The Cold Tube: Membrane assisted radiant cooling for condensation-free outdoor comfort in the tropics

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Abstract. Air conditioning demand is projected to increase rapidly over the next 50 years, particularly in already hot and humid climates. Radiant cooling can be an energy efficient strategy to mitigate comfort energy demand with high air temperatures, thereby reducing both sensible and latent loads in spaces. We have built an outdoor radiant cooling pavilion, the Cold Tube, which is able to produce a mean radiant temperature up to 10 °C below the air temperature in hot and humid Singapore. It avoids condensation and unwanted air cooling by separating cold surfaces from the outside air with a membrane transparent to the radiant cooling heat transfer. This strategy eliminated unwanted convective losses in the form of sensible (air conditioning) and latent (condensation) losses. Controlling the system to avoid condensation was a major feature of the research, and the results show that as cooling demand increases due to warmer air temperatures, the cooling capacity of the Cold Tube also increased to compensate, providing comfortable setpoints to all measured ambient conditions over the duration of the experiment. For ambient air conditions on site in Singapore of 31 °C and 65 %RH, we were able to maintain a 22 °C mean radiant temperature inside of the pavilion. The additional cooling increased heat flux from exposed human skin to 156 W m\textsuperscript{-2} and was successful at avoiding condensation. While this study was conducted outdoors, this demonstration and evaluation will help inform subsequent applications of the technology, such as augmenting comfort in naturally ventilated indoor environments.

1. Introduction
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 [1] Already in the United States, air conditioning is responsible for nearly 12% of all household energy demand [2] and is one of the primary $CO_2$ emission sectors. The question becomes how to ensure we can design energy-efficient systems without creating a comfort-constrained world.

Air conditioning is an attractive choice for cooling 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 [3]. However, dehumidification requires subcooling the air, an energetically and exergetically intensive process [4].
In contrast, hydronic radiant cooling is a method for cooling people whereby chilled surfaces exchange heat through radiation with occupants, instead of relying on air. These water-based systems circulated chilled water, using surfaces for comfort and air for ventilation only. Using radiant systems for cooling and solid desiccants for dehumidification is an efficient combination [5]. Yet relying on radiant systems for comfort is difficult, since warm climates are often humid, and the surface temperature required for cooling may be well below the dewpoint, causing condensation on surfaces leading to slippery and moldy interiors. Additionally, radiant cooling panels that are directly in contact with air convectively exchange heat with the air, providing unwanted cooling to the air, acting as an inefficient air conditioner. Thermodynamically, achieving large air to surface temperature gradients is energy intensive.

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 [6]. 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. This initial concept was revisited with modern analytical techniques to be adapted for the tropics, eliminating the need for components such as an internal heater and radiation shields originally proposed by Morse [7].

The result was the construction of an outdoor radiant cooling pavilion, known as the Cold Tube, that provided occupants with sufficient radiant comfort [8], avoiding condensation and unwanted air conditioning. In this paper, we provide the design, construction, and evaluation criteria and results, as well as demonstrate other use cases beyond outdoor space conditioning.

2. Methods

The Cold Tube was constructed at the United World College, Southeast Asia (UWCSEA), Dover campus, in Singapore from August to October 2018. The pavilion is enclosed by ten 1.2m x 2.1m 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 79.9% transparent to thermal blackbody radiation. A schematic of heat transfer about a single vertical panel is shown in figure 1.

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 noncontacting infrared temperature sensor (Melexis MLX90614; +/- 0.3 °C), sealed inside the radiant panel facing the chilled capillary mats. Measurements were taken at 10 second intervals, which were further smoothed by the minute for analysis in this paper.

For all measurements in this paper, only one panel was turned on and the occupant stood 1 m from the center of the panel. Consistently, $T_{dp}$ was between 23 and 24 °C during experiments.

Heat flux measurements from the gSKIN sensor were net heat flux, meaning both convection and radiation fluxes entangled together. Heat flux measurements were taken with three supply water conditions, warm at 26 °C, ‘LowEx’ (short for low exergy [4]) 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 $T_{MRT} = T_{\text{skin}}$. This extrapolated heat flux with no radiant heat flux would represent the convective heat flux, $Q_{\text{conv}}$ that occurs at $T_{\text{air}}$. This was treated as a constant value, and allowed correction of the net heat flux, $Q_{\text{net}}$ for the radiant heat flux, $Q_{\text{rad}}$ as in equation 1.

$$Q_{\text{rad}} = Q_{\text{net}} - Q_{\text{conv}} \tag{1}$$

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

$$T_{MRT,\text{hemi}} = \sqrt{\frac{Q_{\text{rad}}}{\varepsilon \sigma}} - T_{\text{skin}} \tag{2}$$

3. Results
The completed 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 alto transparent to infrared radiation, with a hemispherical transmissivity of 0.799 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 primary research question was on allowable chilled water supply temperatures, as this type of environment has never been constructed. 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
Figure 2. The completed Cold Tube.

Figure 3. (a - left) 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. (b - right) The data in (a) can be inverted to calculate the membrane surface temperature for a given air and water supply temperature, with the measured data corresponding to the color bar.

A rate of 4 °C per hour and watched for signs of condensation. When condensation occurred, the air temperature and supply water temperature were recorded. A plot of this data is shown in figure 3a. 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.

Inverting this data, a relationship between the membrane surface temperature and the water and air temperatures can be developed, assuming that the membrane surface temperature, $T_{membrane}$, can be adequately approximated as $T_{dp}$ at the onset of condensation. Remapping this relationship is shown in figure 3b. The trend of temperatures is in good agreement.

Skin heat flux and temperature measurements are plotted against system measurements in figure 4b. Figure 4a shows using a thermal and visible light camera an author in front of a
Figure 4. 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.

Radiant cooling panel in the Cold Tube. 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 increases 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 strictly radiant. 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.

4. Discussion

Combining the measured environmental conditions, system control logic for condensation avoidance, and physiological response, a model was created demonstrating the availability of cooling provided by the cold tube allowable without condensation. This model demonstrates that for every environmental condition encountered over the course of the testing period, there would be a possible comfortable response for a properly controlled Cold Tube system. This front is shown as a purple line in figure 5, with the environmental data shown as blue points. Further, this map reiterates the elegant control logic shown in the results, namely that as cooling demand increases because of warmer air temperatures, more cooling can be provided since that warmer air heats the outer membrane surface up to avoid condensation when lower temperature chilled water is supplied. Future work could further move the purple threshold line from figure 5 higher with a more transparent membrane.

Implementing a Cold Tube style radiant cooling panel to a traditional indoor environment such as a classroom or an office space could be successful, allowing windows to be opened without energy penalties. Challenges to overcome on the design include robustness and controls. Specifically, the membrane panels were 0.5 mm thick polyethylene sheets, which had decent tensile strength, but could be easily punctured. Developing an infrared-transparent membrane with more structural rigidity could be beneficial to allow vertical panels to be placed indoors. Additionally, sensors to control exclusively radiant systems would be difficult to implement, as
Figure 5. Thermal comfort as determined by a heat balance can be achieved for all environmental data points recorded throughout experiments without condensation, with an upper bound shown with the purple line.

conventional thermostats only measure air conditions.

5. Conclusions
The Cold Tube radiant cooling pavilion was a successful demonstration that metabolic heat could be exclusively handled with a radiant system, as the fraction of heat lost to convection versus radiation was a factor of two higher at the highest point. The environment produced a hemispherical mean radiant temperature of 14.3 °C below the ambient air temperature that was sufficient for radiatively and convectively removing up to 156 W m⁻² from an occupant. Additionally, the feasibility of such a system in a tropical setting was demonstrated, as these data were collected without condensation, despite the high 24 °C dewpoint. Future work will be conducted to assess the perceived thermal comfort in the environment. Potential areas for future exploration are energy savings when paired with a chilled water loop for air conditioning, as many return water loops operate at temperatures that could be directly supplied to the Cold Tube system, extracting cooling for areas that may not otherwise have a comfort system.

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