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The Thermoheliodome – "Air conditioning" without conditioning the air, using radiant cooling and indirect evaporation

Forrest Meggers[a,b,*], Hongshan Guo[a], Eric Teitelbaum[a], Gideon Aschwanden[c], Jake Read[d], Nicholas Houchois[e], Jovan Pantelic[f], Emanuele Calabrò[g]

[a] Princeton University School of Architecture, Princeton, NJ, USA
[b] Princeton University Andlinger Center for Energy and the Environment, Princeton, NJ, USA
[c] University of Melbourne, Melbourne School of Design, Australia
[d] University of Waterloo, Waterloo Architecture, Canada
[e] Columbia University, New York, USA
[f] Center for the Built Environment, University of California Berkeley, USA
[g] Reddington Group, London, UK

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ABSTRACT

The Thermoheliodome is an experimental pavilion that explores cooling without air conditioning. The two research aims were to explore the use of indirect evaporative cooling and the geometric reflection of radiant cooling. For evaporative cooling we utilize a cooling tower outside of the pavilion to indirectly supply water chilled near the wet-bulb temperature. The radiant cooling system is made up of 55 coaxial chilled pipes each located in the central axis of cones with reflective surfaces that spectrally reflect the surface of the pipes and expand their radiant view factor to the occupants inside the pavilion. The specific geometry was digitally fabricated using an industrial robot and hot-wire foam cutter. The mean radiant temperature (MRT) was shown to be significantly decreased using thermal imaging cameras and with a novel scanning MRT sensor. The radiant cooling delivered from the fluid is maximized by reflection and concentration of heat emitted by occupants on the pipes, while the convective cooling of the air is minimized because only the small pipes are cooled and the reflecting surfaces are not, so the convective heat transfer surface area is small. Under typical indoor office conditions the ratio of radiant to convective cooling is slightly greater than one. For the Thermoheliodome the radiant ratio was greater than 10. Occupant surveys found that although the air temperature was not modified, they felt that inside the space there is a cooling sensation ($p \leq 0.01$). The day of the survey they felt on average 3 °C cooler.

1. Introduction

Providing cooling in the built environment generally implies the use of air conditioning, which usually refers to some combination of heating, cooling, and ventilation systems. These systems have the largest energy demand in buildings, and buildings are one of the largest single sectors of global primary energy demand and CO2 emissions [1]. Air conditioning (AC) also more often connotes cooling, which although currently smaller than heating, is growing rapidly. With the vast majority of the developing world closer to the equator, the cooling demand is expected to increase by 72% in the coming century while heating remains the same, with cooling surpassing heating in demand by 2060 [2] – assuming standard AC installations.

We propose a system that gives an occupant the perception of an air conditioned space while actually minimizing any cooling of the air. The Thermoheliodome is an open air pavilion that provides cooling without cooling the outside. The objective is to demonstrate the effectiveness of radiant cooling as an alternative to traditional air-based cooling in an unconventional deployment outside where cooling the air is a waste of energy. Misters are often deployed to decrease the temperature of hot air, but they add humidity, which if the air is not dry enough, can result in an even less comfortable condition. We use evaporative cooling to chill water rather than to chill air, and then use that water indirectly in a novel cooling apparatus.

The Thermoheliodome leverages radiant heat transfer with reflective concentration to maximize the absorption of radiant heat

* Corresponding author at: Princeton University School of Architecture & the Andlinger Center for Energy and the Environment, Princeton, NJ, USA.
E-mail address: fmeggers@princeton.edu (F. Meggers).

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Fig. 1. The Thermoheliodome just after the construction of structure and system was completed in 2014, where the dome's arch follows the sun path on the summer solstice, and the cones will be lined with mylar to reflect radiation onto the coaxial pipes for radiant cooling.

emissions from occupants. Passive indirect evaporative cooling activates piping in the radiant cooling system to achieve high temperature cooling based on low exergy principles [3]. The system is deployed in a 4 m pavilion dome shown in Fig. 1, and the dome is cut to match the solar path on the summer solstice, thereby optimizing the shading, and maximizing the potential of the radiant cooling within. The result is a space that uses radiation to shift the occupant's perception of temperature while minimizing any actual convective cooling of the outside air. The mean radiant temperature (MRT) is depressed by the wet bulb surface temperature of the indirect evaporative cooling system, creating a unique experience of feeling cooled without any actual air conditioning in the space.

2. Background: low exergy radiant systems

2.1. Low exergy radiant systems

It has been established by previous studies that radiant heat exchange can deliver thermal comfort at lower temperatures for heating and higher temperatures for cooling [4]. While remaining independent of the actual heating or cooling energy demand, the temperatures as part of the thermodynamic concept of exergy enable great performance improvement opportunities [5]. In addition research has demonstrated radiant heat transfer to deliver not just more effective technical performance, but also a better human body thermal comfort through human body exergy modeling [6]. Exergy enables a matching of potential to ensure effective use of energy sources. In the case of buildings, the required potential is inherently low, and the most efficient system delivers heating or cooling at the lowest temperature difference. Low temperature differences also help mitigate comfort problems, and are easiest to achieve with radiant systems.

Radiant heating is more common than radiant cooling. Low exergy cooling is challenged by meeting dehumidification demands, while also avoiding condensation on surfaces. In many climates, a low enough wet bulb temperature can be acquired by evaporative cooling for radiant systems as deployed in the Thermoheliodome, but the challenges of precise air conditioning and humidity management required by comfort standards limits the indoor application. Research has considered exergy optimization for cooling systems [7], showing that low exergy radiant cooling has better energy and comfort performance than air conditioning. Radiant cooling was introduced in the form of thermally activated concrete core as early as 1991, in the "Down Building" in Zurich. Indirect evaporative radiant cooling as suggested by [8] in 2012 has been discussed, but in conjunction with central indoor climate control the application is limited. Another practice of indirect evaporative cooling is the Maisotsenko Cycle, as has been heavily researched by Caliskan et al. [9].

The relationship between radiant heat transfer and thermal comfort has been thoroughly academically studied, even if not widely commercially implemented. A close relationship between the perception of outdoor thermal comfort and the surrounding surface temperatures has been demonstrated [10]. A similar result was also reached through a numerical study on outdoor thermal comfort using the PET index [11]. This led to the advancement in understanding the adaptive thermal comfort with relation to radiant temperature [12], considering the comfort effects of radiant heat transfer on occupants, mainly from short wave solar gains, but also related to the long wave emissions from surfaces.

2.2. Thermoheliodome

For the Thermoheliodome, the engineering realization was based on the principles of radiant heat transfer and convective heat transfer coupled with evaporative cooling for the evaporative cooling tower. Such a system is psychrometrically self-regulating to always avoid condensation so the radiant surfaces will never wet. Radiant cooling systems that employ panels with pipes embedded are regularly used in buildings today. Cooling towers are very common in traditional central cooling systems where they are used to reject the heat from the chiller at cooler temperatures. These can be combined, and an architectural solution can be achieved by digital fabrication. The use of robotic arms for architectural digital fabrication is a growing field of exploration, which can be leveraged for precise geometric fabrication [13].

The Thermoheliodome shown in Fig. 1 was built at the Princeton Architectural Laboratory in the summer of 2014. It is named for our predecessors at Princeton who built a Thermoheliodon in the 1950s to study radiation on buildings [14]. For our pavilion, the name refers to its thermal manipulation of radiation, sun-path shading, and dome shape. Some initial results demonstrated its ability to reduce the mean radiant temperature as described in previous papers from IBPC 2015 in Torino [15,16]. The work also resulted in the development of a new mean radiant temperature sensor system, which we have studied broader applicaitons [17,18], and used for analysis of the mean radiant temperature of the Thermoheliodome.

3. Methods

3.1. Objective

The objective was to achieve a shaded space open to the outside air that was perceived as cooler without cooling the air. There were engineering goals in the deployment of evaporative cooling and the surface treatment to reflect and concentrate the radiation. There were also design and architectural aims to create an occupiable space shaded from the sun. The pavilion was designed to answer the following two fundamental research questions:

1 Can we reflect thermal radiation in the infrared using formal geometry to actively cool occupants of a pavilion without cooling the air – i.e. cooling without air conditioning?
2 Can we use evaporative cooling to indirectly achieve the wet bulb temperature of a cooled fluid inside the formal geometry without dependence on high-exergy vapor-compression cooling or refrigeration systems?

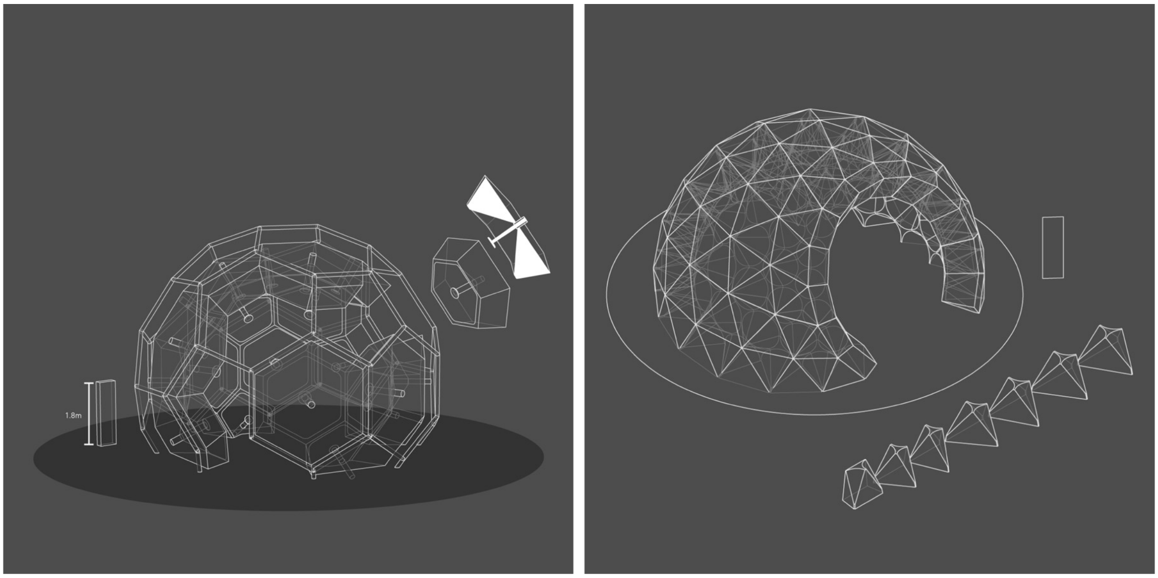

Fig. 2. The models developed in Rhinoceros for 3D modeling and Grasshopper for parameterizing the ray tracing for radiant reflection for the development of the concept for focusing of emissions onto the pipe surface at the center, and to subdivide the structure into manageable pieces for construction.

The methods aim to optimize the cooling of the occupant by radiation and thereby maximize the heat absorbed by evaporative cooling from the pavilion system.

3.2. Design and fabrication

The objective of the Thermoheliodome geometric design was to optimally collect the radiation from the occupant by strategic reflection onto cooled pipes. A central design objective for the Thermoheliodome is for this conical geometry to collect diffuse radiation emitted from a human occupant on an evaporatively cooled collector pipe or "bulb" placed along the focal line of the cone, which maximized the heat collected from occupants via radiation while minimizing heat loss by convection to the air. The development of the geometry is shown in Fig. 2.

Formally speaking, the dome shape was derived from the sun path on the summer solstice, shown in the right of Fig. 2, maximizing shading during the warm season and preventing the sun from coming in the large North opening. On the interior, initial concepts considered using parabolic troughs to focus the radiation, but a parabolic form requires parallel light for concentration. Therefore cones with pipes along the axis were used to catch non-parallel diffuse radiation emitted by occupants, as was developed in the model on the left of Fig. 2, which shows the section of the cone system in the upper right. The geometry was created using a parametric CAD modeling tool, and the radiant reflections were parameterized allowing for exploration of the ideal shape and distribution of cones. The geometry of the cones magnifies the effect of the pipes by expanding the cold surface area across the entire disc of the cone. The final model that used the solar path is in the right of Fig. 2 with 55 cones. The cones had 3 different base diameters, 11 at 0.813 m, 22 at 0.781 m, and 22 at 0.681 m, which represent the surface area presented to the occupant for radiant exchange. The cylindrical geometry of the bulbs had a small surface area of 0.121 m^2 exposed to convection, which we aim to minimize. Through reflection, this geometry was expanded by a factor of 3.7. The radiant heat transfer is dependent on this expanded view factor and is thereby increased.

The Thermoheliodome was fabricated by an industrial robot programmed to pass expanded polystyrene blocks through a fixed hot-wire cutter to create precise geometries as shown in Fig. 3. Foam blocks were cut into precise pieces for assembly of the dome, and to create the cone geometry for radiant reflection.

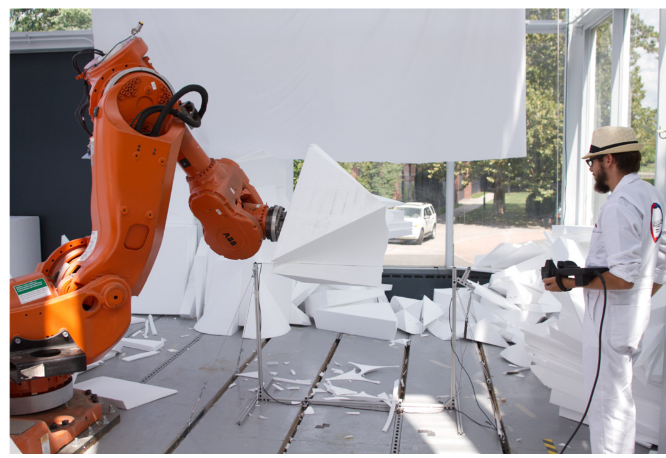

Fig. 3. Operation of the digital fabrication where the parametric models were programmed to output ABB Robot code of cutting paths for the robotic fabrication to generate the foam pieces by having the robot pick up rough cut blocks and then drag the foam through a large hot wire to create specific geometric surfaces.

The piping network is connected to a cooling tower shown in the schematic in Fig. 5, and a pump delivers the evaporatively cooled water via insulated pipes to coaxially piped bulbs in the center of the cones. These bulbs have a cold surface from a coaxial flow of water near the wet-bulb temperature. It flows down the outer annulus of the bulb and returns up the center, shown in Fig. 4. The resulting cooling bulb collects the heat from the occupants focused by the cone, which is coated with aluminized foil, to effectively spectrally reflect the radiation. The radiant heat transfer to the bulb is increased by reflection of the cones, effectively expanding the radiant surface of the bulb to the entire cone face. In contrast the convective heat transfer occurs only on the small surface area of the bulb itself, thereby limiting convective cooling of the outside air while increasing radiant heat exchange with occupants.

3.3. Sensors and data collection

A series of sensors were employed to measure the cooling performance of the Thermoheliodome. Fig. 5 provides a diagram of the sensing and operating components of the Thermoheliodome.

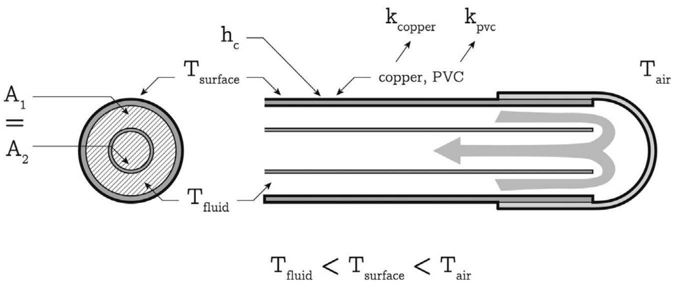

Fig. 4. Schematic of the cooling bulb designed as coaxial pipe with water cooled to close to the wet-bulb temperature in a cooling tower distributed to the bulbs and supplied down the outside annulus and returned up the center so that the outside surface has the lowest temperature for radiant heat exchange where the cones concentrate heat. Initially PVC was used and those were replaced with copper for its higher thermal conductivity.

Ambient conditions measurements. Ambient conditions were monitored with DHT22 (AM2302) sensors that measure humidity (RH ±5%), and temperature (±0.5 °C). Temperature and relative humidity are important for gauging both the occupant's perception of the air temperature and humidity in the dome, as well as monitoring the wet-bulb conditions that determine the temperature depression possible from the cooling tower.

Water Temperature and Flow. Evaporative cooling thermodynamically dictates the lowest supply temperatures is the wet bulb temperature of the air entering the cooling tower. A sensor was placed in the well of the cooling tower to monitor the temperature of the water being supplied to the Thermoheliodome, as solar, microclimatic, or other gains may influence the cooling tower performance. A second temperature sensor was placed after the pump, before water entered the radiant geometry within the dome. A third temperature sensor was placed at the outlet of the dome's piping. These three temperature sensors were DS18B20 waterproof temperature sensors placed in brass temperature wells installed in the piping, and set in place tightly with friction. The accuracy of the sensors is ±0.5 °C. Water flow sensors were placed at the inlet of each of the five rows to measure water flow rate, which was regulated with valves against the fixed speed pump. The sensors used were standard pulse sensors sold by Adafruit, accurate to 10%.

Mean Radiant Temperature Sensing. The major factor contributing to the MRT reduction inside the Thermoheliodome was the surface temperature of the bulbs. As such, surface temperatures on the cooling bulbs were measured with surface temperature sensors ON-409-PP manufactured by Omega, with accuracy of ±0.1 °C. This represents the temperature reflected towards occupants, and completes our understanding of the temperature profile from cooling tower to the radiative surfaces.

The radiant cooling performance of the dome is quantitatively evaluated using new sensors developed at the Princeton CHAOS Lab, the Scanning Motion Average Radiant Temperature (SMART) sensor [18,17]. Due to the special geometry of the dome, it is important that we develop a method to not only account for the air temperature and the water temperature coming in and exiting the structure, but also a metric for apparent surface temperature, conventionally measured as the mean radiant temperature [19]. We developed a system that measures temperature independently from the convective disturbances from the air movement unlike conventional MRT globe thermometers, which were sensitive to varying wind in the outdoor pavilion. Measurements from black globe thermometers as traditionally used for indoor MRT measurements are not easily temporally adjusted in periods of significant wind [20]. The literature contains examples involving multiple radiometers aimed orthogonally from one another in one scenario [20], but that is as close as data becomes to being spatially resolved. The SMART sensor's data is fully resolved into 5° increments that inform an output that the operator can see the surface temperature at each location inside the measured space.

To improve upon this method, two sensors were developed. The fixed one is a cube shaped sensor that instantaneously reads the average surface temperature in each octant of 3 dimensional Cartesian space from each corner of the cube, providing a good reading of the MRT and shown in the left of Fig. 6. Each octant was measured using a Melexis MLX90614 90° field of view (FOV) non-contacting temperature sensor. These sensors provide an instantaneous average surface temperature reading of all objects in a 90° FOV. The average over 8 octants therefore is equivalent to the MRT perceived by an occupant positioned at the point of the sensor.

However, a spatially resolved MRT reading was desired which lead to the invention of the Spherical Motion Average Radiant Temperature (SMART) sensor shown on the right of Fig. 6. This sensor device leverages a 5° FOV Melexis non-contacting temperature sensor and a LidarLite range finder, and by moving this combination of sensors through space using two orthogonally positioned servos, the entire surface of the imaginary sphere around the sensor body can be imaged in 5° increments. Each reading contains a surface temperature, azimuthal, polar, and radial coordinates which with some simple post processing allows the investigator to reconstruct

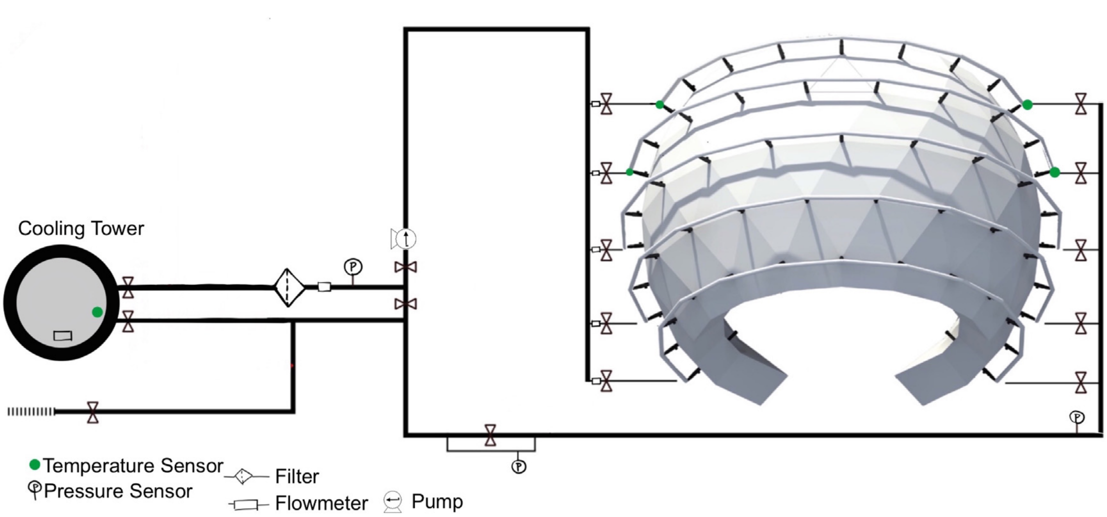

Fig. 5. Schematic diagram of the Thermoheliodome operation with the supply loop pumped from the cooling tower to the insulated distribution pipes and into the coaxial bulbs along with the temperature and flow rate sensors use to measure performance.

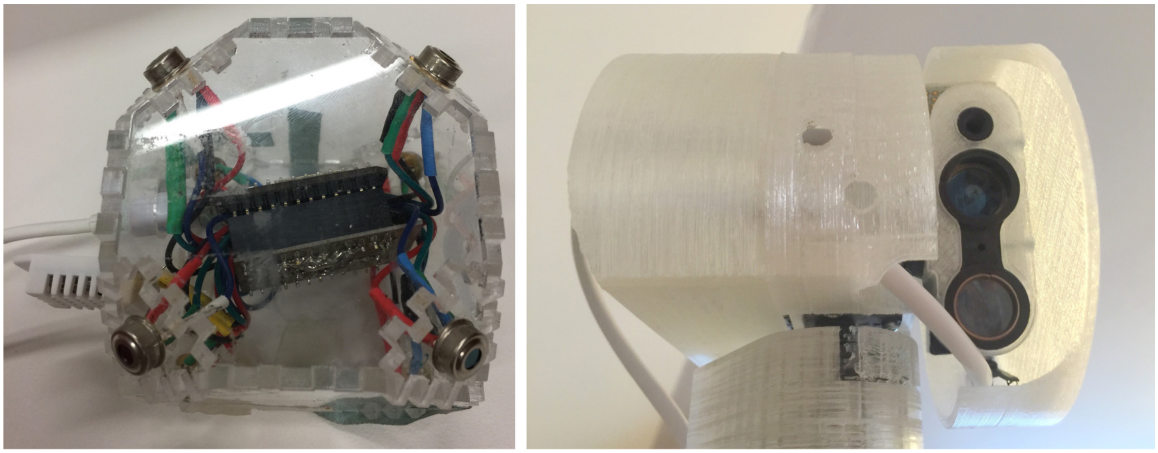

Fig. 6. Cube sensor (left) and SMART sensor (right) which were both used to evaluate the MRT inside the Thermoheliodome.

the space in 3 dimensional renderings to visually see the MRT at all points in the dome [18]. Additionally, warm surfaces from adjacent buildings heated up by the summer sun are monitored due to their impact on local MRT inside the dome.

3.4. Occupant thermal analysis

The assumed human body thermal emission was based on Stark et al. [21] in 2006: The seated human body has an approximate metabolism rate of 1 Met, equivalent to 58 W/m^2. The mean surface area, the Du-Bois area, of the human body is approximately 1.8 m^2 (19.4 ft^2), giving a total of 104 W released from the body by convection, conduction and radiation [22]. It is possible for an occupant's metabolic rate to range from 0.8 Met (46 W/m^2) while sleeping and 9.5 Met (550 W/m^2) during sports activities, but 100 W was selected as a working reference rate. Research comparing convective to radiative heat transfer experimentally found that radiant heat exchange provide 40% more heat transfer than the convection in typically conditioned spaces, a ratio of 1.4 [23] assuming air movement of 0.2 m/s. But for air movement of a 1 m/s breeze the ratio changes to 0.3, or 3 times more by convection [24]. In our system the dome structure aims to limit air movement and air cooling, and the radiant cooling becomes dominant with the objective of having a ratio greater than 2:1.

In our design the warm outdoor conditions further reduce the convective cooling because the temperature difference to the warm outside air is lower. Under normal conditions the occupant would increase his or her surface temperature by capillary dilation and eventually start sweating, or alternatively manually reduce clothing level, but the reduced MRT around the occupant compensates for the warmer air temperature before the body has to. Our system explores the ability of the occupant to maintain sufficient heat rejection as influenced by the lowered mean radiant temperature inside the Thermoheliodome.

We analyze this difference by considering the convective heat transfer in equation set (1), and compare that to the radiant heat transfer in equation set (2). These can be combined to generate a ratio of radiant to convective heat transfer making some assumptions about airflow in a simple free convection regime. This ratio can be calculated from the experimental data taken for the Thermoheliodome and illustrates its ability to maintain occupant cooling via radiation as convective cooling becomes limited as the air temperature approaches an occupant's skin temperature [25,24]. Latent exchanges through sweating are also possible, and are shown in equation set (3).

$$Q_{conv} = h_c(T_{skin} - T_{air});$$
$$h_{c,free} = 0.78(T_{skin} - T_{air})^{0.56}; \quad (1)$$
$$h_{c,forced} = 10.4v_{air}^{0.56}$$

$$Q_{rad} = h_r\epsilon(T_{skin} - T_{MRT});$$
$$h_r = 4\epsilon\sigma\frac{A_R}{A_D}\left[273.15 + \frac{T_{skin} + T_{MRT}}{2}\right]^3; \quad (2)$$
$$\frac{A_R}{A_D} = 0.70$$

$$Q_{evap} = w * h_e(P_{skin,sat} - P_{air}); \quad (3)$$
$$h_e = 16.5h_c$$

3.5. Occupant survey

To better understand the performance with real people, we performed an occupant comfort survey. This small survey examines occupant reaction towards the thermal conditions in the structure on September 19th, 2015, a typical summer afternoon with an average temperature of 28 °C and 50% relative humidity. A total of 17 participants were involved in the experiment, and the response data was statistically analyzed for significance.

The Thermoheliodome was pre-circulated with evaporatively-cooled tap water 30 min prior to the start of the experiment, and circulation was confirmed with temperature measurements. The participants waited in an unconditioned shaded area, and picked up the survey questionnaire from a table outside of the Thermoheliodome. The occupants then sat in the chair placed in the center of the Thermoheliodome, and took as long as they felt necessary to consider thermal conditions inside the Thermoheliodome while filling out a survey questionnaire. In the questionnaire, occupants were invited to provide their thermal assessments of the air before and after entering the dome on a thermal comfort scale bar – as shown in Fig. 7 – and their speculated air temperatures. The occupants were also invited to make educated guesses on the functionality of the Thermoheliodome and whether they considered themselves as being thermally sensitive to environmental changes.

The questionnaire was designed intentionally to allow explicit and implicit responses towards the thermal environment inside the dome. Conventionally, it is possible to obtain the PMV-PPD estimation for occupants. However, as was pointed by Chen and Ng in 2012

Fig. 7. Thermal comfort scale displayed on the questionnaire to rate comfort before and after being in the Thermoheliodome from the survey distributed to participants prior to entering the dome.

[26], the use of PMV-PPD model for outdoor environment can have significant deviation from the actual thermal sensation vote (ASV), and that the idea would be ideal to combine that with PET (Physiological Equivalent Temperature). The questionnaire was therefore designed to collect the ASV and the perceived temperature profiles by circling on a bar graph of the Gagge 7-point voting scheme before and during the experiment. This approach may also been seen in Cheng and Ng et al. [27] for the review of different approaches for outdoor thermal comfort estimation [28] on different outdoor thermal comfort experiments.

Within the six questions posed, there are two sets that asked the same questions for before and after being in the Thermoheliodome to directly assess the effectiveness. Questions were prepared to avoid the Hawthorne effect by requesting mixed (quantitative and qualitative) responses throughout the experiment. This also acknowledges the possibility that some participants were also aware of the functionality of the dome prior to their volunteering in the project in that the dual question mechanism provides the potential to mitigate the bias resulted by pre-exposure to the experiment narrative.

The participants were invited to estimate the air temperature inside and outside of the Thermoheliodome. A small trick is played here in the questionnaire towards the participants to implicitly provide their thermal sensation feedback: although it is not commonly understood how humans "feel" actual temperature as our heat balance changes, many people tend to quantify their thermal sensation into temperature as air temperatures. According to Kenshalo et al. [29], with the skin exposed and the temperature constant, the one variable that leads to temperature sensing is controlled solely by the rate at which the temperature of the skin is changed. Put into thermodynamics terminology, this is also known as heat flux. Asking whether the participants "felt a temperature change" would therefore be equivalent as asking them if they felt the heat flux.

4. Results

4.1. Thermoheliodome performance

The Thermoheliodome, as shown in Fig. 8, resulted in an engaging piece of experimental architecture. It was successfully constructed and operated with reflective cones expanding the radiant cooling from indirectly evaporatively cooled bulbs. This enabled the analysis of passive reflected radiant cooling and thermal comfort managed by radiant heat transfer.

Fig. 9 shows the air, water, bulb surface, mean radiant temperature, and wet-bulb (calculated) temperatures and the averages (heavier line) for a 6–7 day period in August/September. In general, water temperature in the cooling tower remains constant throughout the day, the average hovering around 20 °C during daylight hours. The pump, convective and solar gains on insulated circulation piping, and on the bulbs inside the dome raise the water temperature between 2 and 5 °C during the day from the temperature exiting the cooling tower. As seen in Fig. 9, this value still remains below the air temperature.

The MRT depression, defined as the difference between air temperature and MRT as measured in the center of the dome, increases steadily between 9:00 and 12:00. On average for this period, the largest MRT depression is about 5 °C at midday, causing a significant change in perceived temperature. However, after 12:00 an adjacent wall facing the large north opening of the dome is exposed to direct sunlight and heats up, increasing the MRT experienced inside the dome. This undesirable result is confirmed with the SMART sensor [18], the sensor shown in Fig. 6 in Section 3.2. Fig. 10 shows the output of the SMART sensor when scanning the Thermoheliodome. The hot, red points correspond to the warm, 50 °C, wall. Despite the non-ideal radiant transfer from adjacent buildings, important results can be drawn from the data concerning radiative and convective heat transfer magnitudes, and before the wall is heated an ideal operation can be observed. This also points to the importance of understanding radiant emission in the context of thermal comfort in urban environments.

Fig. 9 shows both the water temperature in the cooling tower and the wet bulb temperature calculated based off of ambient temperature and relative humidity conditions. Overnight the wet-bulb temperature is lower than the bulk cooling tower water, which makes sense as the local climate around the cooling tower was likely humid and therefore not receptive to evaporation. During the day, and when there is good MRT depression, the bulk fluid temperature is close to the wet bulb temperature. Values below the wet-bulb temperature are thermodynamically prohibited for an evaporative cooling tower, but could be due to thermal mass in the system or to sensor or calculation error as an empirical relationship between relative humidity and web bulb was used [30].

4.2. Radiant heat transfer optimization

The Thermoheliodome can also increase the radiant heat transfer ratio relative to traditional convective cooling by more than 50:1 for still conditions. The temperature difference between an occupant's surface temperature and the Thermoheliodome interior radiant temperature can be much larger than the difference between the occupant's skin temperature and the warm air temperature. The exact ratio of radiant to convective heat transfer depends on Eqs. (1)–(3), specifically on the amount of air movement and the convection coefficient, h, in Eq. (1). For $h_c = 3.3\ \mathrm{W/m^2/K}$ as presented by [24] for experiments with minimal air movement, the average ratio for Q_{rad} to Q_{conv} can be 55:1 at mid-day, and 5:1 when the evaporative cooling and MRT depression is reduced at night based on the average profiles as shown in Fig. 9.

From the underlying datasets that determine the averages, there are more extreme scenarios during drier, hotter conditions where the ratio increases all the way to 50, meaning almost all the cooling is coming from radiation if there is little air movement. This does not solely indicate the magnitude of radiant exchange, but it indicates a human would nearly be in convective equilibrium with the air, so Q_{conv} would be approaching 0. Therefore, in the absence of convection, the radiant exchange dominates.

Performing the same calculations with a higher air speed and greater convection coefficient value of $h_c = 13.3\ \mathrm{W/m^2}$ close to values found in previous studies for a breezy 1 m/s air movement [24], the best ratio of radiant to convective cooling is reduced to 5.5. The ratio is 0.5 for minimal MRT depression conditions, such as the mid-day decrease in MRT depression as shown in Fig. 9, which shows that radiant exchange is still significant even in windy conditions.

Fig. 8. The Thermoheliodome in its fully functional state with reflective cones and evaporatively cooled supply water circuits. The photo on the right shows a thermal image of a cone during operation on the television screen, demonstrating the apparently uniform cool (blue) surface achieved via reflection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

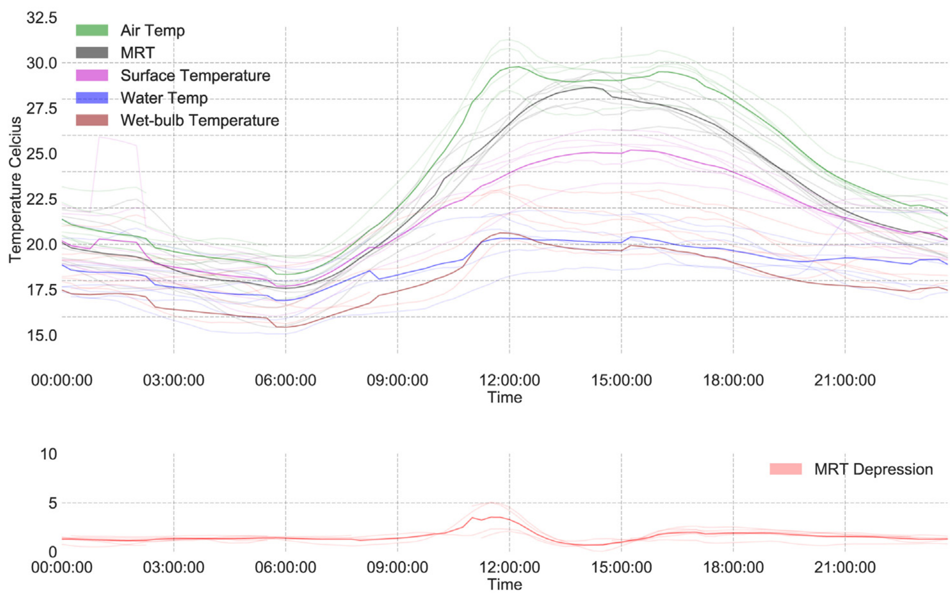

Fig. 9. Average daily operation of the Thermoheliodome from August/September 2015 in Princeton, NJ. Translucent lines are daily time-series measurements, and thick, opaque lines are the average values for air, water, bulb surface, and mean radiant temperature, and wet-bulb temperatures.

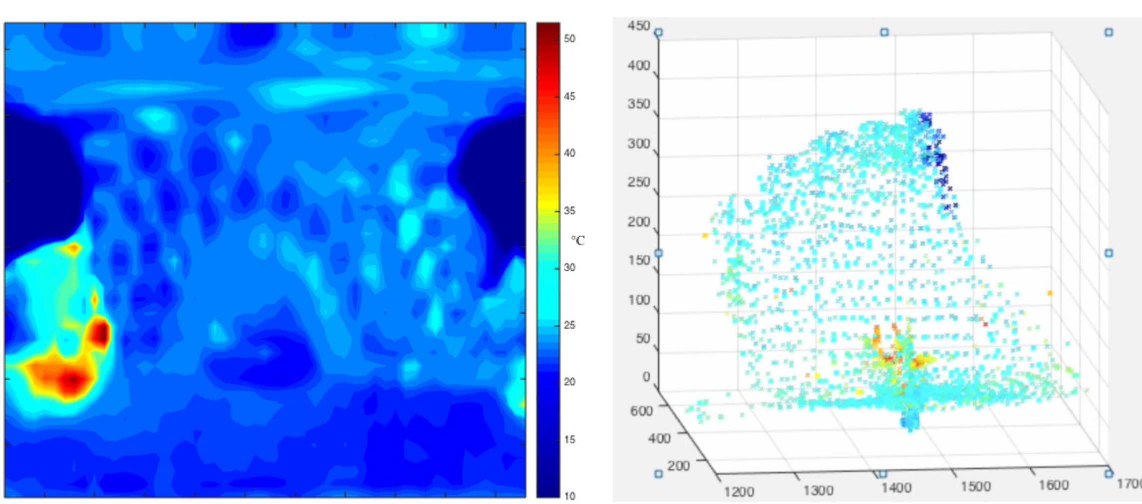

Fig. 10. Spatially resolved images of the Thermoheliodome from the SMART sensor used to calculate the MRT.

4.3. Thermal comfort survey

The experiment lasted for approximately 20 min in total, which maintained similar outdoor and operating conditions throughout the test. The average occupant used roughly 1.2 min to assess the performance and to fill out the forms while seated alone in the dome.

Before converting the survey data to numerical values, a simple analysis of the verbal response corresponding to the Gagge scale showed 75.5% of the participants responded with the correct functionality of the Thermoheliodome. This is surprisingly consistent with the "guesses" that the participants were asked to perform. A total of 87.5% of respondents lowered their temperature estimation after being in the Thermoheliodome, which suggests that it successfully provides perceptible cooling. The average number that the participants chose to quantify this cooling sensation with was a 3.16 °C drop of air temperature estimation. The statistical test of the responses demonstrate that the Thermoheliodome does provide a cooling sensation ($p \leq 0.01$), which is particularly true for the "thermally sensitive" participants ($p \leq 0.001$).

5. Discussion and outlook

The design of the Thermoheliodome was effective, and the concept might be applied to many climate conditions. Even with relatively high humidity levels, the indirect evaporative cooling can provide significant reductions in temperature that can depress the MRT. The Thermoheliodome achieves this with a small system, as the piping is drastically reduced by using radiant reflection. The concept could be adapted to many scenarios, and although it is specific to the outdoor condition, similar concepts could be applied to transitional zones in buildings. The effects could be augmented by adaptive comfort philosophies where transitions from hot spaces augment cooling perception, as in the transition from outside to the shade and cool radiation of the Thermoheliodome.

This analysis does not consider the fan and pump systems used to drive and circulate the evaporatively cooled water. These systems were off the shelf components available in construction and could be further optimized, and the specific varieties supplied were a constant speed fan at 200 W for the evaporative cooling tower, and a constant speed pump that drew 1.8 kW. One concept that was also developed in conjunction with this project was the direct evaporation through the external shell of the pavilion using media that allows water to circulate in liquid form while water vapor can pass through to the exterior and generate evaporative cooling [31]. This could be further developed to reduce or eliminate the pumping and fan power needed.

The Thermoheliodome is an outdoor pavilion, and therefore air velocity variation could not be controlled. We estimated the exchange of heat through convection for a range of values and found even with moderate wind, with warm air, the MRT depression is still the dominant cooling factor. In future research and experimentation, it would be warranted to include more detailed measurement of air movement, for example using sensitive hot-point anemometers or doing simulations of air movement in the space.

For the comfort study it would also be ideal to run the experiment across the neutral point, i.e. PMV = 0, so that the occupants would rate the initial outside thermal sensation with a broader range of thermal conditions in contrast to the neutral to slightly cold scenario in this experiment. The pavilion's performance may then provide even more interesting results. It would also be beneficial to extend the amount of time that individuals are required to acclimate inside the Thermoheliodome as traditional acclimatization usually takes up to 3 min even for transient thermal comfort studies [32]. Finally, a longer-term and more extensive comfort study could be carried out to consider a wider set of outdoor conditions and the nuances of different comfort influences, but the location and test subject availability were limited for this prototype.

Our ongoing and future work considers the broader implications of designing systems to leverage radiant heat transfer for comfort delivery [25], and considering the potential for using optimal human body exergy analysis to control heating and cooling thereby moving away from conditioning rooms and towards conditioning people [33]. In that vein, the SMART sensor that was developed for scanning the MRT in the Thermoheliodome has the potential to define the MRT in rooms with radiant cooling panels or heated floors that are poorly controlled by thermostats that only measure air temperature, and can also detect the presence and surface temperature of occupants for better comfort control [18]. Finally, we are working on ways the reflective radiant cooling system of the Thermoheliodome might be deployed for outdoor installations like bus stops in hot and humid climates like Singapore where we have investigated radiant systems [34].

6. Conclusion

The Thermoheliodome successfully combined efforts from different design and engineering disciplines to create a unique passive comfort performance. The resulting structure and system successfully demonstrate an alternative paradigm for radiant cooling systems and architecture. The performance was substantiated by calculations of cooling effect by radiation and from the survey results. The cooling was successfully generated by the passive evaporation of water into the air using a cooling tower, and indirectly supplying that sensible cooling to the radiant system. The rate of radiant cooling was increased substantially to offset the reduced convective cooling of the human body as the air temperature rises. The reflection off the bulbs increased the radiant heat transfer while minimizing any cooling of the outdoor air.

The system successfully achieved the objectives of indirect evaporative cooling and reflective radiant heat transfer to cool the occupant. The application of the concept in this pavilion is specific and future work will aim to clarify the performance with improved analysis of the systems, expanded occupant survey, and considering broader application for multiple occupants and developed with integrated evaporative cooling systems. Both the fields of passive cooling methods and radiant heat transfer manipulation will benefit from considering the results and potential of the Thermoheliodome concept.

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