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Condensation-free radiant cooling using infrared-transparent enclosures of chilled panels

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ABSTRACT

Radiant cooling power in the humid climates is inherently limited by condensation. This research investigates a type of radiant cooling methodology whereby the cold temperature source is convectively and conductively isolated from the environment with a membrane transparent to visible radiation to allow supply temperatures to be decreased for radiant cooling systems in humid climates. We conduct an FTIR analysis on three candidate membrane materials and fabricate a prototype experimental test panel that allows for thermal performance evaluation at different panel orientation and depths. Our study shows that for a 5 °C chilled panel temperature, the exterior membrane surface temperature reaches 26 °C in a 32 °C / 70% RH environment resulting in an effective panel temperature of 15.8 °C. Such a panel construction would avoid condensation in many humid environments and allow for radiant cooling without any latent load handling.

INTRODUCTION

Radiant cooling environmental systems are a class of measures and technologies for space cooling in the built environment. They involve exposing building occupants to mechanically-cooled indoor enclosures, or parts of entire enclosures, allowing for a greater degree of heat to be rejected radiatively by the human body to the ambient environment than would otherwise occur. While thermal comfort models demonstrate the potential for radiant cooling systems to provide comfortable conditions in spaces with high indoor air temperatures (de Dear et al. 1996; Arens et al. 2006), in practice generating large air-to-panel temperature differences is hard to achieve without risking condensation occurring on chilled surfaces (Teitelbaum and Meggers, 2017; Feng, 2014). It is for this reason that radiant cooling systems are nearly always combined with mechanical ventilation systems that supply dehumidified air to interior spaces, ensuring indoor air dew point temperatures are sufficiently low to prevent condensation arising on cooled surfaces.

An alternative solution to mitigating the risk of condensation can be found through a more focused investigation of the specific radiant heat transfer and convection processes occurring within and around radiant panel assemblies. In 1963, Morse (Morse, 1963) described a new type

of radiant cooling panel for the tropical environments of Australia, whereby a membrane transparent to long wave infrared radiation is used to enclose, or isolate, the cold panel from the warm, humid ambient air as shown in figure 1a. Since the radiant panel and humans emit in the longwave regime, typically defined as wavelengths between 2.5 and 50 microns, their radiation is able to exchange proportionally to the transmissivity of the membrane. If the enclosure volume would be sufficiently large, and filled with dry air, internal convection would not be significant enough to lower the surface temperature of the membrane below the ambient dewpoint temperature of the interior space, thereby preventing condensation.

Today, whilst there are some emerging commercial applications of Morse's original idea (interpanel, 2018), there remains a lack of understanding of the spectral quality of potential membrane materials and how different material and geometric configurations of such panel assemblies affect overall radiant cooling flux and condensation risks. This paper presents an empirical study which expands on Morse's original chilled panel design by carrying out: 1) Fourier Transfer Infrared (FTIR) Spectroscopy analysis of infrared transparent materials to select the most suitable, common building material for a future panel membrane; and 2) an experimental study of the radiant flux achieved with a prototype radiant cooling panel against varying geometric parameters such as the distance between the membrane and chilled panel, and the vertical/horizontal orientation of the panel itself.

The objective of the overall study is to identify a potentially *optimal* radiant cooling panel design which would provide the greatest cooling flux in a very hot and humid environment without condensation occurring.

MATERIALS AND METHODS

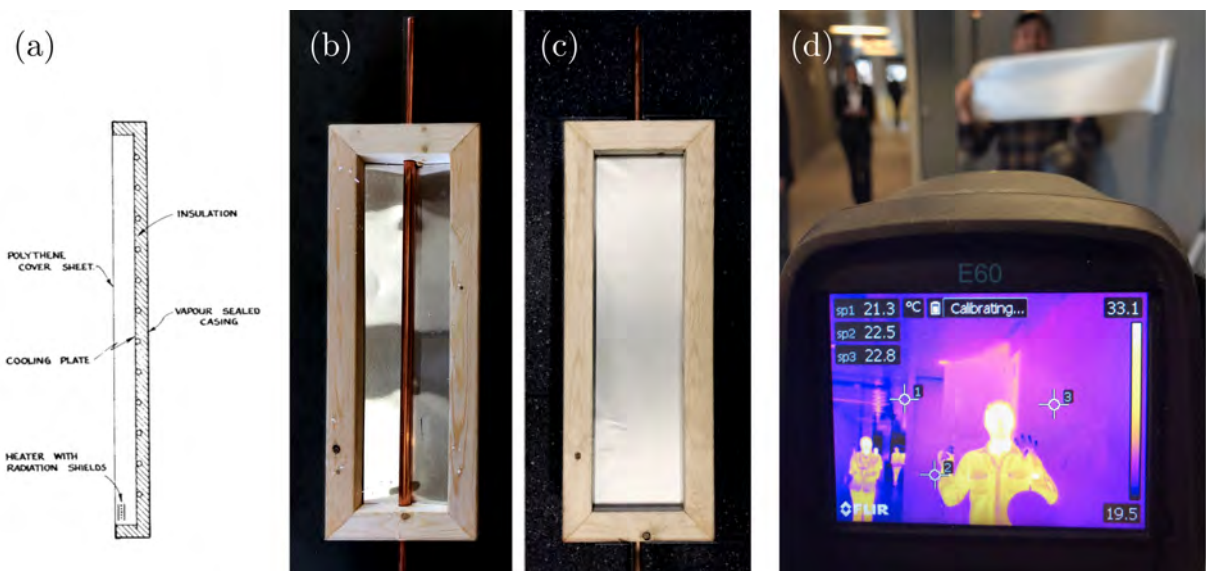


Figure 1: (a) Original infrared transparent radiant cooling panel (Morse, 1963). (b) Test panel prior to black paint. (c) Finished panel with the PP membrane. (d) Visible image of the author holding a sample PP membrane sheet (background) in comparison to the equivalent infrared image of the scene (foreground)

FTIR Analysis

Many common household materials are transparent to longwave infrared radiation, such as high density polyethylene (HDPE) trash bags and low density polyethylene (LDPE) or polypropylene (PP) bottles. However, the comparatively large wavelengths for infrared radiation and correspondingly low frequencies contribute to faster extinction and absorption of the radiation in materials, so it becomes difficult to select these materials for a potential infrared transparent membrane without a detailed representation of their individual spectral properties. Three specific types of prototype LDPE, PP, and HDPE panels were procured for this research, respectively United States Plastic, 1/32" LDPE #42568; United States Plastic, 1/8" HDPE #42587 and a 50 micron-thick polypropylene panel produced proprietarily for interpanel GmbH, FTIR spectroscopy was conducted using a Nicolet i10 infrared spectrophotometer to measure the wavelength-based transmission spectra for each material between 2.5 and 15 microns. The FTIR transmission spectra was overlaid with a true black body emission curve to visualize the ability of each membrane to transmit radiation between the panel and a human. The resulting curve is a true spectral radiance diagram providing radiant power per steradian per micron. Integrating the curve numerically between the measured wavelengths provides a panel radiance value, in units $W/m^2/sr$. Assuming a Lambertian emission function over an arbitrary hemisphere about any point on the panel provides the integration constant for converting radiance to radiant exitance as π , providing a panel radiant power in W/m^2 . This number is calculated for a panel of a known temperature through each candidate membrane. Dividing this number by the radiant exitance of a true black body provided the hemispherical transmissivity, τ .

Panel Evaluation

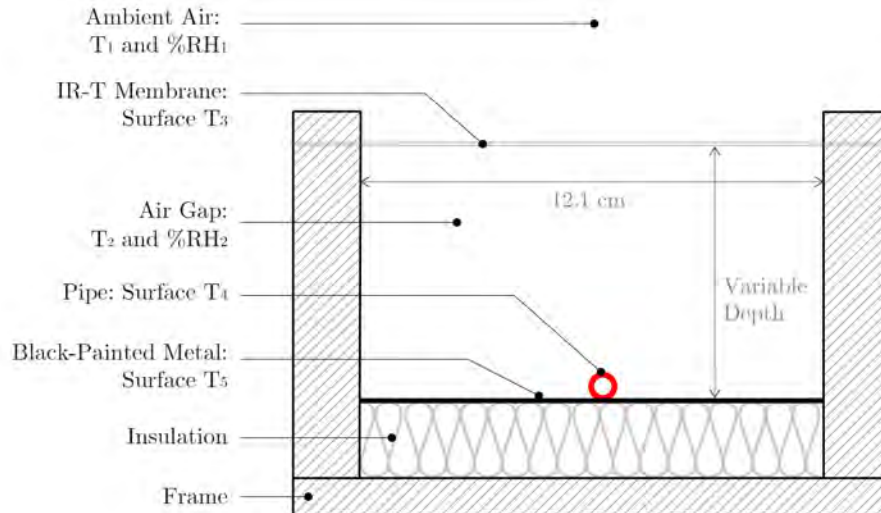


Figure 2: Schematic of panel and sensor layout on cross section up “upwards” facing panel.

Radiant panel frames were constructed with plywood, foam insulation, copper tubing, and aluminum. Douglas fir lumber was fashioned into a 53 by 20 cm open-face box, 7 cm deep with a 1.3 cm plywood back. The framing wood was 3.9cm thick, providing interior panel dimensions of 45.7 by 12.1 cm. Inside the open faced box, 3 cm foam insulation was cut to fit flush along the back of the frame, followed by a piece of 0.8 mm thick aluminum cut to fit flush against the pink insulation. This provided a base panel depth of 3.5 cm from the front face to the aluminum. A straight through copper pipe was then inserted through the top of the frame into the box,

shown in figure 1. This copper pipe contains the chilled flowing fluid. The interior of the box was then spray painted black to make the metallic surfaces emissive ($\epsilon = 0.95$). A schematic of the cross section of the panel is shown in figure 2.

The performance evaluation of the panel was carried in a 1.5 x 2 x 2 meter room at the Embodied Computation Lab of Princeton University. Ultrasonic humidifiers, steam, and the building's in-floor radiant heat were used to generate indoor conditions in the room that would emulate a hot, tropical environment - maintaining an air temperature of 30 to 32 °C and 70 to 80 %RH. Temperature and humidity were continuously monitored with Sensirion's SHT75 temperature and relative humidity sensor (± 0.3 °C; ± 1.8 %RH) and were recorded at 5 second intervals during experimentation.

The radiant panel frames were then outfitted with either HDPE, LDPE, or PP across the top, sealed in a dry environment to minimize humidity inside the dry air gap. The depth between the membrane and panel backing was varied with wooden spacers to allow for 4 different depths: 3.5 cm, 7.8 cm, 9.9 cm, and 12.4 cm. The panels were outfitted with 4 Omega ® Precision Surface Temperature Thermistors (± 0.1 °C), one place on the copper pipe, another inside the panel on the metal heat spreader midway between the copper pipe and the panel wall, and two more on the surface above the two inside. In addition, air temperature and relative humidity were measured inside the panel with an SHT75. Measurements were taken for 4 different panel configurations, facing "upwards" towards the ceiling, "downwards" towards the floor, "horizontally" facing a wall with the long dimension parallel to the floor, and "tilted" angled 30° towards the floor.

RESULTS AND DISCUSSION

Spectral Analysis

The calculated hemispherical transmissivity at 278 K for LDPE, HDPE, and PP was found to be 0.247, 0.298 and 0.597, respectively. Additionally, their respective thicknesses were 0.76, 3.4, and 0.05 mm. The values for τ were then used through the remaining 15-50 microns in the panel's emission spectrum, estimating the full range of thermal radiation transmission at wavelengths above 15 microns. Spectral radiance curves of each membrane material are shown in figure 3, demonstrating, for each candidate membrane material, the predicted radiant heat transfer between a idealized human body at 30 °C and a chilled panel cooled to 5 °C. Blue represents radiation transmitted through the panel, and is replotted below for comparison. Gray area represents absorbed radiation. In the HDPE plot, radiation above the black body line is caused by a measurement error, with random reflection in the laboratory pushing transmission above 100%.

Panel Evaluation

Despite initial promising images with a thermal camera measuring reasonably low temperatures of a cold source behind each panel (see figure 1c), it was found after the FTIR analysis that, in comparison to PP, LDPE and HDPE are relatively poor transmitters of infrared heat at temperature ranges of 5°C to 30°C. This was an unfortunate finding, as otherwise the LDPE and HDPE materials could be advantageous in being structurally rigid and able to support dual role as both a membrane and part of the structural housing of an entire cooling panel assembly membrane.

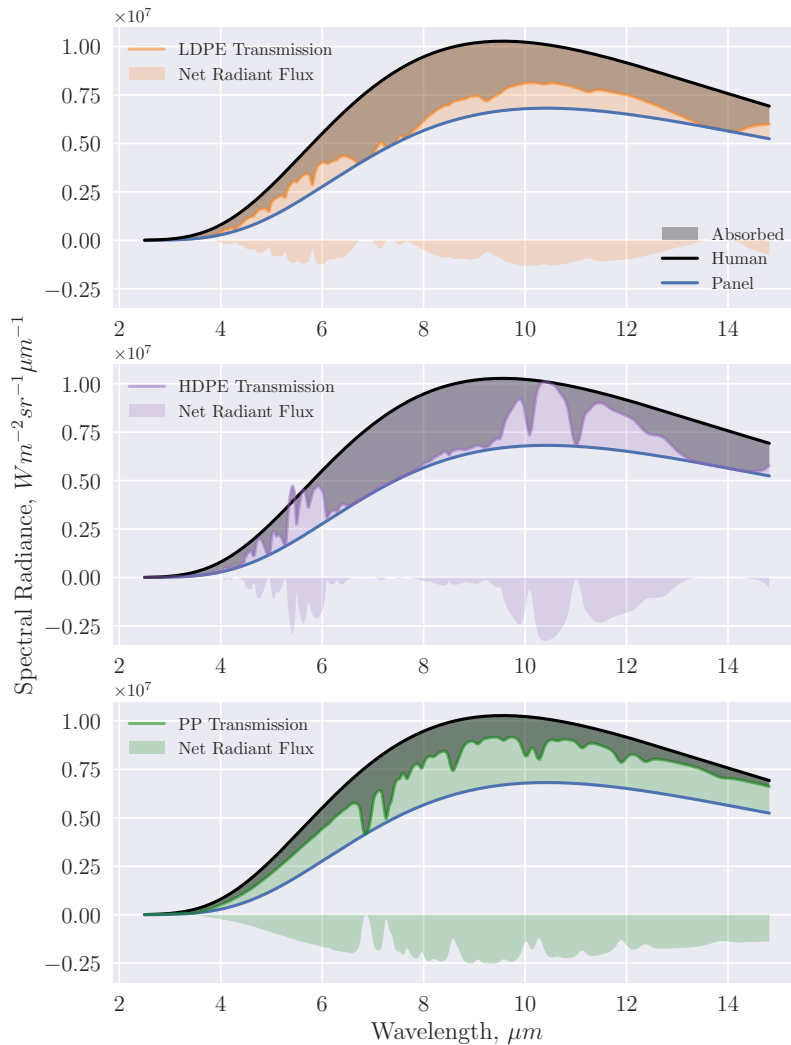


Figure 3: (a-c) FTIR transmission data for each membrane material, LDPE, HDPE, and PP top to bottom, modifying the spectral radiance for a 5 °C panel radiantly exchanging with a 30 °C surface.

The thin PP membrane was therefore the only tested material that was viewed to be able to provide a sufficiently transparent barrier between the chilled panel and ambient environment, and was subsequently used as the membrane for the assembled experimental test panel. Figure 4a shows the temperature profile within the panel at each measurement location for three panel orientations of a 124 mm deep panel outfitted with the PP membrane. The height of each point represents \pm one standard deviation calculated over 60 sampled points. The outer surface of the membrane always remains above the dew point, confirmed visually and through touch during the course of the experiment that no condensation occurred. Data in figure 4b shows the dependence of the membrane's outer surface temperature on both panel orientation and depth, important design information. There is a rough equivalence between membrane surface temperatures at 99 mm panel depth, implying at this point orientation is a non-contributor. Additionally, horizontally positioned panels do not show much membrane temperature variation. Also on figure 4b is the effective panel temperature of 15.8°C which represents fictitious panel temperature with which a body exchanges. The low value is exciting not only for observing no

condensation at this effective temperature, but it represents a 14 °C gradient from the ambient air temperature, a gradient difficult to sustain with existing technology.

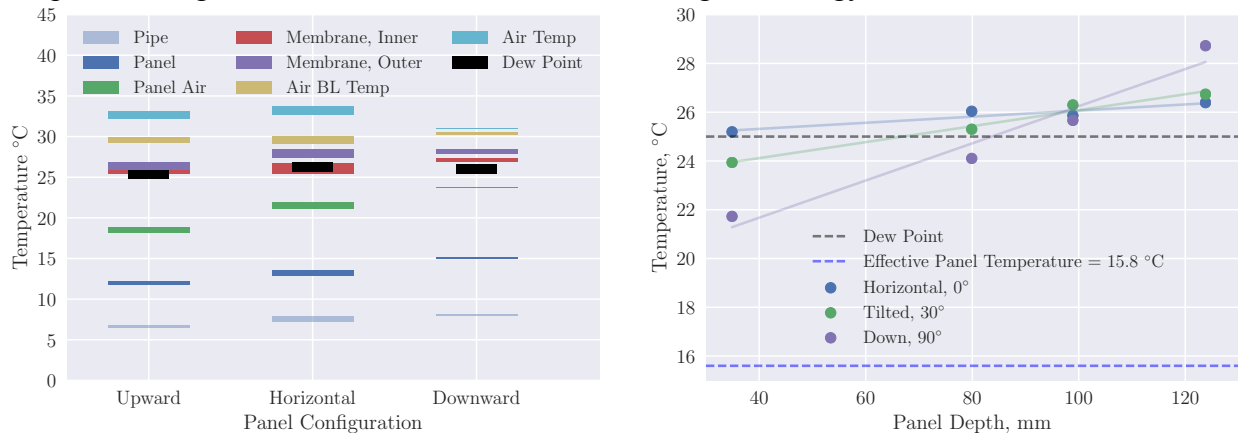


Figure 4: (a, left) Temperature profile within a 124 mm deep panel. The height of each measurement represents +/- one standard deviation of 60 measurements at steady state for each configuration. (b, right) Membrane outer surface temperature measurements for three panel orientations against panel depth.

CONCLUSIONS

This study was particularly successful at demonstrating required design considerations for increased radiant cooling power through an IR-T membrane in warm and also humid environments. Starting with fundamental understanding about how each membrane influences a body's radiant exchange with a panel with a 5 °C supplied water temperature, and building an applied knowledge base about how to design and operate the type of radiant cooling panel described herein to maximize cooling power while avoiding condensation was achieved. A major result indicates there exist equivalence points between radiation, conduction, and convection, such as the one observed at a 9.9 cm panel depth, whereby membrane outer surface temperatures are the same across all orientations. Future work should seek to further parametrize the data, in particular for panel slenderness ratio of the panel to further improve design guidance. Eventually, a model incorporating FTIR data into CFD analysis, for example, would be worthwhile to create.

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