# Membrane-assisted radiant cooling for expanding thermal comfort zones globally without air conditioning

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Edited by Alexis T. Bell, University of California, Berkeley, CA, and approved July 20, 2020 (received for review January 28, 2020)

**We present results of a radiant cooling system that made the hot and humid tropical climate of Singapore feel cool and comfortable. Thermal radiation exchange between occupants and surfaces in the built environment can augment thermal comfort. The lack of widespread commercial adoption of radiant-cooling technologies is due to two widely held views: 1) The low temperature required for radiant cooling in 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 provides proof-of-concept solutions examined for a transient thermal-comfort scenario. 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 below the dew point. Test subjects who experienced the pavilion ($n$ = 37) reported a "satisfactory" thermal sensation 79% of the time, despite experiencing 29.6 ± 0.9 °C air at 66.5 ± 5% relative humidity and with low air movement of 0.26 ± 0.18 $\mathrm{m \cdot s^{-1}}$. Comfort was achieved with a coincident mean radiant temperature of 23.9 ± 0.8 °C, requiring a chilled water-supply temperature of 17.0 ± 1.8 °C. The pavilion operated successfully without any observed condensation on exposed surfaces, despite an observed dew-point temperature of 23.7 ± 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.**

radiant cooling | thermal comfort | energy efficiency | photonics

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 comfortable outdoors in tropical Singapore; they reported 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 (1–4), a database of buildings spanning 23 countries containing 81,846 complete sets of objective indoor climatic observations (5) does not contain a single data point with a mean radiant temperature (MRT; the weighted temperature of surrounding surfaces) more than 4 °C below the air temperature for air temperatures above 28 °C. This fact, in conjunction with further literature review (2, 6, 7), leads us to believe that such an environment has never been designed, measured, or studied. Moreover, our recent work suggests that, although these types of conditions are uncommon, they do produce potential thermal-comfort solutions (8, 9), but they require addressing risks of condensation and coupling the surface temperature to air temperature (10).

In 1963, Morse (6) proposed radiant cooling system to be used in tropical climates, which relied on a membrane transparent to thermal radiation in the 5 to 50 μm range to convectively isolate a chilled surface from the ambient environment. Despite being convectively isolated from the environment, thermal radiation is still able to pass through the membrane, cooling occupants radiatively.

While this idea has been proposed, a full-scale system comprising many panels has never been built, testing whether the uniqueness of conditions will actually provide comfort for people (5). The conditions of high air temperature and low MRT do not occur naturally anywhere, as chilled surfaces act as heat exchangers, cooling the air. Using a membrane transparent to longwave thermal radiation (commercially available 50 μm low-density polyethylene [LDPE] film) as a convection shield, we eliminate this unwanted convection as a mechanism of heat transfer. Further, we transformed the initial 1963 concept with modern analytical techniques to improve the system's

## Significance

**In this paper, we present results from a radiant cooling pavilion, demonstrating a method of cooling people without cooling the air. Instead, surfaces are chilled, and thermal radiation is used to keep people cool. A thermally transparent membrane is used to prevent unwanted air cooling and condensation, a required precursor to deploying radiant cooling panels without humidity control in tropical environments. The results from this thermal-comfort study demonstrate the ability to keep people comfortable with radiation in warm air, a paradigm-shifting approach to thermal comfort that may help curb global cooling-demand projections.**

Author contributions: E.T., K.W.C., D.A., K.B., L.R., D.S., M.T., F.M., J.P., and A.R. designed research; E.T., K.W.C., D.A., K.B., L.R., D.S., M.T., F.M., J.P., and A.R. performed research; E.T., K.W.C., M.T., F.M., J.P., and A.R. analyzed data; and E.T., K.W.C., and D.A. wrote the paper.

Competing interest statement: A.T.B., M.T., and J.P. are affiliated with University of California, Berkeley.

This article is a PNAS Direct Submission.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2001678117/-/DCSupplemental.

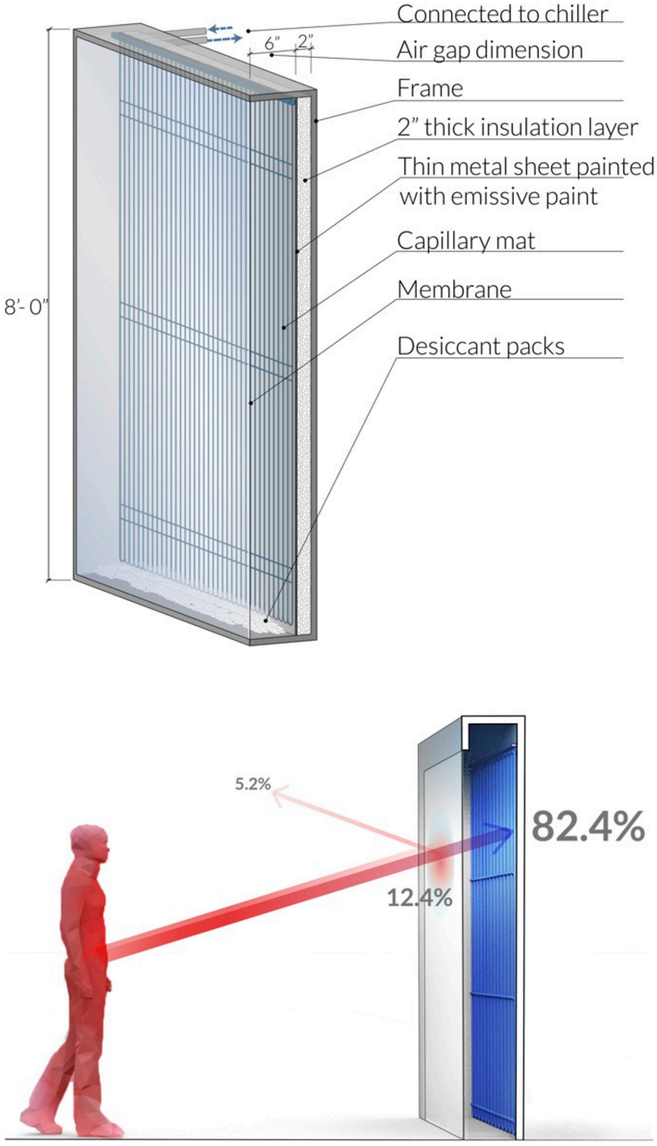

**Fig. 1.** Schematic of a Cold Tube radiant cooling panel (*Upper*) and radiant heat transfer through the IR-transparent membrane (*Lower*).

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 (10). Promising results from this initial study (10) expanded 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 air temperatures, producing comfort datapoints not yet part of current comfort databases (5), and testing expanded potentials for thermal comfort (9).

Typically, building occupants associate comfort with air conditions, meaning air temperature, relative humidity, and air speed. Often, the only means of thermal control in traditional buildings is through thermostat feedback on air temperature or by manual air-speed adjustments, which some argue are the only necessary parameters for predicting and prescribing comfort conditions (7). We had the goal of demonstrating that if radiant cooling is separated from comfort cooling, it can be relied upon independently as a heat-transfer mechanism to provide comfort. Fans and natural ventilation are often leveraged as very efficient mechanisms to increase cooling independent of mechanical conditioning with just air speed, but as air temperature and humidity increase, their effectiveness is diminished. The membrane-assisted panel we investigate enables radiant cooling under humid conditions. We aim to demonstrate the potential of it as a cooling mechanism that can be operated independent of convection-constrained air conditions, and without any mechanical treatment of the air. 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 thermal environment.

Such a radiant cooling system is notable, since air-conditioning demand is anticipated to reach 50 EJ by 2100, eclipsing global heating demand near 2070 (11). Curbing this sharp increase in global energy demand is critical to mitigating carbon emissions. In the United States alone, air conditioning already accounts for nearly 9% of all primary energy demand (12). Historically, air conditioning was a deceptively efficient system for comfort, as, fundamentally, an air conditioner must both dehumidify and cool air simultaneously, desirable processes from a thermal-comfort perspective. However, energy for dehumidification, referred to as the "latent load," can be significantly larger than the actual cooling-energy demand, or "sensible load," in tropical, humid climates (13). 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). More broadly, separation of these latent and

**Fig. 2.** The completed Cold Tube.

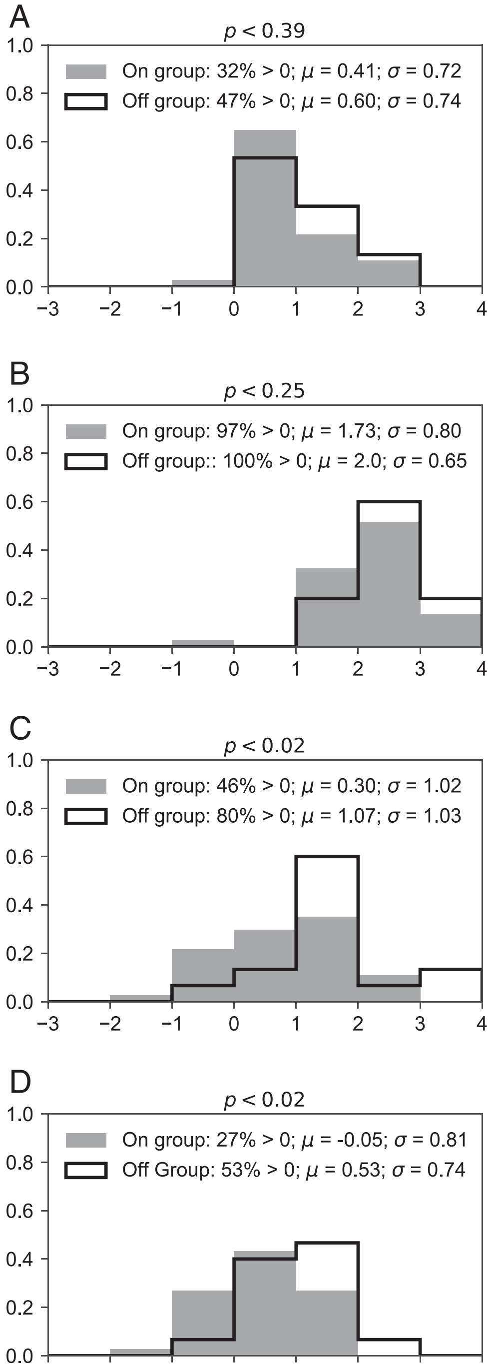

**Fig. 3.** The thermal-sensation votes reported by occupants are compared between the Cold Tube on and off groups. The histograms show the thermal perception response data from the survey participants. A vote of −3 is very cold, 0 is neutral, and +3 is very warm. The subplots are responses during the initial conditioning period (*A*), after 7 min of walking (*B*), after spending 1 min in the Cold Tube (*C*), and 10 min in the Cold Tube (*D*). Responses with the Cold Tube on are solid gray bars, and responses with the Cold Tube off are the solid black lines. Included are CIs that the "off" population is different from the "on" population from a *t* test, the measured mean vote, $\mu$, the SD among responses, $\sigma$, and the percentage of responses above 0 (warm votes). Within 1 min of entering the Cold Tube, occupants report feeling cool, and after 10 min, the mean vote shifts cool, going below 0 to 0.05.

sensible loads represents an exciting paradigm for changing the comfort-energy-demand profile, and this study demonstrates potentials for radiant cooling to create comfortable conditions, while doing nothing to the air.

Further, 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. Using 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, such as at bus stops, all without wasting cooling energy to the air. We hope this study can act as a reference for thermal comfort through only thermally radiative mechanisms, particularly in an environment such as outdoors in the tropics, where convection and evaporation are limited by the warm and humid air.

## Results

Fig. 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 radiant heat from outside surfaces, independent of the outside air's temperature. Without this technology, it was previously impossible to remove heat from people with radiant panels without the panel also cooling the ambient air it was in direct contact with. For further explanation of the full experimental methods and procedures, see *Materials and Methods*.

Photos of the completed system, referred to during the project as the "Cold Tube," are shown in Fig. 2. The outside of the Cold Tube is shown in Fig. 2, *Upper*, comprising three vertical panels on the west face painted white to reflect solar radiation, minimizing solar heat gain. The east-facing side looks the same, whereas the north and south sides have single vertical panels. There are two horizontal cooling panels across the top of the pavilion. The interior is shown in Fig. 2, *Lower* facing south, and the top and single vertical panels can be seen. The optically transparent membrane on the interior face of the panels is also transparent to infrared (IR) radiation in the 5 to 50 μm range, with a hemispherical transmissivity of 0.824 at 300 $K$. Chilled water was circulated by using a variable-speed circulation pump through the blue capillary mats in between the panel wall and the membrane, where they were convectively isolated from the ambient environment. These blue capillary mats were installed in strong thermal contact with the substrate, using screws and washers every 20 cm. The substrate was a thin aluminum sheet, painted white to increase the hemispherical emissivity of the metal to 0.95 at 300 $K$. The basic system setup is also described in a conference publication (18).

The coldest MRT 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 MRT was 3.6 °C below the dew point. Such comfort conditions have never been reported (5) in the built environment with conventional radiant systems.

In addition to achieving sub-dew-point radiant cooling, we considered both variability MRT inside the pavilion due to geometry and the necessary supply temperatures to maintain comfort throughout using a simulation. Based on the expanded comfort criteria (9), a necessary MRT of 23 to 25 °C was determined, and the high spatial-resolution simulation showed that the interior of the pavilion MRT varied from 21 to 25 °C with a supply temperature of 18 °C.

A full thermal-comfort study was necessary to experimentally validate whether thermal comfort could be achieved in the hot, humid outdoors. A total of 55 individuals participated in a subjective thermal-comfort study in the Cold Tube carried out from January 8 through January 27, 2019. A total of 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 min in order to achieve thermal neutrality with outdoor conditions.

Fig. 3 shows histograms of cumulative data for thermal responses on a seven-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 7 min to the Cold Tube, 2) after sitting in the Cold Tube for 1 min, and 3) after sitting in the Cold Tube for 10 min. Data from both the operational and nonoperational Cold Tube participants are displayed side by side in the histograms. Statistics about the distributions, as well as $P$ values assessing the likelihood of the responses from both the Cold Tube on and off groups, are related based on a $t$ test.

Data in Fig. 3 show 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 1 min 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 min. More importantly, the mean vote dropped below 0, implying that 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% CI 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 Fig. 4*A*. Using the operative temperature calculated in Eq. **1**, the outdoor air temperature was used as the $x$ axis, and data are 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 was a visible segmentation between the on and off groups, which shows that this type of system has potential for augmenting comfort in naturally ventilated spaces without air conditioning.

The same data are transformed in Fig. 4*B*, plotting the raw MRT data against the air temperature for each survey point. Again, there is a clear separation of Cold Tube on and off clusters.

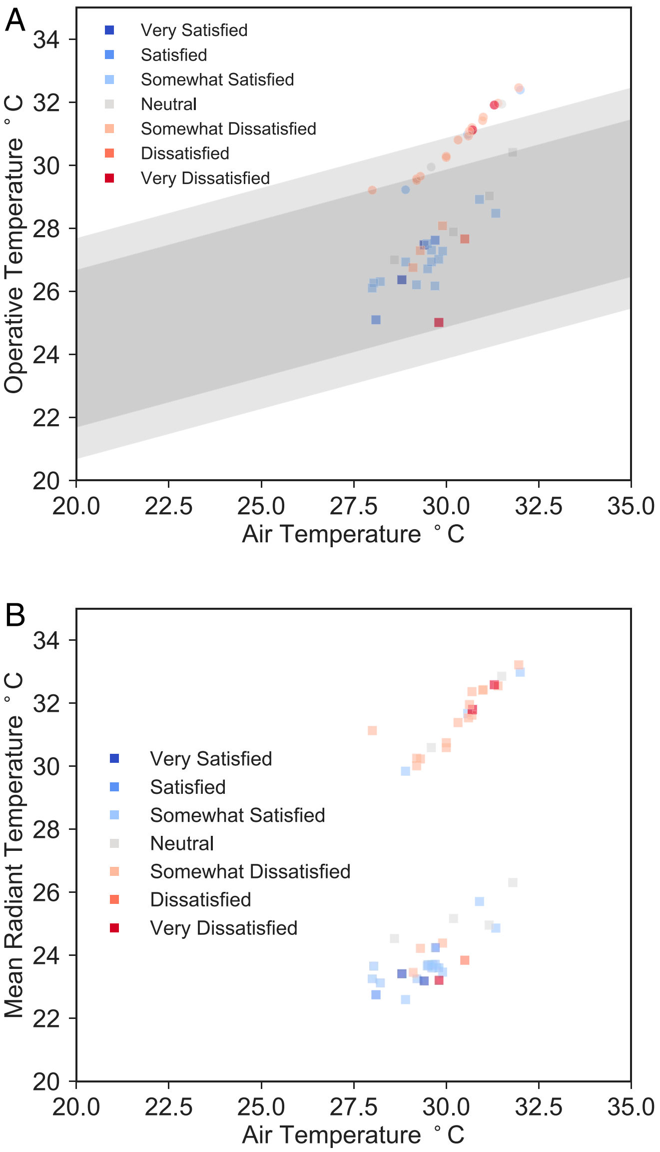

**Fig. 4.** (*A*) Adaptive comfort window for air speed of 0.3 m/s appended with data from the thermal-comfort survey responses. (*B*) The MRT plotted against air temperature for each survey response. The colors of the data are assigned based on occupant satisfaction votes. Each point is placed at the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

**Physiological Measurements.** Skin heat flux and temperature measurements are plotted against system measurements in Fig. 5*B*. Fig. 5*A* shows both visible and thermal images superimposed of an author standing in front (50 cm away) of a single active Cold Tube panel. The warm skin compared to the cold panel as indicated by the thermal image is the potential for radiative cooling from the occupant to the panel through the membrane. As the temperature of the water circulating in the panel decreases, more heat flux was measured from the occupant's wrist to the Cold Tube panel. The coldest water temperature supplied was 13 °C, which had a coincident heat flux of 156.8 W·m$^{-2}$. Despite the low chilled water temperature, the air temperature inside the Cold Tube was largely unaffected, changing from 31 to 30 °C, as measured inside the Cold Tube. These data are evidence that the Cold Tube panels convectively isolated radiative cooling from convective cooling, with the large increase of occupant cooling due to radiant losses to the chilled water, not convective.

While an evaporative flux was not measured, physiologically, skin wettedness can be logically assumed not to increase for the constant ambient temperatures during the data0collection period of 2 h to produce Fig. 5. So, although the evaporative flux is missing, this increase of heat transfer is assumed to be due to radiative cooling and is large enough to explain the findings of the thermal-comfort study.

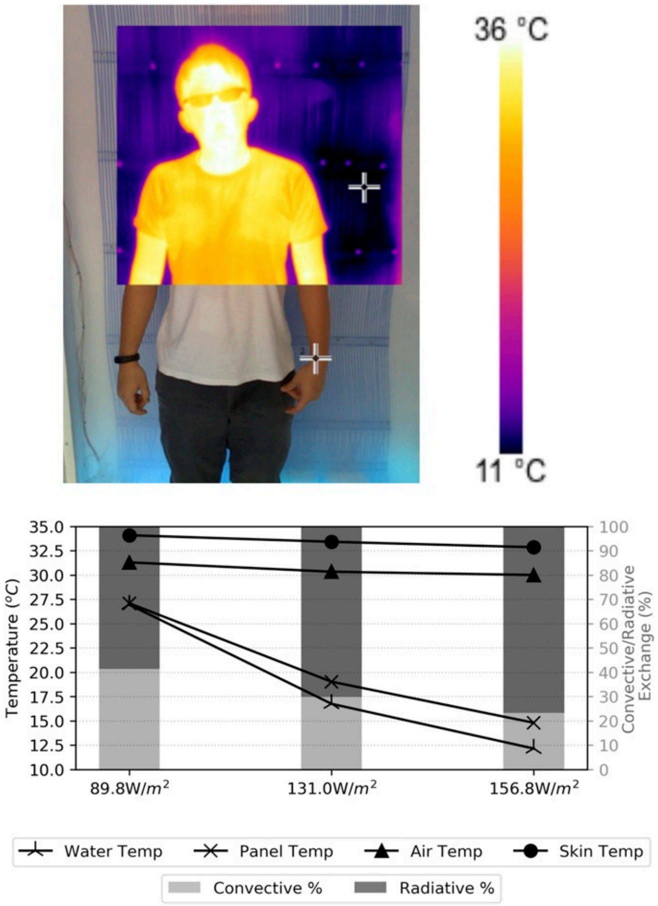

**Fig. 5.** Heat flux between an author's wrist for three chilled water temperatures, including coincident measurements of the temperature gradient in the Cold Tube. All values are mean measurements.

These physiological data offer 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. The membrane surface temperature is difficult to directly measure, since sensors placed on the IR-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 at the bottom of the membrane. We chose the bottom of the membrane as the test location, since the air internally was stratified, making the membrane toward the bottom the coldest point that was most prone to condensation. When condensation occurred, the air temperature in the Cold Tube near the condensing panel, and supply-water temperature were recorded. A plot of these data is shown in Fig. 6. The data are shown as the air temperature, $T_{air}$, minus the dew point, $T_{dp}$, on the $x$ axis, versus the $y$ axis containing the dew point $T_{dp}$ minus the water temperature, $T_{water}$. The resulting relationship not only allows for a simple control strategy for the minimum allowable supply-water temperature, knowing the ambient air and dew-point temperatures, but also demonstrates that, as more sensible heat is in available in the air for convectively heating the outer face of the membrane, colder water can be supplied. This is an elegant relationship, since more sensible heat means occupants will require more cooling, which can, in fact, be supplied without increasing the condensation risk.

## Discussion

The Cold Tube enabled exploration of modes of achieving thermal comfort. As previously discussed, the temperature range produced in the Cold Tube has never been observed in the built environment (5); however, the findings presented in Fig. 4 appear to be consistent with the adaptive-comfort framework (19). More specifically, the environment produced in the Cold Tube is predicted to be comfortable, not only with a heat balance described in *Materials and Methods* similar to the predicted mean vote (PMV) model, but also 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, for future investigation.

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, fundamentally, the climate-conditioning paradigm is changed. 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 (20). Using higher-temperature hydronic radiant cooling has also been demonstrated to reduce the energy consumption of climate conditioning, as higher temperatures of 17 to 20 °C can be used instead of the more traditional 4 to 8 °C used by conventional air systems (14). Of course, since heat transfer is always potential-driven, the same benefits described for a radiant system apply to air-based convective systems as well. And, indeed, cool surfaces in an environment with cool and dry air

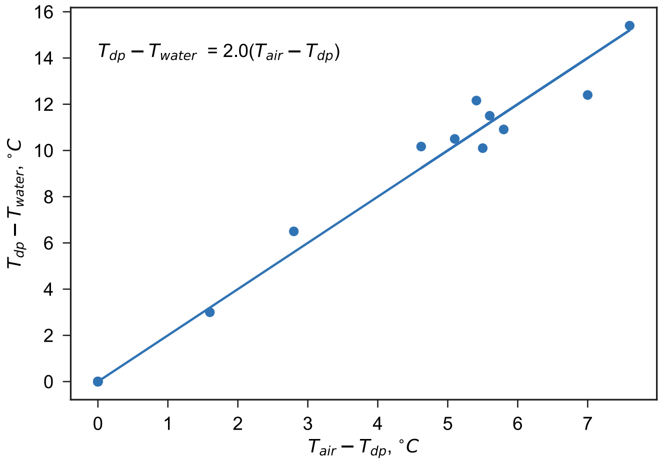

**Fig. 6.** Water was increasingly cooled until condensation was observed at any point on the outer face of the membrane. The coincident air and dew-point temperatures were collected. Plotting the air temperature minus the dew point versus the dew point minus the water temperature produced a correlation approximated linearly between the two, allowing for an elegant condensation control strategy.

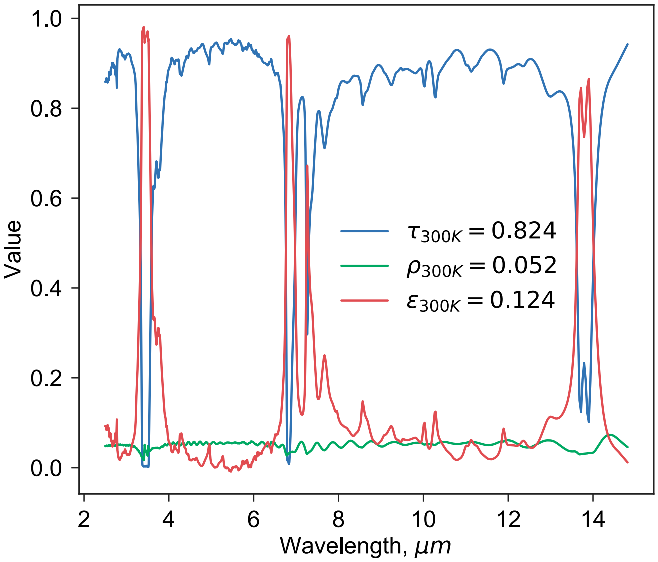

**Fig. 7.** FTIR spectra of the LDPE IR-transparent membrane material.

will act synergistically to remove heat from an occupant through both convection and radiation. However, our study demonstrates that more heat can be shifted radiatively as had previously been presented within the field. It should be noted that the thermal-comfort study was measuring participants' responses for transient thermal comfort, which limits the applicability of comparison of results to steady-state comfort models, such as the PMV model.

## Conclusions

A system was designed to achieve up to 10 K of separation between the MRT and the air temperature, producing no condensation, as the supply temperatures and MRTs were well below the dew point, up to 20 and 3.5 K, respectively. The Cold Tube is a step forward for demonstrating 1) that radiation and convection can be separated for comfort conditioning; and 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 built at the United World College, Southeast Asia (UWCSEA), Dover campus, in Singapore in late 2018, with the thermal-comfort study commencing in January 2019. The pavilion is composed of 10 panels of 1.2 × 2.1 m (4 × 8 feet): two horizontal panels at the top and eight vertical panels, with north- and south-facing entrances. The capillary mats inside the panels were cooled down below the dew point by chilled water from custom variable-speed chillers to provide radiant cooling. The capillary mats were isolated from the hot and humid environment to avoid condensation by 2-inch polyisocyanurate insulation on the back and IR0transparent membranes transparent to 82.4% of blackbody thermal radiation at 300 *K*. A diagram representing radiant heat transfer between an occupant and a panel is shown in Fig. 1, and the Fourier transform IR (FTIR) spectra of the 50-$\mu$m-thick LDPE IR-transparent material is shown in Fig. 7. While thin and flimsy, the membrane had reasonable tensile strength and puncture resistance for a demonstrator to last on the order of months. Longer installations in the occupied range of 0 to 2 m height would need a stronger material. However, increasing the thickness would exponentially decrease the IR transmittance of an LDPE sheet. Future work could be spent designing better-stabilized polymers. Reducing IR transmittance would not only sacrifice radiative heat flux, but also produce condensation at higher temperatures, due to radiatively forcing the membrane surface temperature below the dew point at a higher water-supply temperature. Aesthetically and functionally, the visible color of the membrane does not typically affect the LDPE membrane's transmittance in the IR region, giving design freedom over the color. We chose clear mostly for this study, so we could visibly confirm that there was never condensation internally; however, we also used white for the membrane. The FTIR spectrum for the white membrane of equal thickness of 50 $\mu$m was nearly identical, at $\tau$ = 0.80. This is in contrast to increasing the thickness to 5 mm, where the transmittance drops to 0.25 (10).

The water inlet and outlet temperature of three unique panels (a horizontal, middle vertical, and edge vertical) were collected by using high-accuracy thermistors (10 K Precision Epoxy Thermistor, 3950 negative temperature coefficient; ±1%). The radiant heat transfer from the chilled panels to a location where an occupant was standing was measured within a 150 field of view ° 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). These sensors were directed by the occupant in the same direction of the wrist temperature and heat-flux sensor (gSKIN® BodyTEMP Patch; ±0.3 °C). These heat-flux measurements were "net heat flux," meaning that they were combined radiant and convective heat transfer. Measurements were taken at different water temperatures, 50 cm from the Cold Tube panel. Both the air temperature and the MRT, as assessed by globe thermometers, inside the Cold Tube were measured with Pt-100 thermistors (±0.1 °C). 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. To shield the air-temperature sensor from radiant cooling produced by the Cold Tube, it was surrounded by a silvered cone. The air-speed sensor was a spherical omnidirectional air-speed sensor with temperature compensation (±0.02 m·s$^{-1}$). The relative-humidity sensor had ±2% accuracy. All measurements were taken at 10-s intervals, which were time-averaged by the minute for analysis in this paper (18). Time-averaged values for air speed, $v_{air}$, air temperature, $t_a$, and MRT, $t_r$, were used to calculate the operative temperature, $t_o$, by Eq. **1** (21).

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

***MRT Simulation.*** Weather data collected at the site were used to determine the required setpoint for comfort in the constructed pavilion using a heat-balance approach to expanding the psychrometric comfort zone (8, 9). 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 Fig. 8 covered by the air temperature and humidity data points shows the range of required MRTs 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

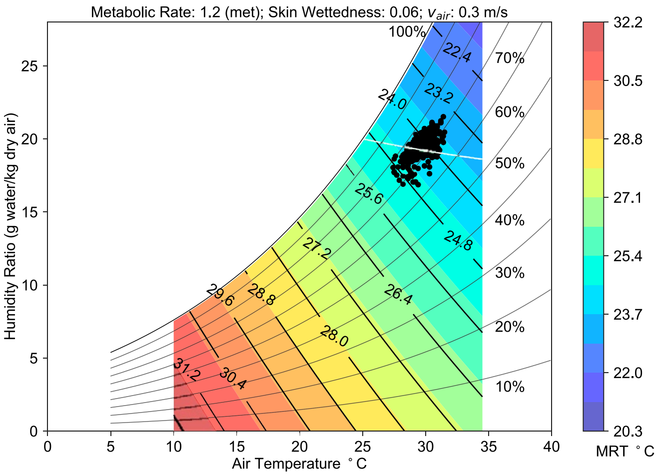

**Fig. 8.** Expanded psychrometrics heat balance to determine the MRT required to produce comfort.

line traversing the chart through the environmental data points shows the set of points where the required MRT for comfort is the dew-point temperature. Points above this line require a MRT 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 MRTs, a geometric simulation was conducted to spatially map the MRT in the Cold Tube. To do this, first, a grid of 750 points was created on a plane at a fixed height of 1 m 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 temperature value at each intersection was averaged and recorded as the MRT at each point on the grid. A color gradient was then created based on the MRT values. Further discussion of this simulation method from our previous work can be found in ref. 22. The result from this simulation is shown in Fig. 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 range of MRTs required for comfort shown in Fig. 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 IR transparent panels maintained to avoid condensation and air conditioning was sufficient to cool occupants at short (1 min) and longer (10 min) time intervals. These time intervals are indicative of transient comfort or thermal delight, and steady-state thermal comfort.

Specifically, 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-conditioned lobby after walking in a hot outdoor environment for a prolonged duration. Those individuals feel pleasure when a rush of cold air blows over their hot and sweaty bodies and are said to be experiencing "thermal delight" (23).

In contrast, 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, MRT, 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 UWCSEA Dover campus. Once participants arrived at the first location, the study commenced by 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 20180-12-11636). All participants provided informed consent.

1) Each participant reached a state of thermal neutrality by sitting for 10 to 15 min 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 min, the participants would evaluate their thermal comfort and decide if an additional 5 min beneath the fan would be required. After reaching the thermal-neutrality state, 15 min 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 *SI Appendix*.
    - 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 participant's clothing level was then be recorded by the survey administrator.
2) The participant was asked to spend 7 min 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 was the second time they filled 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 min sitting in the pavilion, the third and fourth time they completed the survey, respectively.
    - The objective of the third survey (1 min after entering the pavilion) was to evaluate whether there was the effect of thermal delight or significant feeling of heat relief due to rapid heat release.
    - The objective of the fourth survey (10 min after entering the pavilion) was 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 in 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 were:

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 to 15 °C water to the radiant cooling panels, which created a perceived MRT between 22 and 24 °C. The air temperature would be outdoor conditions of 28 to 32 °C and 60 to 80% relative humidity. There were 39 participants 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

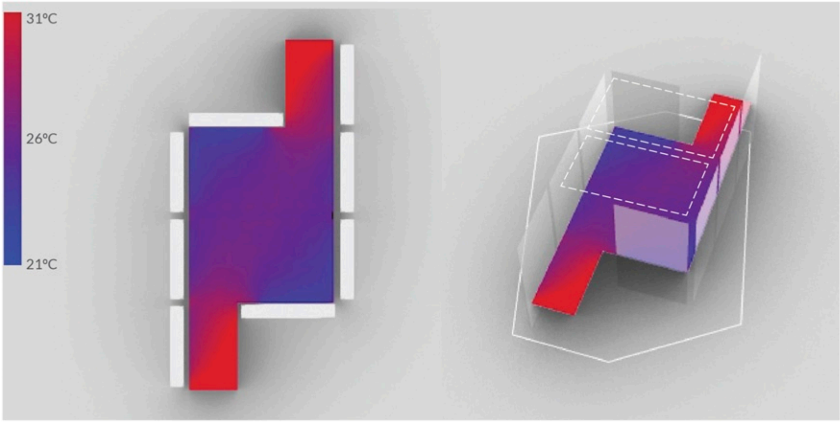

**Fig. 9.** A simulated map of the MRT distribution at a 1-m height in the Cold Tube with a supply water temperature of 18 °C.

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. A total of 18 participants were recruited for this study, yet only 16 survey responses were analyzed due to ambient weather-condition changes and data loss.

**Data Availability.** All study data are publicly available along with an accompanying Jupyter Notebook that was used to create the figures from the dataset. Data is permanently available on GitHub at https://github.com/eteitelb/coldTubeData.

**ACKNOWLEDGMENTS.** This project was supported by National Research Foundation IntraCREATE Grant NRF2016-ITC001-005 (to J.P. and A.R.). The authors acknowledge the use of Princeton's Imaging and Analysis Center, which is partially supported by the Princeton Center for Complex Materials, a National Science Foundation Materials Research Science and Engineering Centers program (DMR-1420541). This study was funded in part by the US National Science Foundation's Sustainability Research Network Cooperative Agreement #1444758. We also personally thank Simon Thomas and the UWCSEA Facilities staff for all of their help facilitating the construction of the Cold Tube demonstrator. This paper is the full and complete thermal-comfort study and performance characterization of the Cold Tube, greatly extending some initial system performance results we originally presented in a conference paper.

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