Predicted Energy Savings by Adopting Novel Radiant Cooling Systems in Combination with Natural Ventilation in the Tropics

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Abstract
Membrane-assisted radiant panels have demonstrated the ability to provide sub dew-point cooling in humid climates without condensing air moisture. However, there has previously been no method of simulating the energy usage of a building that utilizes this method of cooling. This paper proposes a framework that allows a thermophysics model developed for membrane-assisted panels to operate within energy simulation software. Methods are developed that allows the thermophysics model to communicate with a TRNSYS environment. The framework is then used to predict the potential energy savings that could be obtained by implementing this technology in Singapore. It was found that this climate can benefit from the adoption of a cooling system that combines membrane-assisted radiant cooling with natural ventilation. The framework developed in this study will bring membrane-assisted radiant cooling closer to widespread implementation.

Key Innovation
- Proposes a framework that allows for the energy simulation of a building that utilizes membrane-assisted radiant cooling panels
- Demonstrates the energy saving potential of combining membrane-assisted radiant cooling with natural ventilation in hot and humid climates

Practical Implications
This paper completes the bridge between the experimental results of the panel’s performance and building simulation by creating a TRNSYS framework that allows for the simulation of a building energy system that utilizes membrane-assisted radiant panel technology. The framework developed in this study will bring this technology closer to widespread implementation, as modelers will be able to optimize the design of a radiant system before its construction in a building.

Introduction
The world is in critical need of technologies that will make a significant and immediate impact in our fight against global climate change. To achieve this goal, we must target the most demanding energy end-use sectors and develop technologies that will reduce their energy demands. As climate change increases the average global temperature, heating demand in buildings could drop by up to 34% by the year 2100, however, cooling demands could rise by 72% (Isaac and Van Vuuren, 2009), meaning that the development of energy efficient space cooling technologies is becoming increasingly important.

One space cooling technology with the potential to address these challenges is the radiant cooling panel. This technology can provide cooling in many climates with significant energy savings when compared to conventional air conditioning systems, Miriel et al. (2002); Zhang and Niu (2003); Niu et al. (2002). Radiant cooling can also provide increased thermal comfort to occupants, as it cools the human body more evenly, Imanari et al. (1999). However, the cooling output of a conventional radiant system is limited by the dew point of the environment it is in, and often can not supply sufficient space cooling in humid climates without additional interventions.

Pairing radiant cooling with dehumidification is a common approach used to avoid condensation. However, researchers have begun to realize the potential of membrane-assisted radiant cooling, which was first proposed by Morse (1963) in 1963. A modern version of this technology has been developed with the purpose of providing radiant cooling to hot and humid climates without mechanical dehumidification. This technology has been named the Cold Tube, Teitelbaum et al. (2019), and can be seen in Figure 1.

The Cold Tube allows the temperature of its chilled surface to be below the dew point of the ambient air by isolating the surface using a semi-transparent membrane and air-tight cavity. The membrane is kept at a temperature higher than the dew point of the ambient air, and allows radiant energy to pass between the chilled surface and its surroundings due
to the membrane’s transparency to infrared radiation. This technology was demonstrated during a field experiment in Singapore called the Cold Tube pavilion, where thermal comfort was achieved in a non-air-conditioned outdoor space without condensation occurring on the panels, Teitelbaum et al. (2020). This pavilion can be seen in Figure 2.

To operate a membrane-assisted panel, one must be able to predict the temperature of the membrane. A thermophysics model was created that allows for both the prediction of membrane temperature and the estimation of heat transfer between the panel and its surroundings, Sheppard (2020). This paper proposes a framework that integrates the thermophysics model within a TRNSYS environment. This allows for the energy modeling and thermal comfort evaluation of a building that uses technology. Additionally, the framework controls the temperature of the panel so that the maximum thermal comfort can be provided to occupants while avoiding moisture condensation on the membrane.

Methods

The development of the framework consists of accomplishing three primary objectives. The fist objective is the development of the TRNSYS simulation itself.

Building Energy Modelling

The building energy model was developed using TRNSYS as it allows for the transient, or time varying, simulation of very detailed mechanical systems, Klein et al. (1994); Koschenz and Dorer (1999); Saelens et al. (2011). The simulated environment reflects an energy efficient office floor in Singapore, as the membrane-assisted panel was designed for hot, humid, tropical climates.

Integration of Simulation Method

A novel framework allows for the cooling supplied by the membrane-assisted panel, which is calculated using a previously developed Python thermophysics model, Sheppard (2020), to be simulated within a TRNSYS environment. Figure 3 illustrates the sub-tasks that the framework performs.

While several of the methods are based on well-established heat transfer and thermal comfort concepts, Cannistraro et al. (1992); Du Bois (1989); Kwon and Choi (2013); Enescu (2017), only the novel methods developed for this study are presented in this section. The methods behind each of these sub-tasks are explained in detail in the Master’s thesis by Sheppard (2020).

At each time step, an equation is determined that correlates the panel’s inlet water temperature and chilled surface temperature. Two quantities of thermal energy absorbed by the panel are calculated using two arbitrary chilled surface temperatures. Using the equation $Q = \dot{m}C_P\Delta T'$, the temperature change across the panel can be determined for both cases, and as the average chilled surface temperature was used to calculate Q, the inlet temperature can be
derived. A linear relationship between inlet water temperature and chilled surface temperature is then determined.

When simulating a naturally ventilated environment, the panel temperature is maintained at $2^\circ$C above the ambient dew point temperature to ensure maximum cooling while avoiding moisture condensation. When simulating a dehumidified environment, the inlet water temperature is modulated so that a consistent level of thermal comfort is maintained. While utilizing both control strategies simultaneously is ideal, sudden significant changes in panel supply temperature can cause convergence errors. Further model development will look to address this issue.

To integrate the thermophysics model within a TRNSYS environment, the model only requires inputs that can readily be produced by TRNSYS and TRNBuild. These include the panel's inlet water temperature and flow rate, environmental parameters, the day of the year (for the adaptive comfort model), and if the simulated space is occupied during the current time step. The model also produced minimal outputs. This improves its ease of implementation in other building performance simulation tools.

A major simplification was made in the modeling of the horizontal ceiling panels used in this simulation. The development of the thermophysics model used to predict cooling supplied by the panel consisted of a calibration process using data obtained from a field experiment in Singapore, Teitelbaum et al. (2020). However, data was only obtained for a vertical panel, and therefore only the vertical panel model was calibrated. To overcome this obstacle, the model first calculates the cooling a calibrated vertical panel would supply to the simulated space. This cooling amount is then scaled by a value that would be expected if the panel was made horizontal. As no data was available to compare the accuracy of the various approaches considered, this option was chosen as it attempts to incorporate both calibration and orientation.

## Thermal Gains

An advantage of using TRNBuild is that the location of a thermal gain within a space can be specified. To simulate the radiative and convective cooling supplied by the panel, radiant heat transfer occurs at the dark blue sphere in the center of the panel as seen in Figure 4. Convective heat transfer is distributed across the five blue spheres along the panel. This spreads out the effect of air cooling across the room rather than having it localized directly above the center.

The thermal gains produced by occupants, lighting and equipment are modeled using the standard office profiles supplied by TRNBuild. The occupants are modeled as being distributed evenly across the floor area. To reflect this, a fifth of the total gains generated by the occupants are located at each of the 5 seated occupants seen in Figure 4. This figure is intended to give a visual representation of how the office space is modeled and where the gains enter the room, and does not reflect the TRNBuild interface.

The location of the electrical equipment gains are the same as the occupant gains. The lighting gains are emitted from the 5 blue spheres distributed across the ceiling.

## Modeling of Electrical Energy Consumption

Modelling the electricity consumption of the various mechanical system configurations was done by combining the electricity usage of the heat pump, water pumps, and fans.

The heat pump was modelled using the Coefficient of Performance (COP) values that are expected in each simulated scenario. A typical Carnot factor of 0.5 was used to determine these values. When any form of air conditioning is required, the heat pump is less efficient because it must supply lower temperature water. In Singapore, when air conditioning is required, the heat pump has a COP of 5.0 and a COP of 6.2 when it is not required.

The system's ability to utilize liquid pumps to move thermal energy throughout a building results in a significant portion of the system's energy saving potential. The electricity usage of these pieces of equipment are modeled using correlations that relate the amount of energy used to the amount of fluid being moved. ASHRAE (2009) standard 189.1 defines a pump power limitation of 0.1 W/l/hr, and ASHRAE (2007) standard 90.1 defines a specific fan power limit of 0.482 W/m³/hr.

## Building Characteristics

Figure 5 illustrates how the simulated office shares similar dimensions with an office in Singapore. A $1000 \text{ m}^2$ office floor is simulated with a floor to ceiling height of 3 m, and an exterior window to wall ratio of 65%. To simulate a $1000 \text{ m}^2$ office floor, a $250 \text{ m}^2$ office floor model was created, with two ex-
terior walls interacting with the simulated Singapore environment and the other two being adiabatic. As some of the TRNSYS components could not handle the loads generated by the larger office space, this approach reflects a 1000 m$^2$ office space while allowing for less simulated volume.

The walls are modeled as have a thickness of 0.377 m and a U-value of 0.250 W/m$^2$K, Adrian et al. (2013). The windows have a U-value of 2.14 W/m$^2$K and a G-value of 0.23, Adrian et al. (2013). The windows employ an automatic internal shade that blocks 70% of the solar energy entering the room when it is closed. The shades switch from open to closed when the radiant energy incident on the window exceeds 140 W/m$^2$. It is assumed that 15 people occupy the 250$^2$ simulated space, giving it an occupancy density of 16.7 m$^2$/person, which is similar to the default office space value of 18.6 m$^2$/person found in ASHRAE (2016) standard 62.

Simulated Scenarios
The objective of the simulations is to identify the incremental energy savings that can be obtained by replacing air conditioning with membrane-assisted radiant cooling, and then integrating natural ventilation. To achieve this goal, a standard air conditioning system is simulated which is followed by a simulation that attempts to be identical to the air conditioned environment, except that sensible cooling is supplied by radiant panels rather than conditioned air. The final scenario removes all modes of air conditioning that were present in the second scenario and implements a high air change rate to simulate a naturally ventilated environment. These three scenarios are modeled in Singapore as it represents the hot and humid climate this technology was designed for. Additionally, it is speculated that the performance of the panel in Singapore will reflect its potential to provide energy efficient space cooling to similar climates.

Mechanical System Configurations
Three mechanical systems are modeled in this study. The first system utilizes radiant cooling alongside natural ventilation, the second utilizes radiant cooling alongside both mechanical dehumidification and fresh air ventilation, and the third is a pure air conditioning system.

The radiant cooling with natural ventilation system consists of a ceiling mounted radiant panel that sends thermal energy extracted from the room to a heat exchanger. The heat exchanger transfers thermal energy to the heat pump while controlling the temperature of the water entering the panel. A diagram of the radiant cooling system that utilizes natural ventilation can be seen in Figure 6.

In the radiant cooling and mechanical dehumidification scenario, the heat pump supplies chilled water to both a heat exchanger which controls the radiant panel and a condenser coil which dehumidifies the space by removing sensible and latent heat from the recirculated indoor air. A heat pipe transfers sensible heat from the air stream leaving the occupied space to the air stream entering the space, thereby diverting a portion of the sensible heat away from the condenser coil. An energy recovery ventilator is used to precondition the outdoor air entering the space. A diagram of the radiant cooling system that utilizes mechanical dehumidification/ventilation can be seen in Figure 7. The air conditioning system consists of a heat pump that supplies chilled water to a cooling coil that provides both sensible and latent cooling to the recirculated indoor air. Additionally, an energy recovery ventilator is again used in this scenario.

Methods for Assessing Thermal Comfort
When modeling thermal comfort inside a space, choosing the correct approach to quantifying thermal comfort is important. All the information used in this section comes from a review paper on thermal com-
fort models by Enescu (2017) unless otherwise cited.

PMV-PPD

The Predicted Mean Vote (PMV) model is based on Fanger’s comfort equation for human body heat exchange and is used to predict the average perceived thermal comfort of large groups of people in steady-state air-conditioned environments. It is used to determine thermal comfort in any simulated scenario that uses a form of mechanical air conditioning. A space is considered thermally comfortable if the PMV value is within the range of -0.5 to 0.5. A value within this range results in a Predicted Percent Dissatisfied (PPD) value of 10% or less, and is the typical range of thermal comfort within buildings. This approach is used to quantify thermal comfort in any simulated scenario that employs air conditioning.

Adaptive Comfort Model

The adaptive model of thermal comfort is a method of predicting thermal comfort that only takes the prevailing mean outdoor temperature into account. The general philosophy is that the occupant will dress according to the recent outdoor weather, and will attempt to adapt to their indoor environment by removing layers of clothing. ASHRAE (2013) standard 55 states that the 80% acceptability limit is for typical applications, while the 90% acceptability limit is used when higher standards of comfort are desired. The adaptive approach is used to quantify thermal comfort in any simulated scenario that employs natural ventilation as it is considered to be more accurate than the PMV method in these environments. The simulated indoor environment is considered comfortable if the operative temperature falls within the 90% acceptability limit.

Results

The results section looks to compare the energy performance of the three mechanical systems. The objectives that drive these simulations are to show that significant energy savings may be obtained through the use of natural ventilation rather than dehumidification/mechanical ventilation alongside radiant cooling, and that sufficient cooling can be supplied to occupants without condensing air moisture. As no data could be used to confirm the performance of the building energy model, results should be primarily used to indicate the energy saving potential of these technologies.

Each scenario was simulated from January 1st to March 1st. Full years were not simulated due to long simulation times, and the fact that Singapore has a consistent climate year round means that using a two month simulation yields a reasonable estimate for yearly cooling loads, Wong and Li (2007). The AC scenario produced an energy usage estimate of 84.5 kWh/m²/yr, which is a reasonable baseline for comparison. Singapore office buildings at the 3rd percentile of energy efficiency consume about 143 kWh/m²/yr of electricity, BCA (2018), of which about 60% is used for space cooling, E2PO (2005), which results in a space cooling energy consumption of 85.8 kWh/m²/yr. The radiant cooling and natural ventilation configuration achieved a 45% energy reduction from the AC only configuration, and a 23% reduction from the dehumidification scenario. The radiant cooling and dehumidification scenario also demonstrated significant energy savings, achieving an energy reduction of 29% relative to the AC scenario. The key findings obtained from the simulations are shown in Figure 8.

Over the course of the simulations, condensation never occurred on the panel’s membrane. Thermal comfort was maintained 99.4% of the time for the radiant cooling plus natural ventilation scenario, and 100% of the time for the radiant cooling plus mechanical ventilation scenario.

The figures in this section display one week of results as displaying the full simulation would produce figures that are too large. Figure 9 compares the chilled surface, membrane, air, and dew point temperatures for the radiant cooling and natural ventilation scenario. It illustrates how the chilled surface of the panel can reach temperatures well below the dew point of the ambient air while maintaining the membrane’s surface temperature above the dew point. Figure 10 depicts the range of operative temperatures that will result in occupant thermal comfort, as well as the simulated indoor operative and air temperatures. It can be seen that in some cases, the difference between the indoor operative temperature and the indoor air temperature is the difference between an occupant feeling thermally comfortable and slightly warm.

Graphs depicting temperature and thermal comfort results obtained from the remaining two scenarios were not included as controlling moisture condensation and maintaining thermal comfort is not a concern for these systems.
Discussion

The first topic of discussion focuses on the performance of the framework used to integrate the Python thermophysics model, Sheppard (2020), within the TRNSYS environment. This will be followed by a discussion regarding the simulated environments and the results obtained from these simulations. Data collected from the field experiment in Singapore was only used to validate the thermophysics model developed in previous work. It was not used in the validation of the TRNSYS simulations.

Framework Performance

The primary purpose of this research is to develop a framework that allows for the simulation of a membrane-assisted radiant panel within a TRNSYS environment. The individual sub-tasks shown in Figure 3 function properly, although there are aspects of each that should be further developed.

The most prominent shortcoming of the framework is the method by which the heat exchange between the panel and the occupied space is simulated. TRN-Build’s internal gains tool is used to simulate the panel’s effect on the room because the rate of heat removal calculated by the Python model can be specified. Using a point source to model radiant heat transfer means that all surrounding surfaces are affected equally. This ensures that the correct amount of radiant cooling is being simulated, however, some of this cooling is applied to the ceiling which does not accurately reflect a real panel. This shortcoming affects the mean radiant temperature (MRT), which is the average radiant temperature of the surfaces surrounding an occupant. This is because radiant cooling is applied to the portion of the ceiling area that is covered by the radiant panel, which is a surface that is not included in the occupants MRT calculations.

A solution is to model the ceiling as being highly reflective, so that the radiant cooling directed towards the ceiling is redirected towards the rest of the room. To calculate the view factor from an occupant to another occupant, view factor obstructions from desks, furniture, and other items within an occupied space are not considered. Various methods could be implemented to account for these obstructions, such as ray tracing or a statistical approximation of the obstructed area that would likely occur.

Conduction through the rear of the panel is not taken into account as it is assumed that it can be insulated to the point were it is irrelevant. Additionally, as the panel can either be attached flush to the wall or suspended, it is difficult to determine which approach should be used to model insulation. A model that can accurately predict conduction through the rear of the panel in either configuration should be developed.

While TRNSYS includes the active layer and chilled ceiling tools which can both model radiant systems, utilizing them to model the radiative and convective cooling supplied by a membrane-assisted panel is not trivial. The included tools can not replace the Python thermophysics model as they can not account...
for the effects of the panel’s membrane on radiative and convective heat transfer. They could potentially be used to reflect the radiative cooling calculated by the model in TRNSYS. However, it is difficult to ensure that the correct amount of radiative cooling is being simulated. Additionally, it is unlikely that the TRNSYS panel will simultaneously apply the correct amount of convective cooling to the simulated space, so thermal point gains are still required to correct for this discrepancy. Using radiative and convective point gains ensures that the correct amount of cooling is being supplied to the simulated environment.

Simulated Environments
The purpose of membrane-assisted radiant panels is to provide low-exergy cooling systems to buildings in humid climates, Meggers et al. (2010). By pairing membrane-assisted panels with natural ventilation, a heat pump no longer needs to produce the low water temperatures required for air conditioning and can instead supply water at the temperature required by the radiant panel. This introduces significant energy saving potential, as the efficiency of a heat pump depends on the temperature of the chilled water it supplies.

The results from this study indicate that sufficient cooling can be supplied year round in Singapore without any active dehumidification. This is significant for many reasons. The results show that implementing natural ventilation can reduce the load on the cooling system as it removes a significant portion of the thermal gains generated within the space. Additionally, integrating natural ventilation can improve the indoor air quality within a space by removing the carbon dioxide that occupants exhale and has been shown to reduce the effects of sick building syndrome, Wong and Huang (2004); Lei et al. (2017). In a post COVID-19 world where indoor ventilation rates will likely be viewed as having a greater importance, this study shows that humid climates like Singapore can implement an energy efficient cooling system while simultaneously achieving very high indoor ventilation rates.

Conclusions
Membrane-assisted radiant cooling is a low-exergy space cooling technology that can be applied in various climates. To bring this technology closer to widespread implementation, a framework has been developed that allows for the integration of a thermophysics model that simulates a membrane-assisted panel within a TRNSYS environment. It is the first study to integrate membrane-assisted cooling within energy modeling software, and will aid in the design and optimization of cooling systems that utilize this technology.

The framework used to simulate membrane-assisted panels within a TRNSYS environment has some shortcomings that need to be addressed, and the lack of real building data to confirm model performance means that further research is required before the framework can be widely adopted. However, solutions to these shortcomings have been proposed and the core functions of the framework that allow for the integration of the thermophysics model operate as designed.

The simulated results suggest that operating radiant cooling alongside natural ventilation can obtain significant energy savings relative to both air conditioning and radiant cooling with dehumidification/mechanical ventilation systems.

Future Work
Real building data should be used to evaluate the energy usage results produced by the TRNSYS framework. Various framework shortcomings are listed below and should be addressed in future model development.

- Automate human to surface view factor calculations and investigate the benefits of implementing ray tracing.
- Improve panel to building surface view factor calculations by accounting for the surface area of the panel rather than calculating view factors from a single point.
- Improve the method by which TRNSYS simulates the panel’s radiant thermal exchange with the occupied space.
- Refine the inlet water temperature control strategy so the level of thermal comfort within the space can be maintained more precisely.
- Implement a method of accurately predicting conduction through the rear of the panel.

Currently, the radiant heat transfer between the panel and its environment is set to zero the moment water is no longer entering the panel. In reality, the panel will stay cool for a time following the removal of chilled water. The model should be updated to account for this heat transfer.

References


