Cooling without Air Conditioning: Membrane-Assisted Radiant Cooling for Expanding Thermal Comfort Zones Globally

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We present results of a world-first radiant cooling system that made the hot and humid tropical climate of Singapore feel relatively cool and comfortable. Thermal radiation exchange between occupants and surfaces in the built environment can augment thermal comfort. Even in air-conditioned spaces, radiation exchanged between occupants and their surroundings accounts for approximately 50% of their perceived comfort(1). The lack of widespread commercial adoption of radiant cooling technologies for indoor air conditioning is due to two widely-held views: (1) the low temperature required for radiant cooling in hot and humid environments will form condensation and (2) cold surfaces will still cool adjacent air via convection, limiting overall radiant cooling effectiveness. This work directly challenges these views and dispenses with them. We constructed a demonstrative outdoor radiant cooling pavilion in Singapore that used an infrared-transparent low density polyethylene membrane to provide radiant cooling at temperatures up to 20 °C below the dew point. Surrounding the radiant cooling surfaces by an air-gap and infrared-transparent membrane permits radiation exchange to occur between the human body and cold surfaces whilst avoiding condensation on any exposed material as well as significant convective heat transfer losses. Test subjects who experienced the pavilion (n=37) reported a 'cool' to 'neutral' thermal sensation 81% of the time, despite experiencing 29.6 $\pm$ 0.9 °C air at 66.5 $\pm$ 5 %RH and with low air movement of 0.26 $\pm$ 0.18 $m\ s^{-1}$. Comfort was achieved with a coincident mean radiant temperature of 23.9 $\pm$ 0.8 °C, requiring a chilled water supply temperature of 17.0 $\pm$ 1.8 °C. The pavilion operated successfully without any observed condensation on exposed surfaces despite an observed dewpoint temperature of 23.7 $\pm$ 0.7 °C. The coldest conditions observed without condensation used a chilled water supply temperature 12.7 °C below the dew point, which resulted in a mean radiant temperature 3.6 °C below the dew point of 23.7 °C.

Radiant Cooling | Thermal Comfort | Energy Efficiency | Photonics

For the first time in known records, a radiant cooling system that makes people comfortable in the hot-humid tropical outdoors, and yet does not condense water, has been created. The cooling panel operates below dew-point temperatures, but is insulated from humid air by a membrane transparent to longwave radiation. It successfully makes people feel comfortable in conditions exceeding 30 °C and 65% relative humidity without modifying the air temperature or humidity circulating around human bodies. By relying instead on thermal radiation, the system created and investigated in this paper made people feel cold outdoors in tropical Singapore, reporting thermal comfort sensations of "cool" as assessed by a thermal comfort survey, despite the unconditioned outdoor air temperature and humidity.

While thermal radiation has been studied for over a century in the context of thermal comfort (2–5), a database of buildings spanning 23 countries containing 81,846 complete sets of objective indoor climatic observations (6) does not contain a single data point with a mean radiant temperature more than 4 °C below the air temperature, for air temperatures above 28 °C. This fact, in conjunction with further literature review (3, 7, 8) leads the authors to believe such an environment has never been designed or studied. For reference, mean radiant temperature is a proxy for the view factor-weighted average temperature of the surroundings.

In 1963, Morse proposed a method for radiant cooling in the tropics, using a membrane-assisted approach to convectively isolate chilled surfaces from the surrounding air (7). The membrane is transparent to thermal radiation in the 5-50 micron range where humans emit, allowing for radiant cooling to occur between the chilled surface and a person through the membrane.

While this idea has been proposed, a full scale system has never been built testing whether the uniqueness of conditions will actually provide comfort for people(6). The conditions of high air temperature and low mean radiant temperature do not occur naturally anywhere, as chilled surfaces act as heat exchangers, cooling the air. Using the thermally transparent membrane as a convection shield, we eliminate this mechanism of heat transfer. Further, we transformed the initial 1963 concept with modern analytical techniques to improve the system's performance in the tropics, eliminating the need for components such as an internal heater and originally proposed by Morse to avoid condensation on the outer surface of the membrane (9). Promising results from this initial study (9) were scaled up to a full scale demonstrator, in which a thermal comfort study was conducted to monitor occupants' responses to the low radiant temperature environment with high outdoor

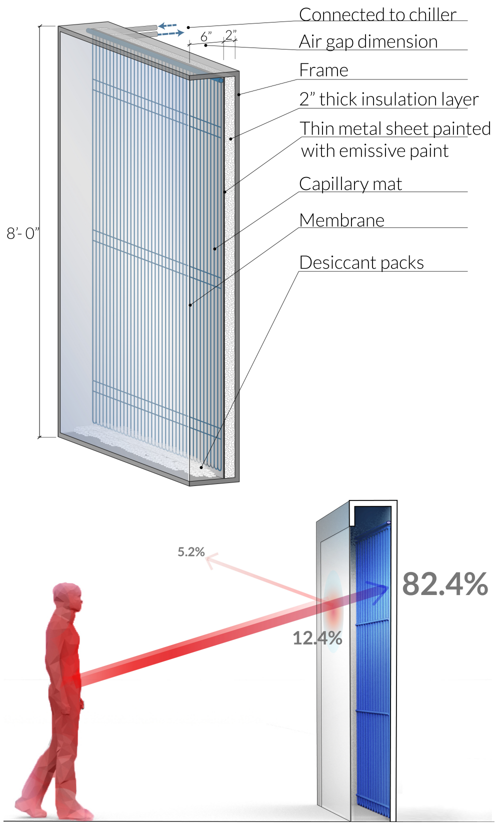


Fig. 1. Schematic of a Cold Tube radiant cooling panel (left) and radiant heat transfer through the infrared-transparent membrane (right).

Fig. 2. The completed Cold Tube.

air temperatures for the first time (6).

Typically, building occupants associate comfort with air temperature and relative humidity, and in traditional buildings, only air temperature is required for a comfort setpoint (8). To demonstrate that our system provides comfort while operating outside the conventional comfort modes, we conducted a thermal comfort study, surveying participants to gauge the perception of the new thermal environment.

Figure 1 schematically illustrates how the system functions, allowing radiation to pass, but not air and humidity, thereby reducing convection and eliminating condensation. Chilled water is circulated in a dense capillary mat internally in the panels. These cold surfaces extract heat independent of the air temperature, but it is previously impossible to remove heat from people radiatively without also cooling the air.

Such a radiative cooling system is notable since a carbon-constrained world is an air conditioning-constrained world, an unavoidable fact as global air conditioning demand is expected to reach 50 exajoules (EJ) by the end of the century, eclipsing global heating demand around 2070 (10). Already in the United States, air conditioning is responsible for nearly 9% of all primary energy demand (11) and is one of the primary CO_2 emission sectors.

Air conditioning is an attractive choice for comfort systems as the refrigeration cycle both dehumidifies and cools air, an important function since much of the ventilation load in the United States and tropics is dehumidification, known as the latent load (12). However, dehumidification requires subcooling the air, an energetically and exergetically intensive process (13), and the two processes cannot be decoupled with conventional vapor compression techniques. Using radiant systems for cooling and desiccants for dehumidification is an efficient combination (14).

With the recent excitement surrounding tunable nanophotonic materials for passive daytime and radiative cooling (15–17), this study helps advance the understanding for the potential of direct occupant radiant cooling. Utilizing these materials for comfort can increase the utility of outdoor space, manage thermal comfort of walking people, and rapidly provide cooling comfort to people outdoors, perhaps at bus stops, all without wasting cooling energy to the air.

Results

The completed pavilion, known further as the Cold Tube, is shown in figure 2. Three vertical panels are shown on the image in the left, and in the interior image on the right both vertical and horizontal ceiling panels are shown. The optically clear membrane is also transparent to infrared radiation, with a hemispherical transmissivity of 0.824 at 300 K. The blue capillary mats inside the panels circulated chilled water produced by a heat pump. The capillaries were in thermal contact with a thin metal sheet painted white (emissivity 0.95 at 300 K). Sensible heat in the air prevents condensation on the membrane surface, maintaining temperatures above the dew point for chilled water up to 20 °C below the dew point supplied to the capillary mats, allowing comfortable conditions with exclusively radiant cooling, no air conditioning.

The coldest mean radiant temperature produced in the Cold Tube was 19.9 °C with a coincident air temperature of 29.3 °C and supply water temperature of 10.8 °C, producing no condensation despite a dew point of 23.5 °C. Not only was the chilled water supply temperature 12.7 °C below the dew point, but the resulting mean radiant temperature was 3.6

°C below the dew point. Such conditions have never been achieved (6) in the built environment.

55 individuals participated in a subjective thermal comfort study in the Cold Tube carried out from January 8 through January 27 in 2019. 37 of the test subjects experienced the Cold Tube operating, and the remaining 18 were a control group experiencing the Cold Tube when turned off (and thus providing shade only). All test subjects were first asked to sit in a shaded outdoor space adjacent to the Cold Tube for a period of 15 minutes in order to achieve thermal neutrality with outdoor conditions.

Figure 3 shows histograms of cumulative data for thermal responses on a 7 point scale, ranging from -3 (cold) to 3 (hot) with 0 as neutral. After reaching thermal neutrality in the shade, which was confirmed verbally by participants, participants were surveyed three more times: 1) after walking seven minutes to the Cold Tube, 2) after sitting in the Cold Tube for one minute, and 3) after sitting in the Cold Tube for 10 minutes. Data from both the operational and non-operational Cold Tube participants are displayed side by side in the histograms. Statistics about the distributions, as well as p-values assessing the likelihood the responses from both the Cold Tube on and off groups are related based on a t-test.

Data in figure 3 shows that when the Cold Tube is on, there is never a ‘Hot’ population in the Cold Tube, and after prolonged sitting in the pavilion, ‘Slightly Warm’ is the warmest vote. While 46% of Cold Tube on responses were warm after only 1 minutes in the Cold Tube, which is greater than the initial state population, this number fell to 27% after being in the Cold Tube for 10 minutes. More importantly, the mean vote drops below 0, implying the mean of the perception is cool. Such a result is without precedent for conditions where air velocities are below 0.4 $m\ s^{-1}$ and air temperature exceeds 30 °C. The t-test provides a p-value less than 0.02, implying a 98% confidence interval that both survey groups were reporting feeling different thermal sensations. Much higher p-values were observed between the populations of Initial State and Walking responses. Similarly, the p-value of the Cold Tube off group compared to the Initial State groups together is 0.74, compared to 0.002 with the Cold Tube on compared with the Initial State population. This implies that the Cold Tube, when turned off, was perceived to provide a similar degree of comfort as sitting under any shaded outdoor structure, but sitting inside the Cold Tube when it was on was absolutely not perceived as similar to a shading-only scenario.

Data from both Cold Tube on and off groups were interpreted in the adaptive comfort framework, plotted in figure 4a. Using the operative temperature calculated in equation 1, the outdoor air temperature was used as the x-axis and data is shaded based on the satisfaction response. When the Cold Tube was operational, 21% of participants were dissatisfied, which is nearly an allowable design criteria within the adaptive comfort framework (80% satisfaction interval), however when the Cold Tube was off, 73% of participants were dissatisfied. There is a clear segmentation between the on and off groups, and shows that this type of system has potential for augmenting comfort in naturally ventilated spaces without air conditioning.

The same data is transformed in figure 4b, plotting the raw mean radiant temperature data against the air temperature for each survey point. Again, there is a clear separation of

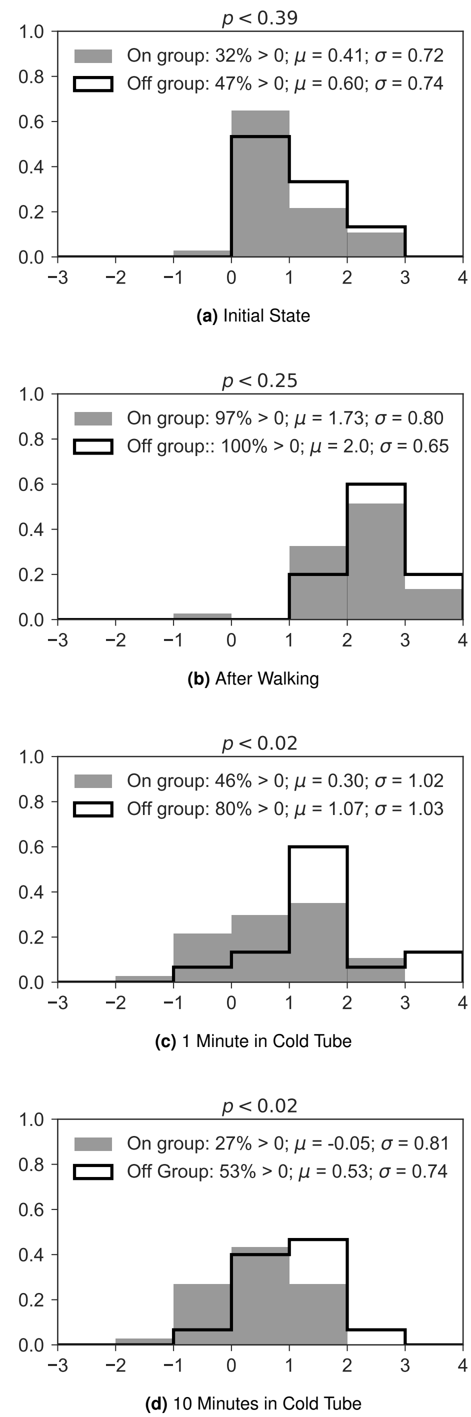
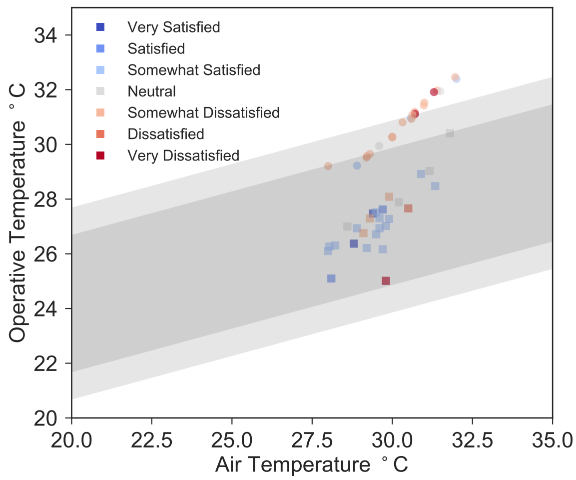
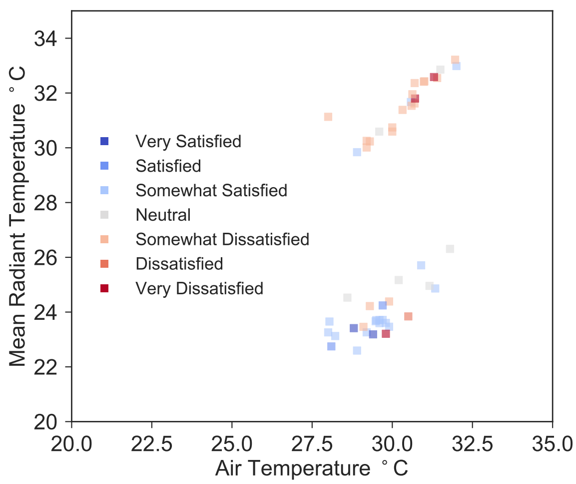


Fig. 3. The thermal sensation votes reported by occupants are compared between the Cold Tube on and off groups. The histograms show the thermal perception response data from the survey participants. A vote of -3 is very cold, 0 is neutral, and +3 is Very Warm. The subplots are responses during the initial conditioning period (a), after 7 minutes of walking (b), after spending 1 minute in the Cold Tube (c), and 10 minutes in the Cold Tube (d). Responses with the Cold Tube on are solid gray bars, and responses with the Cold Tube off is the solid black line. Included are confidence intervals that the off population is different from the experimental population from a t-test, the measured mean vote, μ, the standard deviation among responses, σ, and the percentage of responses above 0 (warm votes). Within 1 minute of entering the Cold Tube, occupants report feeling cool, and after 10 minutes the mean vote shifts cool, going below 0.



(a) Operative Temperature



(b) Mean Radiant Temperature

Fig. 4. (a) Adaptive comfort window for air speed of 0.3 m/s appended with data from the thermal comfort survey responses. (b) The mean radiant temperature plotted against air temperature for each survey response. The color of the data is assigned based on occupant satisfaction votes. Each point is placed at the coincident operative temperature. Clusters emerge with the Cold Tube on and off, with clear differences in the response profiles for nearly the same range of air temperatures.

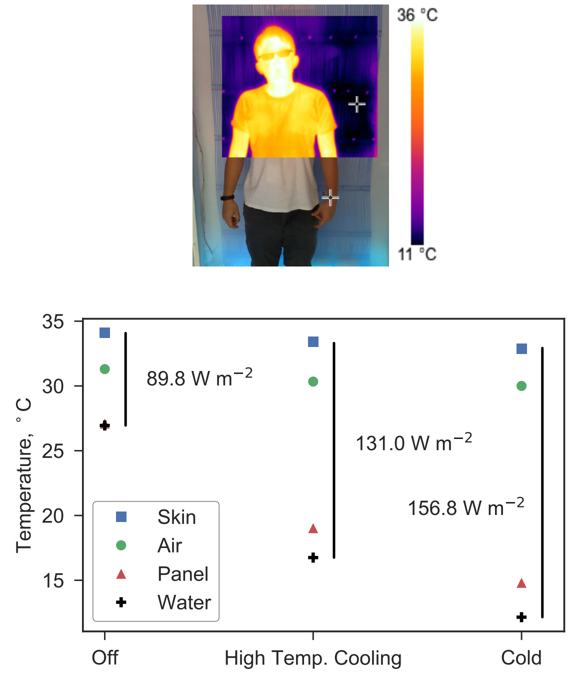


Fig. 5. Heat flux measured from occupants' wrists at three water temperature ranges, showing the full temperature profile in the system from air to water and the associated heat flux.

Cold Tube on and off clusters.

Physiological Measurements. Skin heat flux and temperature measurements are plotted against system measurements in figure 5b. Figure 5a shows an image of an author standing in front (50 cm away) of a radiant cooling panel in the Cold Tube taken using a thermal and visible light camera. The color gradient shows the driving force for radiant heat transfer from a person's skin to the cooling panel. As expected, the net heat flux from a person's skin to the radiant cooling panel scales proportionally to the supply water temperature. The maximum value occurred when the water temperature was 13 °C, which corresponded to 156.8 $W\ m^{-2}$. With this 13 °C water supply, there was not a significant decrease in the air temperature, from 31 to 30 °C. The large increase in radiant heat flux occurred due to the radiant losses to the chilled water.

Comparing the incremental increase in heat flux as water temperature decreases allows one to extrapolate that if the water temperature was the skin temperature, i.e. no radiant heat exchange, allows us to extrapolate that 52.5 $W\ m^{-2}$ were due to convection for each dataset, and the remaining $W\ m^{-2}$ were therefore attributed to radiation. For the cold 13 °C water case, this means that 104.3 $W\ m^{-2}$ were due to radiant heat transfer. This further allows us to back-calculate a T_{MRT} of 15.7 °C on the hemisphere of the body facing the panel. This is consistent with the panel temperature measurement produced with the radiometer.

More importantly, this physiological data offers an explanation for the thermal comfort survey responses. As thermal comfort requires metabolic heat to be lost, the increase in heat flux from a person to the panel as the water temperature decreases despite a nearly constant (close to skin temperature) air temperature confirms that heat is being lost primarily to the panels via radiation.

Condensation Prevention. A primary research objective was to observe chilled water supply temperatures that would be allowable without condensation observed on any surface of the radiant cooling panel. Such an environment has never been constructed before. The membrane surface temperature is difficult to directly measure since sensors placed on the infrared-transparent material locally differed from their surroundings due to radiant cooling. Instead, we slowly lowered the water temperature at a rate of 4 °C per hour and watched for signs of condensation. When condensation occurred, the air

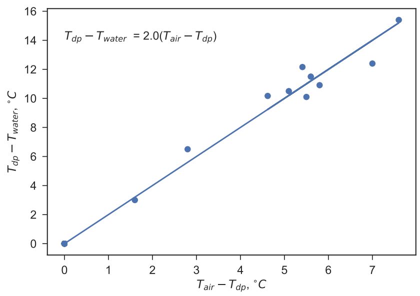


Fig. 6. Chilling water slowly until the onset of condensation is observed allows the air temperature minus the dew point temperature to be plotted against the dew point minus water temperature to understand how cold water can be chilled for supply to the Cold Tube.

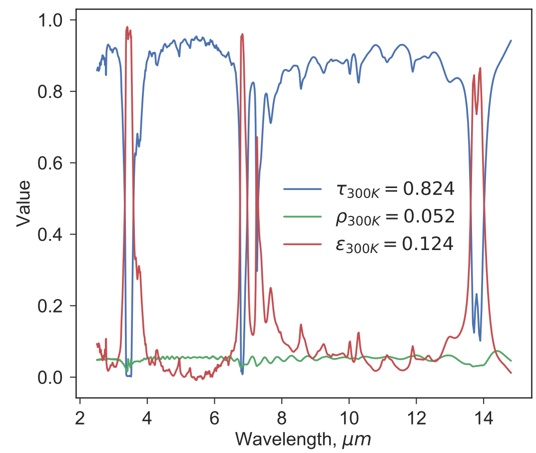


Fig. 7. FTIR spectra of the LDPE infrared-transparent membrane material.

temperature and supply water temperature were recorded. A plot of this data is shown in figure 6a. The data is plotted as the difference in the air temperature, T_{air}, and dew point, T_{dp} on the x-axis, and the y-axis is the difference in T_{dp} and the water temperature, T_{water}. This representation of the data is done to reparametrize the data in terms of the maximal convective heating provided from the air as dictated by $T_{air} - T_{dp}$ before the membrane goes below t_{dp}. This control logic is elegant, as it implies that as more heat in the air is available for membrane heating, more cooling can be provided through cooler chilled water without energy penalties since the chilled membrane is convectively isolated from the warmer air.

Discussion

The Cold Tube was an exciting step forward for exploring novel modes of providing thermal comfort. As previously discussed, the temperature range produced in the Cold Tube has never been observed in the built environment (6), however the findings presented in figure 4 appear to be consistent with the adaptive comfort framework (18). More specifically, the environment produced in the Cold Tube is predicted to be comfortable not only with a heat balance described in the Methods section, but with the existing adaptive comfort framework. Typically in the adaptive framework, the required operative temperatures for comfort would be produced with air or air and radiant systems, not a radiant system alone as achieved in the Cold Tube. The Cold Tube is therefore a first step in validating the adaptive comfort region with radiant heat transfer only, implying that separation of comfort and ventilation air is a plausible method of climate conditioning for the tropics.

Such a requirement is particularly important when large air exchange rates are required to maintain ventilation rates in spaces such as auditoriums, laboratories, classrooms, and shared office spaces. If fresh air can be supplied at an arbitrary rate with little or no energy *or* comfort penalty, this fundamentally changes the climate conditioning paradigm. Further, as preliminarily demonstrated with the data from the Cold Tube, strict dehumidification is also not necessary, which could reduce large dehumidification loads across humid climate regions worldwide (19). Using higher temperature hydronic radiant cooling has also been demonstrated to reduce the energy consumption of climate conditioning, as higher temperatures of 17-20 °C can be used instead of the more traditional 4-8 °C used by conventional air systems (14).

Conclusions. For the first time, a system was designed to achieve 10 K of separation between the mean radiant temperature and the air temperature, producing no condensation as the supply temperatures and mean radiant temperatures were well below the dewpoint, up to 20 K and 3.5 K, respectively. The Cold Tube is an exciting step forward for demonstrating (1) that radiation and convection can be separated for comfort conditioning (2) to rely on radiation alone to produce comfortable conditions based on existing metrics. The thermal comfort study conducted in Singapore in January 2019 is a strong preliminary investigation into the applicability of such a membrane assisted radiant cooling technology applied at scale to reduce comfort-related energy demand worldwide.

Materials and Methods

Cold Tube Design, Construction, and Evaluation. The Cold Tube was constructed at the United World College, Southeast Asia (UWC-SEA), Dover campus, in Singapore from August to October 2018. The pavilion is enclosed by ten 1.2m x 2.1m (4' x 8') panels; two horizontal panels at the top and eight vertical panels, with north and south facing entrances. The surface of the panels are cooled down below the dew point by chilled water from custom variable speed chillers to provide radiant cooling. It is separated from the hot and humid environment to avoid condensation by infrared transparent membranes that are 82.4% transparent to thermal blackbody radiation. A schematic of heat transfer about a single vertical panel is shown in figure 1 and the FTIR spectra of the 50 micron thick LDPE infrared-transparent material is shown in figure 7.

The supply and return temperatures of representative panels were measured with high-precision thermistors (10K Precision Epoxy Thermistor - 3950 NTC; +/- 1%). Net radiant heat transfer between occupants and surfaces within a 150° field of view was measured with a pyrgeometer (Apogee, SL-510-SS; 0.12 mV per $W\ m^{-2}$; 1% measurement repeatability) and pyranometer (Apogee SP-510; 0.057 mV per $W\ m^{-2}$; 1% measurement repeatability), which were manually directed in the direction of heat flux sensing. Skin temperature and heat flux were measured with a skin temperature and heat flux sensor (gSKIN ®BodyTEMP Patch; +/- 0.3 °C). Air temperature and globe temperature were measured inside the pavilion with Pt-100 thermistors (±0.1 ° C). The panel temperature was measured with a non-contacting infrared temperature sensor (Melexis

®MLX90614; +/- 0.3 °C), sealed inside the radiant panel facing the chilled capillary mats. In addition, an air temperature sensor, relative humidity sensor, and air speed sensor from the ThermCondSys 5500 measurement system were placed at the location of the occupant. The air temperature sensor was a Pt-100 thermistor (±0.1 ° C). The air temperature sensor was shielded from radiation with a highly reflective silver cone. The air speed sensor is a spherical omnidirectional air speed sensor with temperature compensation, vacuum covered with an aluminum coating that increases resistance to contamination and decreases the effect of thermal radiation on the accuracy of the measurement (± 0.02 $m\ s^{-1}$). The relative humidity sensor has a ±2% accuracy. Measurements were taken at 10 second intervals, which were further smoothed by the minute for analysis in this paper. Smoothed measurements for air speed, v_{air}, air temperature, t_a, and mean radiant temperature, t_r, were used to compute the operative temperature, t_o, using equation 1 (20).

$$t_o = \frac{t_r + (t_a \times \sqrt{10 v_{air}})}{1 + \sqrt{10 v_{air}}} \quad [1]$$

Heat flux measurements from the gSKIN sensor were net heat flux, meaning both convection and radiation fluxes were measured simultaneously. Heat flux measurements were taken with three supply water conditions, warm at 26 °C, 'LowEx' (short for low exergy (13)) at 17 °C, and cold at 13 °C. If the air temperature is consistent during these measurements, these three data points allow for the regression of heat flux to be made back for water temperature. This regression can be used to find the condition of no radiant heat flux when $T_{MRT} = T_{skin}$. This extrapolated heat flux with no radiant heat flux would represent the convective heat flux, Q_{conv} that occurs at T_{air}. This was treated as a constant value, and allowed correction of the net heat flux, Q_{net} for the radiant heat flux, Q_{rad} as in equation 2.

$$Q_{rad} = Q_{net} - Q_{conv} \quad [2]$$

Further, once a value of Q_{rad} was calculated, knowing the skin temperature, T_{skin} [K], the mean radiant temperature in the hemisphere of the gSKIN sensor's exposure, $T_{MRT,hemi}$ [°C], could be back-calculated as shown in equation 3. In this equation ε is set to 0.95 and σ is the Stephan-Boltzmann constant, $5.67 * 10^{-8}$ [$W\ m^{-2}\ K^{-4}$]. This value was compared to the measured values with the pyrgeometer and pyranometer.

$$T_{MRT,hemi} = \sqrt[4]{\frac{Q_{rad}}{\varepsilon\sigma} - T_{skin}^4} \quad [3]$$

Mean Radiant Temperature Simulation. Weather data collected at the site was used to determine the required setpoint for comfort in the constructed pavilion using a heat balance approach to expanding the psychrometric comfort zone (21, 22). The measured air temperature, relative humidity, and average air speed of 0.3 $m\ s^{-1}$ were used in conjunction with the metabolic rate of a resting person, 1.2 met or 69.8 $W\ m^{-2}$ and a skin wettedness of 0.06 for dry skin. The color gradient in figure 8 covered by the air temperature and humidity data points shows the range of required mean radiant temperature that the system must produce, in order for occupants to feel comfortable, roughly between 23 °C and 25 °C depending on the precise environmental condition. The white line traversing the chart through the environmental data points shows the set of points where the required mean radiant temperature for comfort is the dew point temperature. Points above this line require a mean radiant temperature lower than the dew point for occupants to feel comfortable. This analysis demonstrates the need for a panel construction separating the surface from the humid air to prevent condensation.

To achieve these required mean radiant temperatures, a geometric simulation was conducted to spatially map the mean radiant temperature in the Cold Tube. To do this, first a grid of 750 points is created on a plane at a fixed height of $1m$ above the floor. At each location on this grid 1,280 geodesically distributed rays emanate. They intersect the surfaces around them, with assigned known surface temperatures, and the the temperature value at each intersection is averaged and recorded as the mean radiant temperature at each point on the grid. A color gradient is then created based on the MRT values. Further discussion of this simulation method

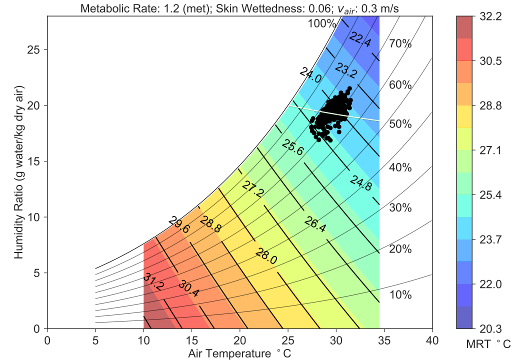


Fig. 8. Expanded Psychrometrics heat balance to determine the mean radiant temperature required to produce comfort.

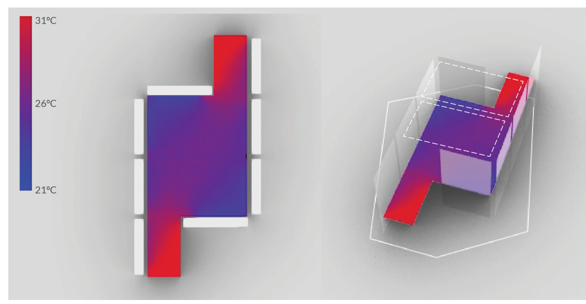


Fig. 9. A simulated map of the mean radiant temperature distribution at a 1m height in the Cold Tube with a supply water temperature of 18 °C.

from our previous work can be found in (23). The result from this simulation is shown in figure 9. This simulation was conducted with a supply water temperature of 18°C water to the panels, with every other temperature set to 31°C. The simulation indicates that the required range of mean radiant temperatures required for comfort shown in figure 8 can be met in the Cold Tube. The mapping of MRT within the Cold Tube space allows for an understanding of the effect of view factor on the perceived temperature as an occupant walks through the space.

Thermal Comfort Study. The primary goal of the thermal comfort study was to assess whether individuals felt cooler in the Cold Tube than just in shade, and whether the cooling provided by the infrared transparent panels maintained to avoid condensation and air conditioning was sufficient to cool occupants at short (1 minute) and longer (10 minute) time intervals. These time intervals are indicative of transient comfort or thermal delight, and steady state thermal comfort.

Thermal delight refers to the instantaneous perception of comfort when one has quickly transitioned from an uncomfortable environment to an environment more amenable to providing thermal comfort. An example is the experience of entering an air-conditioning lobby after walking in a hot outdoor environment for a prolonged duration. Those individuals who feel pleasure when a rush of cold air blows over their hot and sweaty bodies are said to be experiencing "thermal delight".

Thermal comfort is the condition of the mind that expresses satisfaction with one's thermal environment. It is assessed empirically by subjective evaluation, often through the administration of surveys. International standardization organizations, such as the American Society for Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), nevertheless publish mathematical models for estimating perceived thermal comfort of typical humans. Such models are based on the estimated characteristics of clothing levels, metabolic rates of occupants in an environment, and the estimated air temperature, mean radiant temperature, humidity, and wind speed of the environment. Measured data on these parameters are often collected during survey-based studies of thermal comfort in order to compare model predictions of thermal comfort to actual responses.

For the study, participants were escorted by a study administrator to the experimental site on the United World College Southeast Asia (UWCSEA) Dover campus. Once participants arrived at the first location, the study commenced using the following procedure. Permission for the study was obtained from the Institutional Review Board at the University of California, Berkeley who approved the study (CPHS Protocol No. 20180-12-11636).

1. Each participant reached a state of thermal neutrality by sitting 10-15 minutes in a shaded area exposed to elevated air movement. Each participant was given control over the use of a fan to make sure that thermal neutrality would be reached in sufficient time.
   - After 10 minutes, the participants would evaluate their thermal comfort, and decide if an additional 5 minutes beneath the fan would be required. After reaching the thermal neutrality state, 15 minutes maximum under the fan, the participant would be given a thermal comfort survey for the first of four times. The entire thermal comfort survey can be found in Supplemental Materials.
   - During this time, participants were asked to complete a survey asking about their air conditioning and fan preferences at home. This is an important step to understanding how closely our sample resembles the general population. We asked participants what type of cooling they use at home and how often they use it.
   - The participants clothing level was then be recorded by the survey administrator.
2. The participant was asked to spend 7 minutes walking through the shaded, covered and uncovered (sun-exposed) outdoor environment on a predetermined path. After the walk participants were surveyed about the thermal comfort right at that moment. This is the second time they are filling out the thermal comfort survey.
3. Next, the participant was asked to step into the pavilion. Participants were subsequently surveyed after 1 min and after 10 minutes sitting in the pavilion, the third and fourth time they will complete the survey, respectively.
   - The objective of the third survey (1 min after entering the pavilion) is to evaluate whether there is the effect of thermal delight or significant feeling of heat relief due to rapid heat release.
   - The objective of the fourth survey (10 minutes after entering the pavilion) is to understand how participants respond to the pavilion's environment with respect to overall thermal comfort.
4. Finally, participants were asked to qualitatively compare the pavilion environment to the first environment beneath the fan. Participants were also asked to provide feedback about what types of environments they would most like to see this technology installed around Singapore.

This experimental sequence was used to facilitate two different experiments using the Cold Tube pavilion. These are:

1. Evaluation of thermal comfort of people in the active pavilion - This study served as the benchmark information for the pavilion. The pavilion was supplied with 10-15 °C water to the radiant cooling panels, which created a perceived mean radiant temperature between 22-24 °C. The air temperature would be outdoor conditions of 28-32 °C and 60-80 % RH. 39 participants were recruited for this study, yet only 37 survey responses were analyzed due to ambient weather condition changes.
2. Control for comfort caused by the shade provided by the pavilion - The pavilion will provide cooling to individuals by providing shade only, with the active cooling turned off. During the experiment, chilled water will not be supplied to the pavilion, therefore this study is important to understand the contribution of shading to cooling and to demonstrate the additional benefit to the cooling that the active cooling of the water supplies to occupants. 18 participants were recruited for this study, yet only 16 survey responses were analyzed due to ambient weather condition changes and data loss.

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1. DA McIntyre, I Griffiths, Radiant temperature and thermal comfort. Vol. CIB Commission W45, (1972).
2. C Yagoglou, Report of committee to consider the report of the new york state commission on ventilation. *Am. Soc. Heat. Vent. Eng.* **30**, 254–256 (1924).
3. T Bedford, C Warner, The globe thermometer in studies of heating and ventilation. *The J. Hyg.* **34**, 458–473 (1934).
4. A Standard 55, Thermal environmental conditions for human occupancy. *Am. Soc. Heating, Refrig. Air conditioning Eng.* (2017).
5. PO Fanger, *Thermal comfort. Analysis and applications in environmental engineering.* (Copenhagen: Danish Technical Press.), (1970).
6. VF Licina, et al., Development of the ashrae global thermal comfort database ii. *Build. Environ.* **142**, 502 – 512 (2018).
7. R Morse, Radiant cooling. *Archit. Sci. Rev.* **6**, 50–53 (1963).
8. T Cheung, S Schiavon, T Parkinson, P Li, G Brager, Analysis of the accuracy on pmv–ppd model using the ashrae global thermal comfort database ii. *Build. Environ.* **153**, 205–217 (2019).
9. E Teitelbaum, et al., Revisiting radiant cooling: condensation-free heat rejection using infrared-transparent enclosures of chilled panels. *Archit. Sci. Rev.*, 1–8 (2019).
10. M Isaac, DP van Vuuren, Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy* **37**, 507–521 (2009).
11. EI Agency, Residential energy consumption survey, 2015 recs survey data. *Tables HC6* **8** (2015).
12. LG Harriman III, D Plager, D Kosar, Dehumidification and cooling loads from ventilation air. *ASHRAE journal* **39**, 6 (1997).
13. F Meggers, V Ritter, P Goffin, M Baetschmann, H Leibundgut, Low exergy building systems implementation. *Energy* **41**, 48–55 (2012).
14. A Schlueter, A Rysanek, F Meggers, 3for2: Realizing spatial, material, and energy savings through integrated design. *CTBUH J.*, 40–45 (2016).
15. AP Raman, MA Anoma, L Zhu, E Rephaeli, S Fan, Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* **515**, 540 (2014).
16. Y Zhai, et al., Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. *Science* **355**, 1062–1066 (2017).
17. T Li, et al., A radiative cooling structural material. *Science* **364**, 760–763 (2019).
18. F Nicol, Temperature and adaptive comfort in heated, cooled and free-running dwellings. *Build. Res. & Inf.* **45**, 730–744 (2017).
19. B Wellig, B Kegel, M Meier, E Basler, A Partner, "verdopplung der jahresarbeitszahl von klimakälteanlagen durch ausnützung eines kleinen temperaturhubs". *Ernst Basler+ Partner, Zürich, iA Forschungsprogramm UAW, Bundesamt für Energie, Bern* (2006).
20. ISO, 7726, ergonomics of the thermal environment, instruments for measuring physical quantities. *Geneva: Int. Standard Organ.* (1998).
21. E Teitelbaum, F Meggers, Expanded psychrometric landscapes for radiant cooling and natural ventilation system design and optimization. *Energy Procedia* **122**, 1129–1134 (2017).
22. E Teitelbaum, P Jayathissa, C Miller, F Meggers, Design with comfort: Expanding the psychrometric chart with radiation and convection dimensions. *Energy Build.* **209**, 109591 (2020).
23. TKFM Dorit Aviv, Eric Teitelbaum, Generation and simulation of indoor thermal gradients. *Proc. IBPSA Build. Simul. Conf. In Press.* **Rome** (2019).