from 13 different countries: Israel (25 participants), USA (5), India (3), Brazil (2), Germany (2), Russia (2), other countries (7). The Body Mass Index (BMI, calculated as the body weight divided by the square of the body height, expressed in kg/m²) varied between 18.4 ('underweight') and 35.5 kg/m² ('grade II obesity'), according to the categories of the World Health Organization [18]. Table 1 summarizes the physical characteristics of the test subjects.

Table 1 – physical characteristics of test subjects.

	average	std dev
Age (years)	32.6	8.8
BMI (kg/m²)	23.4	3.6
Weight (kg)	67.1	12.9
Height (m)	1.69	0.08

Most of the subjects had just come from thermal environments without air conditioning (63.0 %), some from air-conditioned spaces (30.4 %) and some from public transportation/cars, typically with air conditioning (6.5 %). 32 of the volunteers arrived at the experiment site walking (69.6 %), 10 arrived by bicycle (21.7 %) and 4 by car/bus (8.7 %). 45 of the participants (97.8 %) took less than 10 minutes to arrive at the experiment site.

Most volunteers wore short-sleeved T-shirt, shorts, underwear and sandals, with a mean thermal insulation value of 0.32 clo and median of 0.24 clo.

3. RESULTS

3.1 Roof pond performance

The effect of the roof pond (experimental configuration - EC) was assessed by comparison with conditions measured before (control configuration - CC) installing the evaporative cooling system coupled to the radiant panels. Results of measurements made of air temperature and the temperature of room surfaces including walls, ceiling and cooling panels (RP room only) are summarized in Table 2. During the monitoring period (6/16 – 6/24/2017), the average internal air temperature in the reference room was 2.2 °C higher than the average external temperatures, while in the experimental configuration (7/29 – 8/07/2017) the average was 0.3 lower than the average external temperatures. In the case of the surface temperatures of the ceiling, in the CC, the average value was 2.6 ° C higher than the average of the external air temperatures, while in the EC it was 1.7 ° C lower (the average of the surface temperatures of the radiant panels was even lower, 2.7 ° C lower than the average outdoor temperature).

Table 2 - Averages of surface temperatures and internal and external air temperatures.

	Ta	Ta ex	Ts ceiling	Ts panels
Control Configuration	26,5	24,3	26,9	26,9
Experimental Configuration	26,8	27,1	25,4	24,4

3.2 External and internal environmental conditions

The weather during the experiment was generally warm and dry. During the sessions, the average outdoor temperature was 29.6°C, with a maximum of 34.6°C and a minimum of 24.3°C (Fig. 3). Internal conditions during the sessions were stable and almost uniform: The temperature ranged from 25.8°C (the coolest session) to 28.8°C during the warmest session, with an average of 27.2°C. Air movement (*V_a)* was less than 0.2m/s. Relative humidity averaged 62% , with a minimum of 50%, and a maximum of 70%. Thus, although the room lacked a mechanical AC system, the volunteers were exposed to mild internal environmental conditions. However, during some of the sessions there were substantial differences between external and internal air temperatures. In most cases, the external air temperature was higher than the internal one (Fig. 3), with a maximum difference between $T_{a\,ex}$ and $T_{a\,in}$ of 6.8°C.

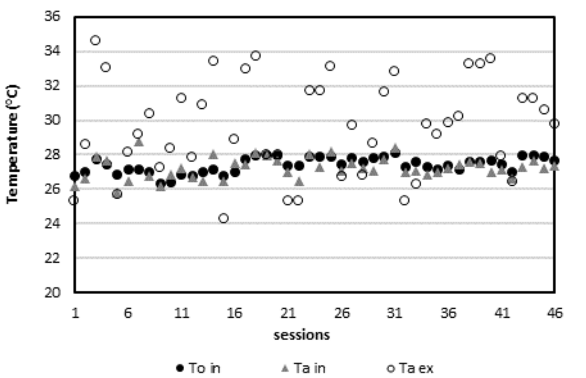

Figure 3 - Indoor and outdoor air temperatures during thermal comfort sessions

3.2 PMV and PPD during the sessions

In general, the values for the PMV (Fig. 4) were close to thermal neutrality (between -0.57 and 0.20, average -0.08). The values for the PPD were close to or below 10% (between 4.9% and 13.2%, average of 6.2%). That is, according to the PMV model, the volunteers were exposed to mostly comfortable environmental conditions during the sessions, or very close to them.

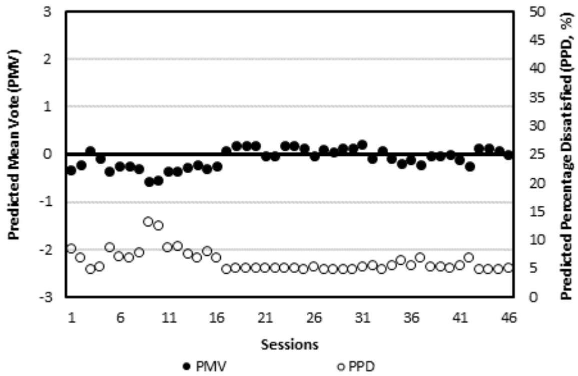

Figure 4 - PMV and PPD during thermal comfort sessions.

3.3 Thermal comfort ranges according to adaptive models during sessions

The operative temperatures during the sessions were plotted on the comfort ranges given by the standards ANSI/ASHRAE Standard 55 [14] (Fig. 5) and EN-15251 [15] (Fig. 6). The average values over the duration of the experiment are shown in Table 3 for the two comfort standards. In the case of the ASHRAE comfort range, the operative temperatures were between the upper limit of the comfort range and the neutral condition. In the case of the comfort range of EN-15251, operative temperatures were, in general, closer to neutral temperatures. Although the operative temperatures were closer to the recommended values for the EN 15251 model than for the ASHRAE model, there was a high probability that the volunteers' votes would indicate satisfaction with the thermal environment provided by the cooling system according to both.

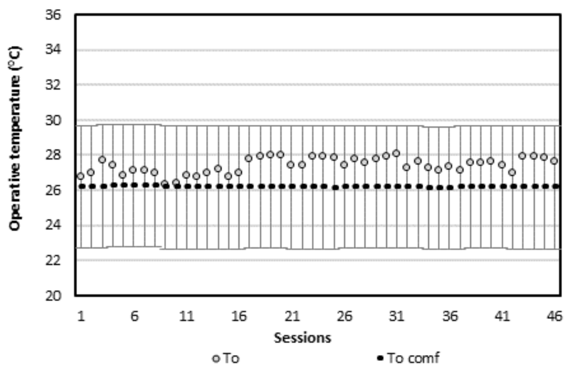

Figure 5 - Operative temperatures in the RP room and comfort range according to ANSI/ASHRAE Standard 55.

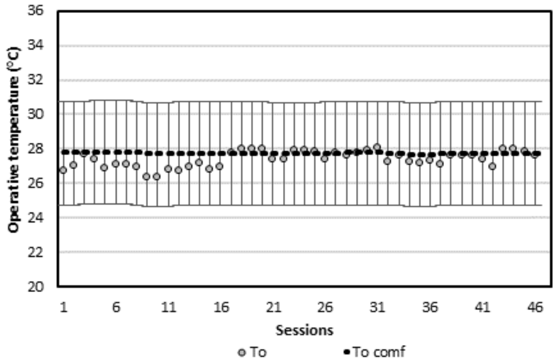

Figure 6 - Operative temperature in the RP room and comfort range according to EN 15251.

Table 3 – Comfort range averages to ANSI/ASHRAE Standard 55 and EN-15251.

	ANSI/ASHRAE 55 [14]	EN-15251 [15]
Upper limit (°C)	29.7	30.7
Neutral operative temperature (°C)	26.2	27.7
Lower limit (°C)	22.7	24.7

3.4 Subject Assessment of the Thermal Environments

THERMAL SENSATION (TS)

In response to Question 1, most of the volunteers considered thermal conditions in the test room to be either neutral (50%) or slightly cool (30.4%) (Fig. 7). The average operative temperature in the room when test participants reported a 'neutral' thermal sensation was 27.3 °C, or 1.1 °C above the ANSI/ASHRAE Standard 55 neutral temperature but 0.4 °C below the value indicated by the EN-15251 standard (Table 4). EN-15251 thus appears to give a better prediction of subjective TS under these conditions, with a trend to slightly cool sensation.

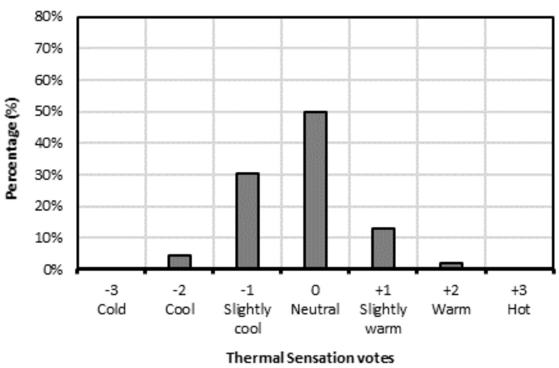

Figure 7 – Thermal sensation votes (TS).

The environment was considered satisfactory by 93.5% of the volunteers (Table 4), indicating a high degree of agreement with the PMV model adopted by ISO 7730 [9], from which it was estimated that 93.8% of the participants would report satisfaction with the thermal environment.

Table 4 - PMV and PPD versus reported data.

	Average PMV	Average reported TS	PPD (%)	Dissatisfied people according to the votes (%)
RP room	-0,08	-0,22	6,2	6,5 (2 due to cold and 1 due to heat)

THERMAL COMFORT (TC)

The average thermal comfort (TC) vote (Question 2), was 2.72 (between neutral and comfortable). Most of the subjects rated conditions as either 'comfortable' (43.5%), or 'neutral'. Only 1 participant found conditions 'uncomfortable', while 4 considered them 'very comfortable' (Fig. 8). The average operative temperature calculated when respondents rated conditions as 'neutral' was 27.5°C, 27.4°C for 'comfortable' conditions and 27.1°C for 'very comfortable' conditions (Fig. 9).

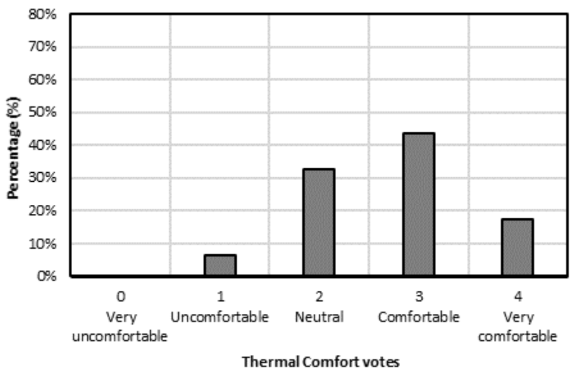

Figure 8 - Thermal comfort (TC) votes

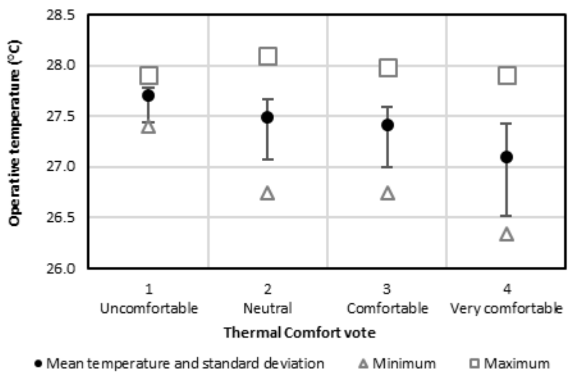

Figure 9 - Operative temperature for each thermal comfort (TC) class

THERMAL PREFERENCE (TP)

In response to Question 3, a majority of the participants voted for conditions to remain 'without change' (65.2%), and a sizable minority (30.4% of the participants) would have preferred 'slightly cooler' conditions (Fig. 10). The average operative temperature of the sessions whose participants opted for the first option (no change) was 27.4°C and that of the sessions whose participants opted for the second option (slightly cooler) was 27.3°C.

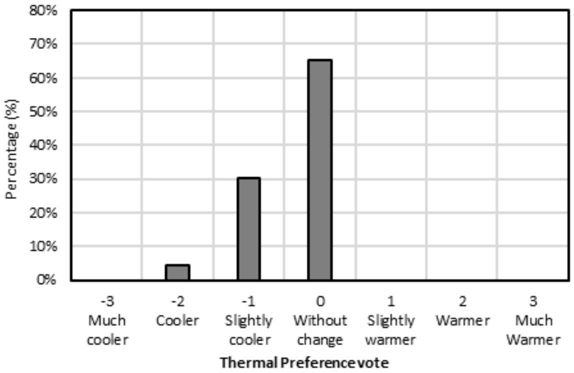

Figure 10 - Thermal preference (TP) votes

There is a small but important discrepancy between the reported thermal sensation (TS), which tended to be to the cool side (Figure 7 and Table 4), and the expressed preference for even cooler conditions (Figure 10). We hypothesize that this may be a reaction to consistently high temperatures people are exposed to outdoors, so that compensation through short-term exposure to conditions that might otherwise be considered too cool elicits a feeling of alliesthesia [19].

4. FINAL CONSIDERATIONS

The cooling system, characterized as 'radiant cooling panels coupled to a roof pond', was able to provide comfortable conditions for volunteers, despite the adverse conditions observed outdoors (summer in a desert climate). Most volunteers reported a sensation of 'thermal neutrality'.

Among the adaptive thermal comfort models assessed, EN-15251 [15] was closest to the stated comfort votes of the participants, but the PMV model was also satisfactory.

The thermal gradient observed in the room due to the colder ceiling did not appear to cause discomfort.

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