TRNSYS modeling of a novel ceiling panel designed to maintain space humidity in an office building

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Abstract

Ceiling cooling panels have one of the highest technical energy savings and they achieve high comfort levels. However, they are unable to maintain the indoor relative humidity as they only transfer sensible heat. In order to overcome this problem, a novel heat and moisture transfer panel (HAMP) is developed and tested. In this paper, the applicability of the HAMP is tested using the TRNSYS simulation program. The impact of the HAMP on space relative humidity is investigated by modeling a 1-storey office building in two Canadian cities (Saskatoon and Toronto) as representatives of the Canadian climatic conditions. The validity of the HAMP and resulting energy savings is represented and compared against a similar building operating with a conventional all air system. The HAMP proved to be able to maintain space relative humidity levels between 22% RH and 55% RH in Saskatoon; and between 23% RH and 57% RH in Toronto.

1. Introduction

Radiant ceiling panels are temperature controlled indoor surfaces placed on ceilings, floors or walls. The temperature can be maintained by circulating water, air, or electric current. The panels transfer heat to the space by convection and radiation. Convection heat transfer takes place between the panels and the room air, while radiation heat transfer takes place between the surface of the panels and the room surfaces and objects. The name “radiant” comes from the fact that 50% or more of the design heat transfer is taking place by thermal radiation. The minimum ventilation required for the space is still provided to meet minimum indoor air quality levels.

Many papers in the literature discuss and document the theory and performance of radiant cooling regarding its comfort, efficiency, and cost effectiveness. Kulpmann (1993) studied a space with chilled ceiling panels and found that the system provided good thermal comfort. Simmonds (1997) studied the first cost and long term energy savings of ceiling radiant cooling panels compared to conventional air conditioning systems (or all air systems) and concluded as follows:

- The first cost is 15% less with experienced contractors.
- The long term savings due to using smaller chillers and reduced fan power is 20-30%.
- There are less moving parts showing potential reduced operational and maintenance costs.
- Simpler and less expensive testing and balancing at commissioning.

With proper selection and installation of the ceiling panels, the only problem faced by this system is condensation. To overcome this problem, many researchers introduced the idea of using radiant ceiling panels integrated with other all air systems. Conroy and Mumma (2001) reported the use of radiant ceiling panels to control sensible load only, while a dedicated outdoor air system (DOAS) controlled 100% of the space latent load so that the dew point temperature of the space could be controlled.

Sodec (1999); Miriel et al. (2002); and Vangtook and Chirarattananon (2006, 2007) all showed that radiant panels, combined with mechanical ventilation systems, consume less energy than all air systems. Miriel et al. (2002) performed computer simulations using experimental results from two winters and one summer in Rennes in western France. The results showed a 10% reduction in energy consumption compared to a conventional all-air system. On the other hand, Sodec (1999) used a numerical simulation to compare an all air system with a radiant ceiling panels system regarding the energy costs, first costs, and the space area requirements. He concluded that the energy savings can be up to 10-20% in cooling, the first costs can be reduced by up to 20%, and the space requirements can be reduced by 40-55%.

Busweiler (1993) introduced the first system that used desiccant cooling with a cooled ceiling system. It was also the first such system installed in Germany. Due to limited space in the plenum above the suspended ceilings in a hotel in Bremen, conventional air conditioning systems could not be installed. This led to the use of a cooled ceiling system with ventilation air coming in from outlets near the floor. A desiccant wheel was used to dehumidify a 100% outdoor air stream, and an evaporative cooler was used to humidify it according to the air conditions. The system ran successfully for a year and proved to save energy and reduce the peak electricity consumption. In general, according to Mumma (2001) ceiling panels with their different applications are more widely used in Europe than in North America.

A novel solution for the condensation problem of this system is using a liquid desiccant. A novel heat and moisture transfer panel (HAMP) is developed, tested and investigated by Fauchoux et al. (2009) and Fauchoux et al. (2008). Figure 1 shows a sketch of the top and side views of the HAMP as used in testing. An actual HAMP might however look different due to other design considerations. A HAMP is a panel constructed from a porous membrane that uses a salt solution as the transfer media so that it can control both temperature and relative humidity. This will allow the space relative humidity to be controlled together with its temperature. The salt solution is held by retaining walls on the top and sides.

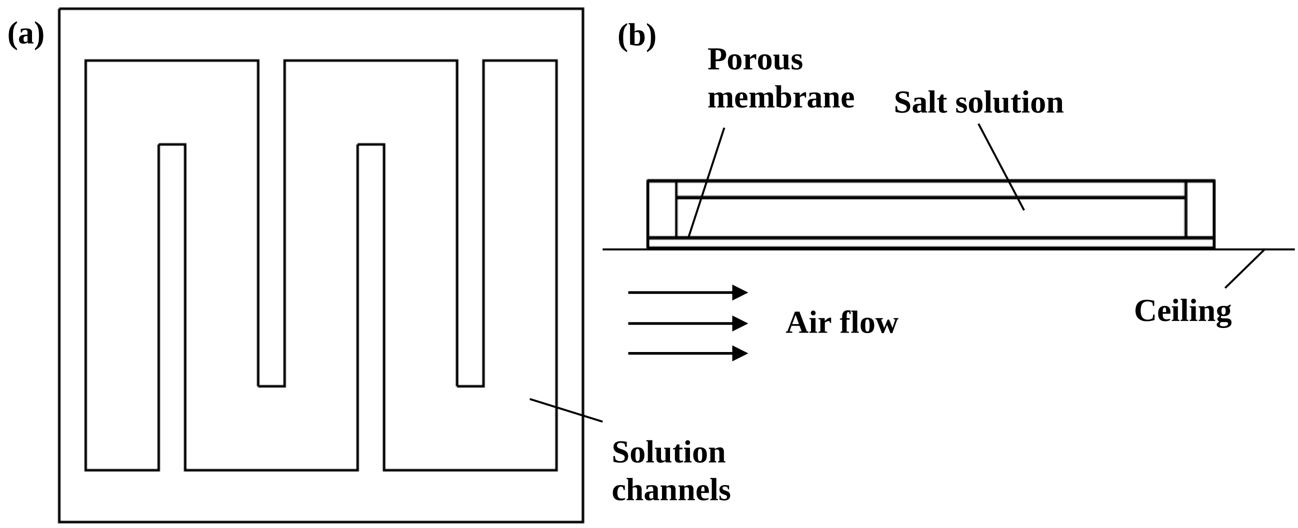

Figure 1: The (a) top view, and (b) side view of the HAMP used in testing

It is important to control moisture in buildings to achieve required comfort levels and avoid condensation problems. Controlling the indoor relative humidity is important for occupant health and productivity. ISO Standard 7730 (1994) suggests that the indoor relative humidity be between 30% and 70%. Bornehag et al. (2001) and Kosonen and Tan (2004) reported that indoor humidity levels outside this range leads to discomfort, lower productivity. Further investigation of the HAMP use in a 1-storey office building using the building simulation program TRNSYS is presented in this paper. The study is done in two Canadian cities, Saskatoon and Toronto, representing the cold dry and humid Canadian climates, respectively.

2. Model description

2.1. TRNSYS

According to a study performed by Fauchoux (2006) on the different types of building simulation programs commercially available, TRNSYS was found to be the best out of 11 programs that suits the required characteristics for this research. TRNSYS is defined by Klein (2000) as a FORTRAN-based transient system simulation program which is designed to solve complex thermal systems by breaking them down into less complicated components. As was shown by Beckman et al. (1994), TRNSYS is characterized by its capability of solving each thermal component independently and then coupling them to solve the main thermal system. Thermal Energy System Specialists, TESS, is one of the major developers of TRNSYS component libraries. TRNSYS 17 and the second version of TESS libraries are used in this study.

2.2. Building

Based on research carried out by the Pacific Northwest national Laboratory (PNL), United States office building stock has been classified into 25 buildings categories. Each of these buildings represents a specific percentage of the US office building stock as determined by a Commercial Building Energy Consumption Survey (CBECS) carried out by the Energy Information Administration (1986) of the U.S. department of energy. The building used for this investigation is chosen from a set of 20 buildings describing the existing building stock as of 1979. The 20 buildings are described in details by Briggs et al. (1987).

A 1-storey office building with a floor area of 730 m^2 and 30% windows area is selected for this study. The building description from the PNL study is based on the location of the building in El Paso, Texas. ASHRAE standard 90.1 (2004) categorizes cities around the world into 8 climatic zones categories starting from the warmest cities in zone 1, and ending at the coldest cities in zone 8. El Paso in Texas is categorized by ASHRAE standard 90.1 (2004) as zone 3B. However, the cities presented in this paper are Toronto and Saskatoon which are categorized as zones 6 and 7, respectively. This enforced some modifications on the insulation of the building walls, roof, floor, and fenestration to be done. Table 1 shows a detailed description of the convective heat transfer coefficients; U values.

Table 1: Building modifications

U-value (W/m^2K)	Wall	Roof	Floor	Fenestration
Original in PNL model	1.250	1.046	0.279	5.68
Building model	0.423	0.254	0.279	1.73
Maximum allowed, according to ASHRAE 90.1 (2004), for zone 7	0.513	0.360	0.496	3.24
Maximum allowed, according to ASHRAE 90.1 (2004), for zone 6	0.592	0.360	0.496	3.24

For this building, lighting, occupancy and equipment have maximum intensity of 14.25 W/m^2, 5 Persons/100m^2 and 11.7 W/m^2, respectively. TESS component type 571 is used to calculate the building infiltration rate as a function of the wind speed; indoor and outdoor temperatures; ambient pressure and relative humidity at each time step. The average value for infiltration is 0.27 ACH. The latent load of this building represents 11.1% and 9.1% of the total load of Saskatoon and Toronto, respectively. Figure 2 shows the hourly schedule of the fractional internal loads and ventilation with respect to the peak values.

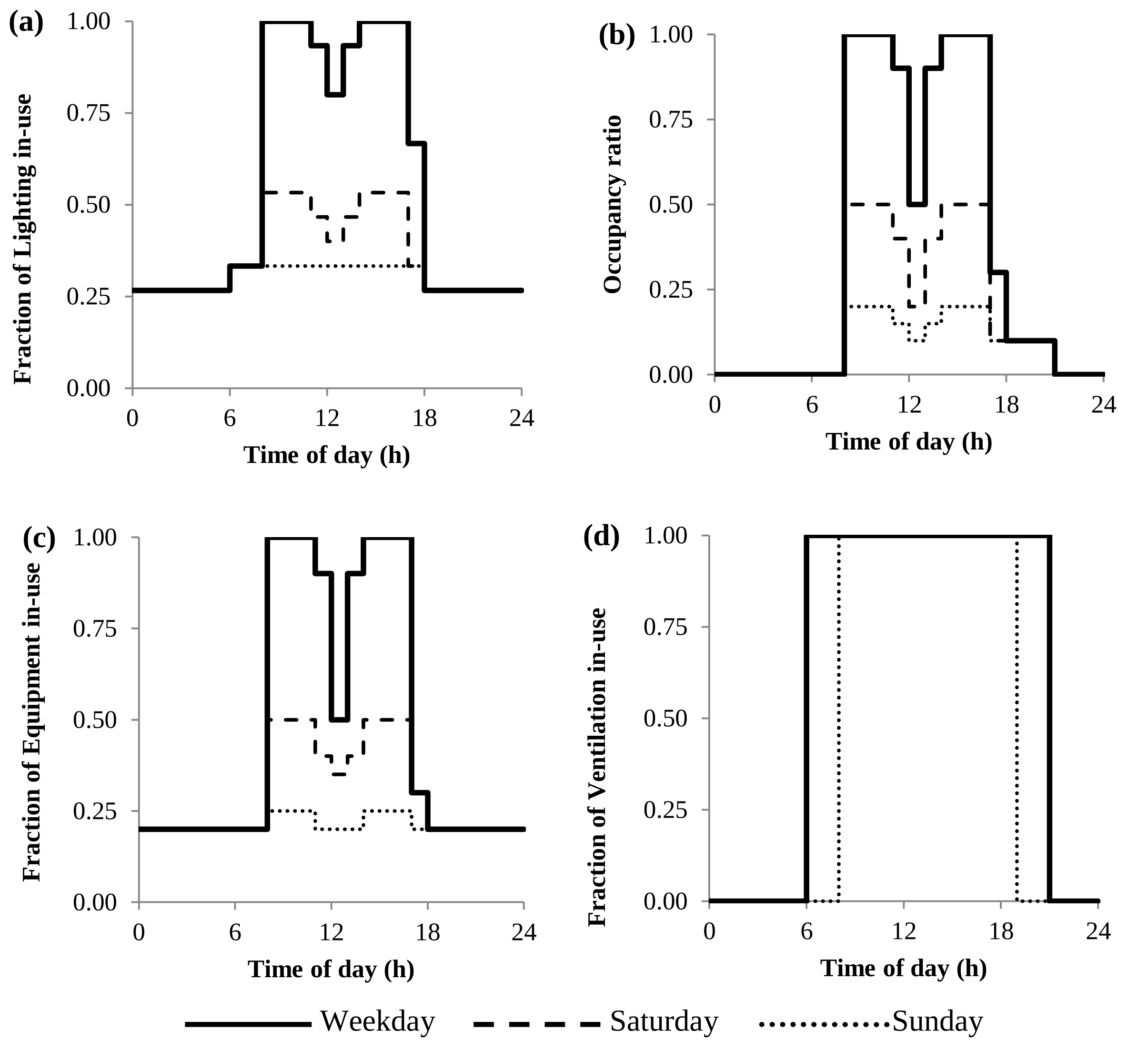

Figure 2: Schedule of (a) lighting, (b) occupancy, (c) equipment, and (d) ventilation in the 1-storey building

2.3. HVAC System

TRNSYS 17 allows the user to define an active layer that act as a radiant ceiling panel with a user defined fluid specific heat and panel heat transfer coefficient. The convective heat transfer coefficient is assumed to be contributed only by natural convection. It is calculated in a separate component for every time step depending on the panel temperature and the space air temperature. Equations 1a and 1b were used to calculate the convective heat transfer coefficients for heating and cooling ceiling panels respectively (ASHRAE 2008).

$$h_c = 0.134\left(T_p - T_a\right)^{0.25} \quad (1a)$$

$$h_c = 2.13\left|T_p - T_a\right|^{0.31} \quad (1b)$$

The radiation heat transfer coefficient is also calculated in a separate component and the total heat transfer coefficient is calculated and given to the building as an input in every time step. The HAMP moisture addition or removal is added or removed as a gain to the space. This gain is calculated using a Matlab code with input information from the building space. The Matlab is integrated into the TRNSYS using Type 155 which calls the Matlab code in every time step. The final equation used to calculate the moisture added or removed is

$$H = h_m A \rho_{dryair}(W_s - W_{air}) \quad (2)$$

Table 2 shows the three systems studied. Case A represents a conventional dedicated outdoor air system (DOAS) that removes only space and ventilation sensible loads. Case B studies the effect of using radiant ceiling panels (RCP) in the space instead of DOAS. In addition, the ventilation latent load is removed using DOAS. The area of the radiant ceiling panel used is 60% of the total ceiling area. Finally, case C studies the same system as case B with the same area of radiant ceiling panels with the addition of using the HAMP to remove the space latent load. A controlled energy wheel is used to precondition the ventilation air in cases B and C. Further heating, cooling, humidification, and dehumidification are then done as required using different control signals in these two cases to precondition the ventilation air.

Table 2: Different cases represented

	Space		Ventilation	
	Sensible	**Latent**	**Sensible**	**Latent**
Case A	DOAS	None	DOAS	None
Case B	RCP	None	DOAS	DOAS
Case C	RCP	HAMP	DOAS	DOAS

2.4. Ventilation

The building is ventilated using a constant flow of 100% outdoor fresh air. The outdoor ventilation rate is 0.31 m^3/s and the ventilation schedule is shown in Figure 2 (d) to meet ASHRAE Standard 62.1 (2007). The outdoor ventilation rate is determined according to the occupancy, area, and building type.

2.5. HAMP

The HAMP used in the office building uses Lithium Chloride (LiCl) as the salt solution. All solution properties used for calculations are based on LiCl properties. The area of the HAMP used is 10% of the total ceiling area. This means that the total area used by RCP and the HAMP is 70% of the total ceiling area. The main purpose of this study is to prove the applicability of the HAMP and its ability to maintain the space relative humidity. Thus, the effect of heat transfer accompanied by the moisture transfer is neglected in this work. However, it is assumed that the heat transferred by the HAMP is included in the total heat transfer of the radiant ceiling panels.

In order to decide on the salt solution concentration and temperature used for either humidification or dehumidification, it is important to define the set point humidity ratio for each case and look closely at how the HAMP surface humidity ratio changes with LiCl concentration and temperature. Figure 3 shows this relation at four different salt solution temperatures. It is shown in the Figure that for a constant solution temperature the surface humidity ratio decreases as the salt concentration increases while for a constant concentration the humidity ratio increases as temperature increase.

The set point humidity ratio for humidification is at 4.91 g/kg which corresponds to a temperature of 22ºC and relative humidity of 30% RH of the space air. Thus, it is required to keep HAMP surface humidity ratio, W_s, above this value to create a mass transfer potential as indicated in equation (2). In order to use a suitable temperature assuming that humidification takes place with heating, a temperature greater than 20ºC is used. The salt solution is thus provided at 22ºC and 34% concentration for humidification which corresponds to W_s of 5.55 g/kg.

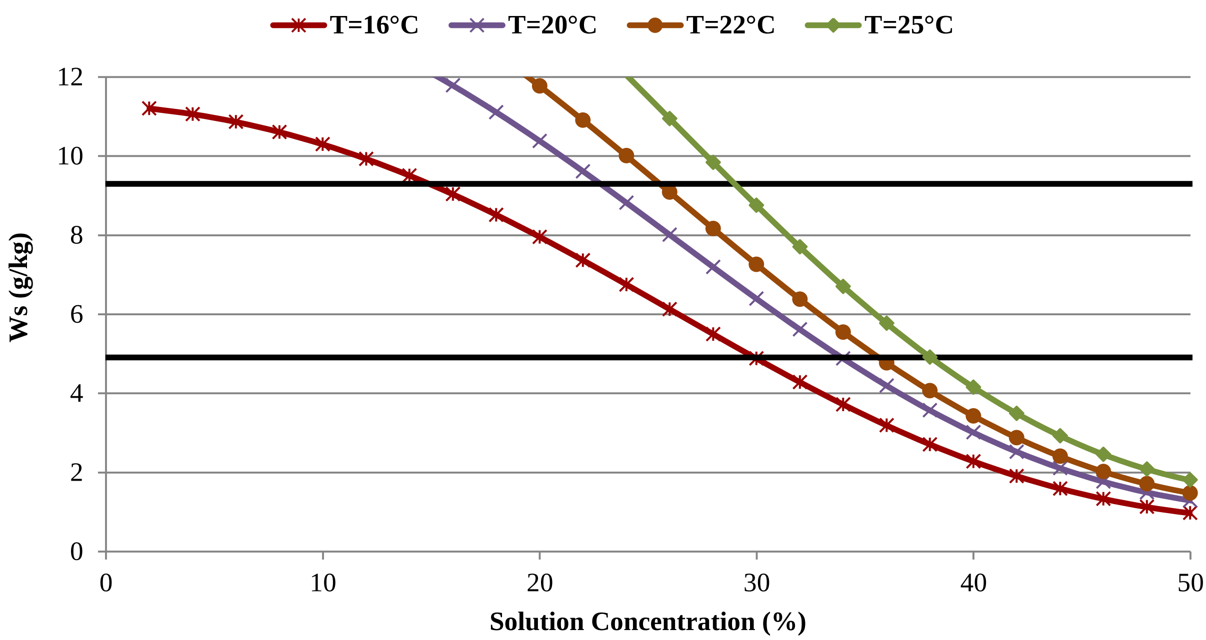

Figure 3: Relation between the HAMP surface humidity ratio and the salt solution concentration at different solution temperatures for LiCl

On the other hand, the set point humidity ratio for dehumidification is at 9.30 g/kg which corresponds to a temperature of 24ºC and 50% RH of the space air. It is required to keep W_s below this value to allow moisture to be transferred to the HAMP which has the lower mass transfer potential. It is assumed that dehumidification takes place with cooling which means that the temperature of the solution should be kept lower than 20ºC. Thus, the salt solution is provided at 16ºC and 24% concentration for dehumidification which corresponds to W_s of 6.75 g/kg.

3. Results and discussion

3.1. Space temperature

To be able to ensure that the radiant ceiling panel is capable of removing the heating and cooling loads, the temperature inside the zone was monitored and compared to the set point temperature in both cities. The set point temperature is 24ºC for cooling and 22ºC for heating. The set point temperature varies according to the building load. In summer, the set point temperature is higher during the night; however, it does not go higher than 28ºC. In winter, the set point temperature is lower during the night; however, it does not go lower than 15ºC.

Figure 4 shows the variation of the space temperature on the winter day with the highest heating load and in the summer day with the highest cooling load for both cities. As shown in the Figure, there is a delay in winter to reach the required set point temperature while there is almost no delay in cooling. This is due to the fact that the convective heat transfer coefficient for ceiling cooling is higher than ceiling heating. However, this problem can be minimized by properly designing the radiant ceiling panels system.

It also should be noted that the zone temperature is maintained even overnight and in the morning when the set point temperature is lower in winter or higher in summer. This is caused by the liquid in the radiant ceiling panel. This means that, although the flow of water is stopped and the heating or cooling equipment is turned off, it takes time for the water inside the tubes to reach steady state with the room air.

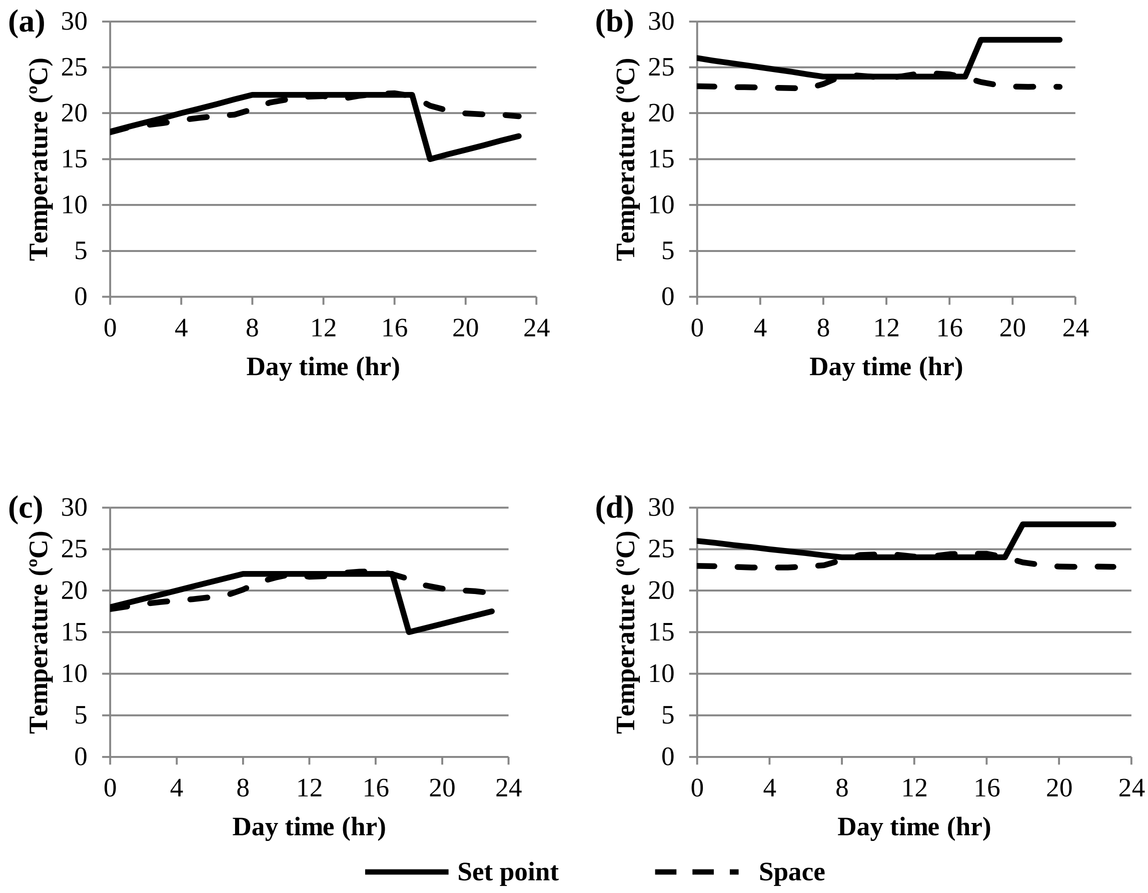

Figure 4: Comparison of zone temperature to set point temperature in Saskatoon on (a) Jan 15, (b) Aug 22, and in Toronto on (c) Jan 14, and (d) Aug 2

3.2. Relative humidity

The resulting relative humidity in the building in the three cases stated in Table 2 were analyzed and are represented in Figure 5 for Saskatoon and Figure 6 for Toronto.

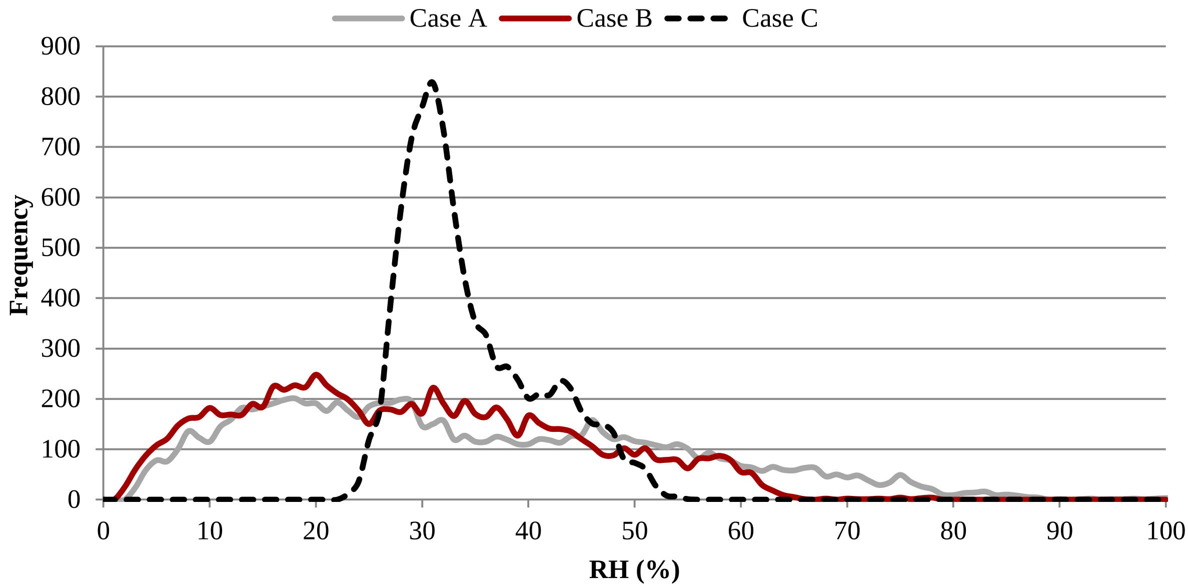

Figure 5: Frequency of relative humidity inside the building throughout the year in Saskatoon

Saskatoon is characterized by dry weather. Figure 5 shows the ability of the HAMP in case C to humidify the space in comparison with the other cases. The space relative humidity is maintained above 22%. The HAMP was able to dehumidify to lower levels than the other two cases. The space relative humidity is maintained below 55%. In cases A and B the space relative humidity in many hours was below 22% or higher than 55%. As mentioned previously, it is recommended that the space relative humidity stays in the range of 30% t0 70%. Case C shows the greatest resemblance to the recommendation.

Toronto has a more humid climate than Saskatoon. Again, the HAMP proved to be able to humidify the air in the space and maintain the relative humidity levels above 23% which is slightly higher than Saskatoon due to less dry weather. It was also able to do dehumidification and maintain the space relative humidity below 57%.

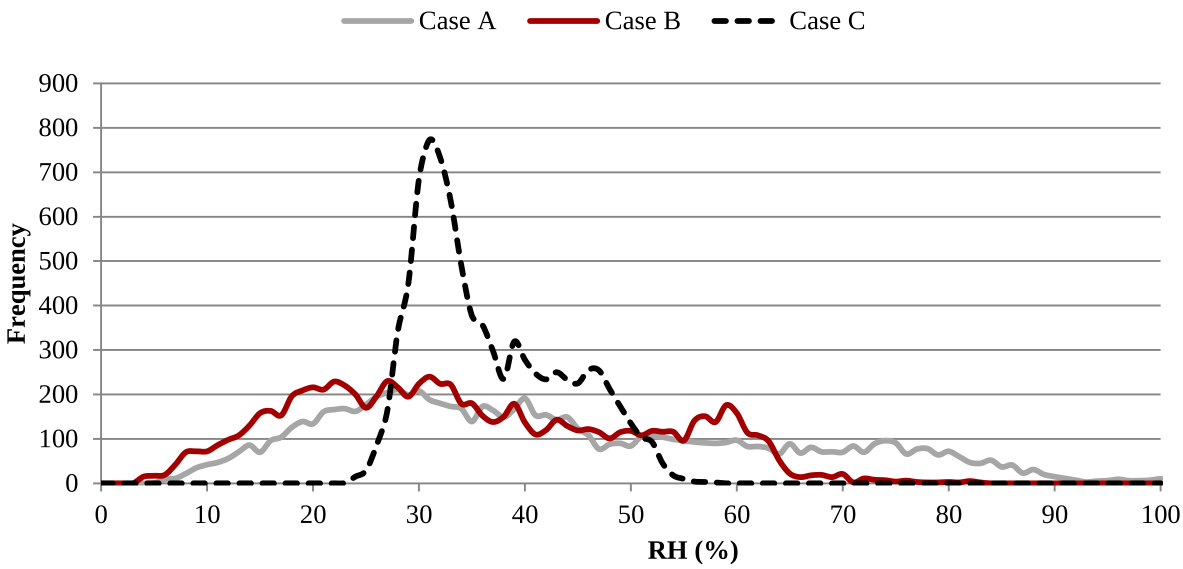

Figure 6: Frequency of relative humidity inside the building throughout the year in Toronto

To be able to control the amount of moisture added or removed by the HAMP, equation (2) shows that it is directly proportional to the HAMP area, the mass transfer coefficient, and the humidity ratio potential between the surface of the HAMP and the space. The HAMP area is generally limited to the space area but can have a great effect on moisture transfer. For humidification, the humidity ratio potential can be much higher than the potential for dehumidification; W_s can be as high as 50 g/kg while for dehumidification; it is restricted to as low as 0.1g/kg. Thus, the humidity ratio potential is limited in the case of dehumidification.

The last parameter we can vary is the mass transfer coefficient which was calculated according to the heat-mass transfer analogy. This means that it depends on the value of the heat transfer coefficient which was calculated based on natural convection. Thus, the moisture transfer by the HAMP can also be enhanced if used with mixed or forced convection rather than natural convection. Some research was done to investigate the effect of mixed convection on the performance and first cost of radiant ceiling panels. Awbi and Hatton (2000) studied mixed convection from a room heated ceiling. Novoselac et al. (2006) developed new correlations for cooled ceiling panels in a room with mixed and stratified flow.

3.3. Energy

Figure 7 shows the heating, cooling, and total space thermal load in the three cases in both cities. In Saskatoon case B saves 35% total energy compared to case A. This shows that radiant ceiling panels consume less energy than conventional DOAS system which was shown in previous research and was expected. In this stage of testing the HAMP, it is challenging to decide on how the salt solution will be practically regenerated. More research is needed to estimate the amount of energy that will be needed for regenerating the HAMP salt solution, thus the regeneration energy is not included in Figure 7. However, the latent load added or removed by the HAMP is added to the space loads for case C and represented in Figure 7. In Toronto case B saves 37% total energy compared to case A. The humidification load that was added by the HAMP into the space is 9.5 MWhr in Saskatoon and 1.6 MWhr in Toronto, while the dehumidification load that was removed by the HAMP is 5.6 MWhr in Saskatoon and 3.4 MWhr in Toronto. The latent load is 12% of the total load in Saskatoon and 13% in Toronto.

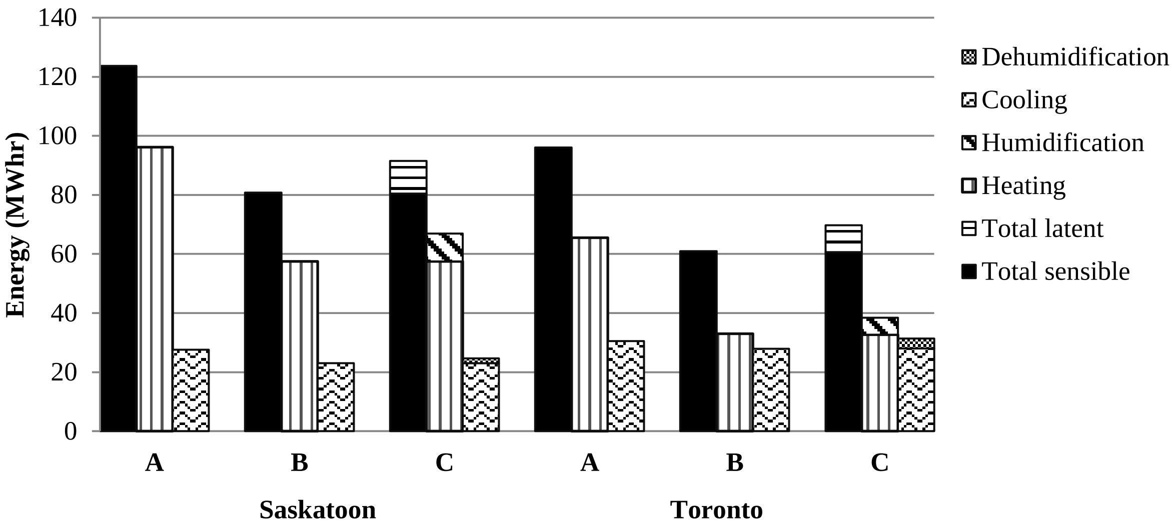

Figure 7: Energy consumption in Saskatoon and Toronto in the three cases

4. Conclusion

The applicability of the HAMP was tested in a typical 1-storey office building in Saskatoon and Toronto. Three cases were tested using conventional DOAS system, radiant ceiling panels with mechanical ventilation, and adding the HAMP to the latter. The HAMP proved to be able to humidify the space to acceptable relative humidity levels; above 22% in Saskatoon and 23% in Toronto. This directly affects the comfort level of the occupants as low humidity levels cause itchy skin, dryness, and lower concentration and productivity. On the other hand, the HAMP also proved to provide the adequate moisture transfer for dehumidification. The HAMP was able to maintain space relative humidity levels below 55% for Saskatoon and 57% for Toronto. Further sensitivity studies need to be done to test the effect of mixed or forced convection heat transfer coefficients correlations on the performance of the HAMP.

The use of radiant ceiling panels showed more favourable energy consumption than conventional DOAS system. The energy saving is 35% in Saskatoon and 37% in Toronto. More research needs to be done to be able to estimate the energy required to regenerate the salt solution in the HAMP. The total latent load removed or added by the HAMP from or to the space is 12% of the total load in Saskatoon and 13% in Toronto. The energy consumption of using the HAMP should be compared to mechanical systems that use energy to remove the same latent load.

5. Acknowledgements

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6. Nomenclature

ρ_{dryair}	Density of dry air, kg/m^3
A	Area of HAMP, m^2
H	Moisture added or removed from space air, kg/s
h_c	Convective heat transfer coefficient of air, W/m^{2}K
h_m	Mass transfer coefficient, m/s
T	Temperature, ºC
T_a	Space air temperature, ºC
T_p	Radiant ceiling panel surface temperature, ºC
U	Heat transfer coefficient, W/m^{2}K
W_{air}	Space air humidity ratio, kg/kg
W_s	HAMP surface humidity ratio, kg/kg

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