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DESICCANT EVAPORATIVE COOLING SYSTEM FOR RESIDENTIAL BUILDINGS

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ABSTRACT

A comprehensive ventilation approach requires not only air exchange but also in many cases indoor humidity control. High humidity levels decrease occupant comfort and increase the likehood of problems, such as mold growth. Occupants presently use air-conditioning systems or dehumidifiers in order to reduce the indoor moisture levels. These systems use large amounts of electricity, are expensive to operate and are useful only a couple of months a year in some regions in Canada. An energy-efficient home may need little cooling during periods of mild temperature, but humid months may result in insufficient dehumidification and higher than desired indoor humidity. One technology that can help improve the dehumidification performance and eventually reduce the electricity consumption for residential air-conditioning is the use of a solid desiccant wheel with indirect-evaporative cooling.

This paper describes a prototype desiccant evaporative cooling system (DEC) and presents its performance in term of indoor humidity control and energy efficiency. Experimental and simulation results show that the desiccant evaporative cooling system can achieve better humidity control and acceptable comfort conditions. The simulation results show that the desiccant cooling system is especially well suited for areas of the country with a high latent load. However the study identified a series of improvement measures to undertake in order to improve the energy efficiency of the unit.

RÉSUMÉ

Une méthode de ventilation globale nécessite non seulement un échange d'air mais aussi dans bien des cas un contrôle de l'humidité intérieure. Des niveaux d'humidité élevés diminuent le confort de l'occupant et augmentent le risque de problèmes comme la formation de moisissures. Les occupants utilisent actuellement des systèmes d'air climatisé ou des déshumidificateurs afin de réduire le niveau d'humidité à l'intérieur de leur maison. Ces systèmes consomment énormément d'électricité, leur fonctionnement est cher et ils ne servent que quelques mois par an dans certaines régions du Canada. Une maison éconergétique peut avoir besoin de peu de refroidissement pendant les périodes douces mais la déshumidification peut être insuffisante pendant les mois humides et l'humidité intérieure supérieure à celle souhaitée. Une technologie qui peut améliorer la performance en matière de déshumidification et éventuellement réduire les dépenses en électricité pour la climatisation est l'utilisation d'une roue dessicante solide avec refroidissement indirect par évaporation.

Cet article décrit un prototype de système de refroidissement à évaporation par déshydratant (DEC) et décrit sa performance en termes de contrôle de l'humidité intérieure et d'efficacité energétique. Les résultats expérimentaux et ceux de la simulation montrent que le système de refroidissement à évaporation par déshydratant peut permettre un meilleur contrôle de l'humidité et fournir des conditions de confort acceptables. Les résultats de la simulation montrent que le système de refroidissement par déshydratant est particulièrement bien adapté pour des zones du pays ayant une charge latente élevée. En revanche, l'étude a identifié une série de mesures d'amélioration à prendre afin d'améliorer l'efficacité énergétique de l'unité.

INTRODUCTION

Energy-efficient construction techniques that emphasize low levels of air leakage have increased the potential for moisture problems in homes. Maintaining a reasonable level of indoor humidity (less than 50%) is the most effective method of moisture control. Dehumidifiers can lower indoor humidity in regions with mild and humid winters; because they are generally designed to operate at higher temperatures and humidity levels, dehumidifiers are unnecessary in cold and dry winters. Incorporating an Energy Recovery Ventilator (ERV) in a house in the summer time has not only offered more efficient humidity control, but also showed substantial reductions in the cooling electricity consumption over the analyzed period (Ouazia et al. 2005). Occupants presently use air-conditioning systems or dehumidifiers in order to reduce the interior moisture levels. These systems are expensive to operate and are useful only a couple of months a year in some regions in Canada. An energy-efficient home may need little cooling during periods of mild temperature, but humid months with little air condition operation may result in insufficient dehumidification (where no dedicated dehumidification system is in use) and higher than desired indoor humidity.

Conventional central air-conditioning systems based on the vapor compression cycle have a rated Sensible Heat Ratio (SHR) of around 75%. The operation of these systems is controlled using only a thermostat and any moisture removed from the space is a by-product of the temperature control. In humid climates the required design latent load of the space to maintain comfortable conditions can be high with a space design Sensible Heat Ratio significantly less than 75%. In this case, using a conventional air-conditioning system leads to uncomfortable conditions with high indoor humidity levels. In addition, if the air-conditioning system is oversized and the supply fan is in continuous mode, part of the condensate in the drain pan of the cooling coil will evaporate back into the air stream and finds its way back inside the conditioned space (Henderson and Rengarajan, 1996).

A desiccant evaporative cooling system is a technology that can help address the previous shortcomings of conventional vapor compression technology. It is based on coupling active desiccant dehumidification with direct evaporative cooling. There is no need for a compressor in this case, the energy used in this system is for pumping water through the evaporative cooler, for pushing the air around the system, and to regenerate the desiccant wheel. The desiccant wheel can be controlled independently using a humidistat that senses the wet-bulb temperature of the space. A thermostat is used to activate the evaporative cooler when there is a need for space sensible cooling. This technology decouples the latent and sensible loads making it possible to condition spaces with a wide range of design Sensible Heat Ratios for better comfort conditions.

In the present study, experimental evaluation of a prototype desiccant evaporative cooling system was conducted using the Canadian Center of Housing and Technology (CCHT). Thermal performance results are presented along with simulation results and recommendations.

AIR CONDITIONING

The definition of air conditioning is a matter of ongoing debate and refinement. When it is related to occupants, it is referred as comfort air conditioning. A comfort air-conditioning system is designed to help maintain body temperature at its normal level and to provide an atmosphere to promote comfort and health. Overcooling of indoor spaces may result in moisture and mould growth problems in buildings in climates where the outdoor dew point temperature is at or above the indoor set point temperature. Ironically, when occupants are subjected to high space humidity, their typical response is to lower the space thermostat setting in an attempt to feel comfortable. The result is that the space cools further, most often increasing the space relative humidity along with the likelihood of condensation of moisture on supply air ducts, floors, and other building surfaces.

Cooling requirements should be addressed not only in terms of temperature (called sensible cooling capacity) but also in terms of humidity (latent cooling) in order to meet a better comfort. The sensible heat ratio (SHR) describes well the two components of the cooling requirement. It is defined as the ratio of the sensible heat gain to the sensible and latent heat gain of the space being conditioned. A low value of this quantity means that the total cooling load is predominately the latent load:

$$SHR = \frac{Sensible\ heat}{Sensible\ heat + Latent\ heat}$$

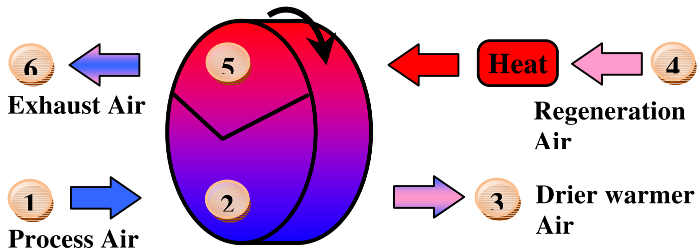
The cooling system ability to remove sensible and latent load can also be addressed using the SHR. The sensible heat ratio of a cooling system is its capacity to remove sensible cooling related to the total (sensible + latent) cooling capacity. A conventional vapour compression sensible heat ratio is around 0.75 (i.e., 75% of an equipment's cooling capability to deal with sensible load and 25% for the latent load). This value has not changed for conventional AC for the last decades, while building loads have changed considerably. The energy efficiency improvement measures have been aimed almost exclusively at reducing sensible cooling loads (better roof and wall insulations, reduced windows U-values, increased solar shadings, more energy efficient lighting, etc.) while latent cooling loads (primarily due to ventilation, infiltration, and occupants) have not changed substantially. The effect for most new constructed or remodelled buildings is to raise the latent cooling load relative to the sensible cooling load at all conditions (design and part-load).

Only when the sensible to total (sensible + latent) heat ratio, SHR, is greater than 0.75 the use of the common conventional vapour compression system could be justified in terms of energy performance and comfort quality (Davanagere, 1999). Conventional unitary air conditioning tends to satisfy the sensible load well before the latent load is met, resulting in a high indoor relative humidity above the desired range. At moderate outdoor temperatures with high outdoor humidity, the low sensible load results in unitary air conditioning cycling "on" – "off" frequently with short "on" cycles. During the "off" cycles, moisture on the coil can evaporate causing further deterioration of the net latent load.

DESICCANT DEHUMIDIFICATION

A desiccant dehumidifier is a tool for controlling humidity (moisture) levels for conditioned air spaces. Desiccant systems work in conjunction with conventional air conditioning systems to dehumidify the air. Desiccant materials are those that attract moisture due to differences in vapor pressure. Desiccants can be in the form of a solid or liquid and have been identified to be appropriate as a component of commercial heating, ventilation and air conditioning (HVAC) systems. These desiccants have been selected based on their ability to hold large quantities of water, their ability to be reactivated, and their cost.

In order to be effective, the desiccant must be capable of addressing the latent cooling load in a continuous process. In order to accomplish this, commercial desiccant systems consist of a process air path and a reactivation air path. The use of a desiccant media in the case of a rotating wheel is illustrated in Figure 1. The model of desiccant wheel considered in this study is made with WSG Desiccant Media, corrugated synthetic fibrous matrix. The desiccant wheel is rotated through a "supply" or "process" air stream. The "active" section of the wheel removes moisture from the air and the drier air is routed to the building. In a standard installation, the dry process air leaving the desiccant then passes over a conventional cooling coil which addresses the sensible cooling work required to meet the air specification of the conditioned space.



1 – Humid air enters the rotating bed of dry desiccant
2 – As air passes through the bed, the desiccant attracts moisture from the air
3 – Air leaves the desiccant bed warm and dry.
4 - A second air stream is heated and passed through the desiccant bed to raise its temperature
5 – Heated desiccant gives off its collected moisture to the reactivation air stream coming from the heater
6 – The moist reactivation air is vented to outside, carrying excess humidity from the building

FIGURE 1: PRINCIPAL OF WORK OF A DESICCANT DEHUMIDIFICATION WHEEL

DESICCANT EVAPORATIVE COOLING UNIT

A desiccant evaporative cooling system is composed of three principle components: a desiccant wheel, a sensible wheel and an indirect evaporative cooler. Figure 2 shows a schematic of the desiccant evaporative cooling unit designed for the CCHT research house. Two counter current air streams, the process (A to G) and the regeneration (H" to L) air streams drive the operation of the desiccant dehumidification / cooling system.

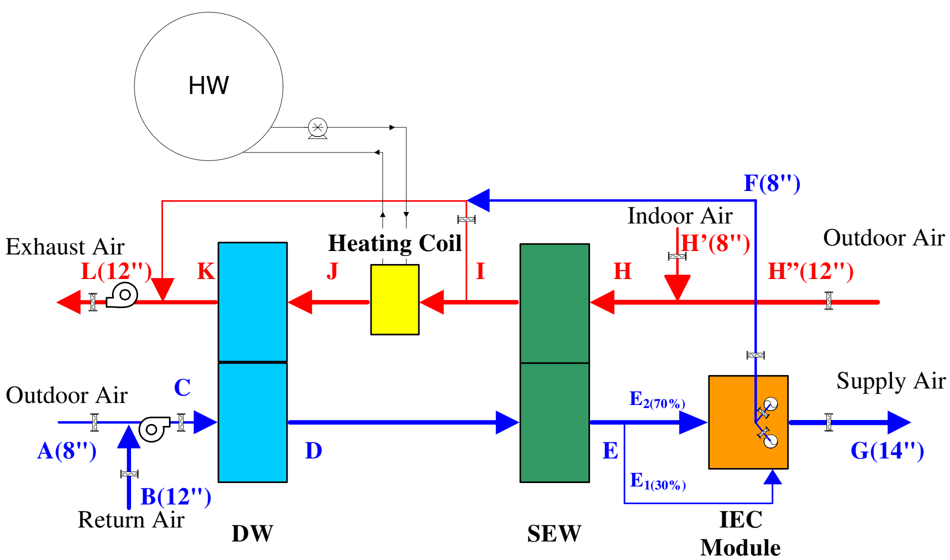


FIGURE 2: DESICCANT EVAPORATIVE COOLING SYSTEM SCHEMATIC.

The desiccant wheel is regenerated using a coil supplied by hot water from a gas fired domestic water heater. A sensible wheel is used after the desiccant wheel to pre-cool the process air. The wheel transfers excess heat to the regeneration air stream (reducing the load on the heating coil).

Indirect evaporative cooling (IEC) incorporates direct evaporative cooling and sensible heat transfer. The IEC core splits a single stream of air into product (primary) and working (exhaust) air streams. In this process, the product air stream flows through a precooling zone in the dry channels where sensible cooling begins. A portion of the product air is then split off and passed through wet channels on both sides of the dry channels. Consequently, the product air experiences sensible cooling while coming into contact with a heat exchange surface that has been cooled evaporatively within the heat exchanger. The heat from the product air is transferred through the plates from the dry side to the wet side where it is carried away as a warm humid working exhaust air stream. The product air gets progressively cooler as it works its way down the length of the heat exchange core. As a result, the product air is cooled below the wet bulb temperature and approaches the dew point temperature of the entering process air stream.

Sate A to C: On the process side, return air from the conditioned space (state A) and fresh outdoor air (state B) are mixed and introduced in the process air at state C.

State C to D: Air is dried, resulting in hot, and dry air at D.

State D to E: Hot and dry air is then cooled sensibly and heat is transferred to the regeneration air stream.

State E: Inlet of the IEC, the process air stream is split into two air streams.

State E to F: Air stream (E-E1-F) is humidified as it passes through wet channels and then enters the exhaust air stream.

State E to G: Air stream (E-E2-G) is chilled by passing through dry channels and is then supplied to the conditioned space, in the IEC its heat is transferred through the plates to the first stream (wet side) where it is carried away by the warm humid exhaust air stream.

State H" to H: On the regeneration side the air stream is a mix of mainly outside air (state H") and a small portion (state H') of indoor air (exhaust duct from the kitchen and bathrooms).

State H to I: Air is preheated by passing through the SEW to recover heat captured by the wheel's structure from the process air stream.

State I to J: Preheated air passes through a hot water coil, in which circulates hot water heated by a gas-fired heater. Air is thus heated up to the required regeneration temperature of the desiccant material.

State J to K: Hot air passes through the desiccant wheel in order to regenerate the desiccant. Warm and very humid air at state K is joined by the IEC wet air stream (F) before it is exhausted.

The desiccant evaporative cooling unit can operate in different ways to meet the indoor air cooling requirements. The system is controlled by a dehumidistat in conjunction with the usual thermostat: When only sensible cooling is needed (temperature over the set point), the process air blower and the indirect evaporative cooler will run to cool the air. The indirect evaporative cooler may continue to run to continue to cool the air if the conditioned space requires cooling. When dehumidification (latent cooling) and sensible cooling are needed, all the subsystems will run. When no sensible cooling is needed both process and regeneration fans are OFF.

THE CCHT TEST FACILITY

The Canadian Centre for Housing Technology features twin research houses, the Reference House and the Test House, to evaluate the whole-house performance of new technologies in side-by-side testing (Figure 3). Built to the R-2000 standard, the twin houses offer an intensively monitored real-world environment for energy performance and thermal comfort evaluation. Features of the houses are listed in Table 1. In addition to these features, the houses include a simulated occupancy system based on home automation technology that simulates the daily water draws and electrical loads of a family of four. The internal heat gains from the occupants are also simulated (Swinton *et al.*, 2001).

EXPERIMENTAL RESULTS

The experiment consisted first of operating the houses with identical setup and identical HVAC systems, in this case a conventional 13 SEER air conditioning system, to generate benchmark performance characteristics. The Desiccant Evaporative Cooling System (DEC) was then installed in the *Test House*, while the *Reference House* remained unchanged as a control. During the testing period, the resulting change in performance due to the DEC was documented relative to the benchmark configuration.

Monitored parameters during benchmarking and the test period included cooling energy consumption, and air temperature and relative humidity at a central location on each floor of the house.

TABLE 1: CCHT RESEARCH HOUSE SPECIFICATIONS

Feature	Details
Construction Standard	R-2000
Liveable Area	210 m^2 (2260 ft^2), 2 storeys
Insulation	Attic: RSI 8.6, Walls: RSI 3.5, Rim joists: RSI 3.5
Basement	Poured concrete, full basement Floor: Concrete slab, no insulation Walls: RSI 3.5 in a framed wall. No vapour barrier.
Garage	Two-car, recessed into the floor plan; isolated control room in the garage
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and sub-floor.
Windows	Low-e coated, argon filled double glazed windows Area: 35.0 m^2 (377 ft^2) total, 16.2 m^2 (174 ft^2) South Facing
Air Barrier System	Exterior, taped fiberboard sheathing with laminated weather resistant barrier. Taped penetrations, including windows.
Airtightness	1.5 air changes per hour @ 50 Pa (1.0 lb/ft^2)
Furnishing	Unfurnished

FIGURE 3: CCHT HOUSES

During benchmarking, the thermostat of each house was set to 24°C, while the humidity was left uncontrolled. Benchmarking results for main floor air temperature (as measured beside the thermostat), and second floor relative humidity are presented in Figures 4 and 5. In identical configuration, the air temperature and relative humidity in the houses track closely.

During the testing period, a humidistat was added to the house with the DEC system (the Test House) and was set to 50% RH. Two separate temperature setpoints were examined in the Test House during this period: 24°C and 25°C.

The main floor air temperature in the Reference House (with conventional HVAC system) and the Test House (with DEC), and also the outdoor temperature over the testing period are shown in Figure 6 and Figure 7. At a setpoint of 24°C, the DEC system was not able to maintain the average indoor temperature below the setpoint, unlike the A/C system in the Reference House, which was able to manage the sensible heat loads effectively. In Figure 6, the thermostat in the Test House with DEC system was set 25°C. At this higher setpoint, the DEC system did a better job of meeting indoor temperature requirements.

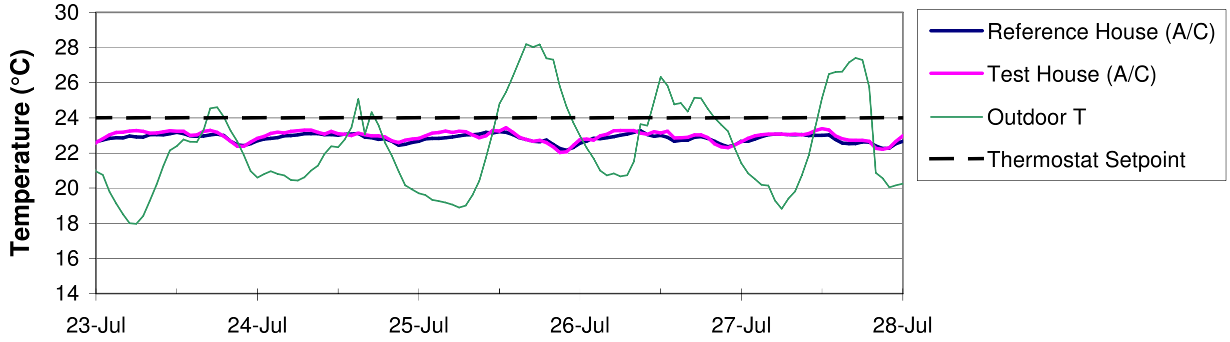


FIGURE 4: MAIN FLOOR AIR TEMPERATURE DURING BENCHMARKING

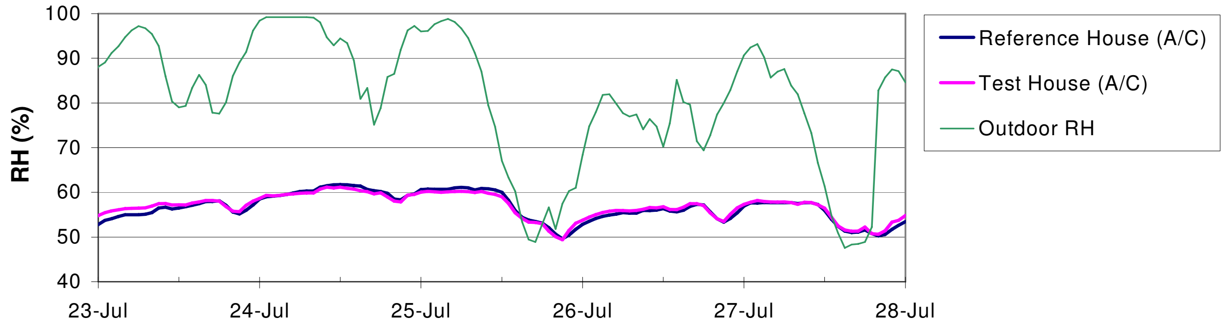


FIGURE 5: SECOND FLOOR RELATIVE HUMIDITY DURING BENCHMARKING

The indoor relative humidity on the second floor of the CCHT houses during the 24°C thermostat setting portion of the test period is shown in Figure 7. When the standard cooling system in the Reference House ran during the afternoon, RH dropped to the desired 50% level, however, when the setpoint temperature was satisfied, the air conditioning system stopped cooling and humidity levels rose. By contrast, the relative humidity in the Test House was lower compared to the value in the Reference House and was kept within a small range about the humidistat set point. This shows that the DEC offered better control of humidity in the house throughout the test period.

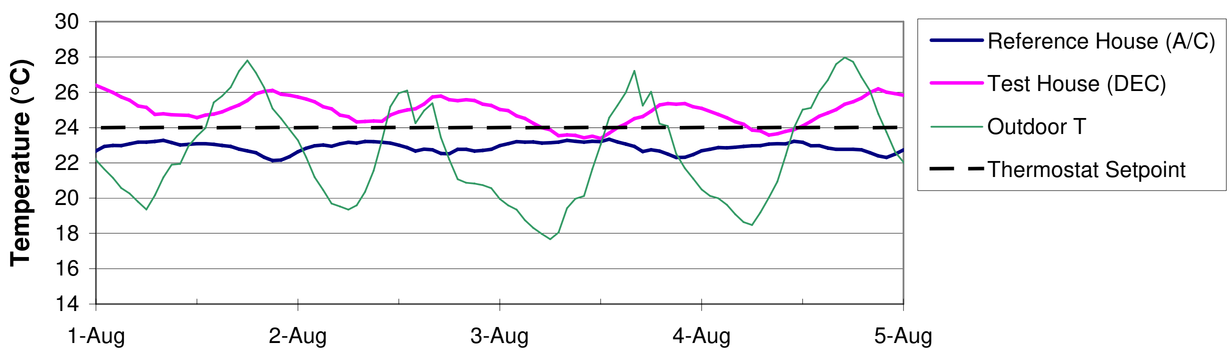


FIGURE 6: MAIN FLOOR AIR TEMPERATURE DURING DEC EXPERIMENT (24^{O}C SET POINT)

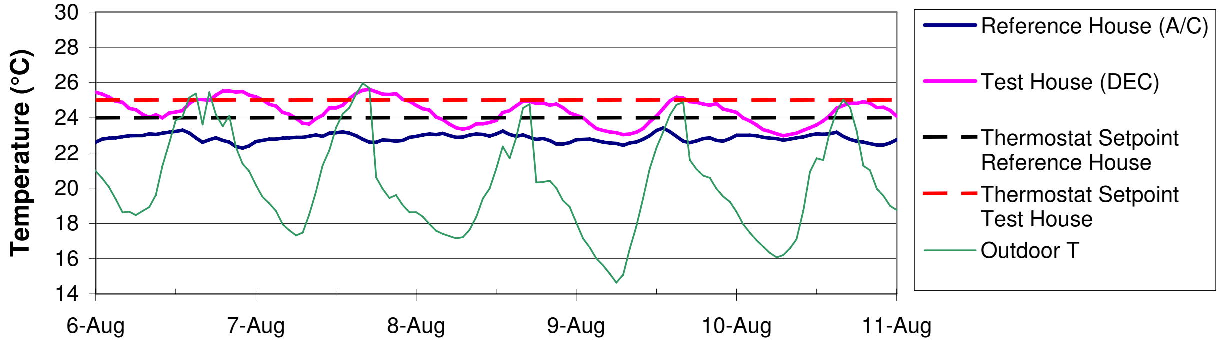


FIGURE 7: MAIN FLOOR AIR TEMPERATURE DURING DEC EXPERIMENT (25^{O}C SET POINT IN TEST HOUSE)

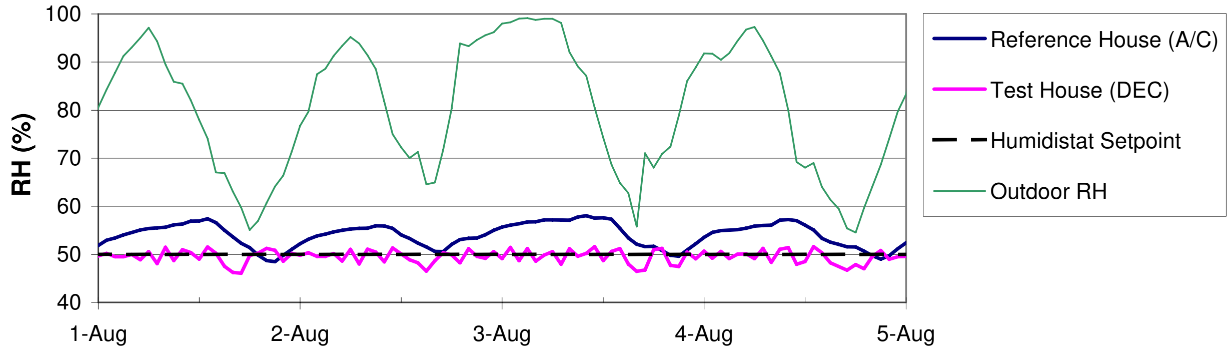


FIGURE 8: SECOND FLOOR RELATIVE HUMIDITY DURING DEC EXPERIMENT (24^{O}C, 50% RH SETPOINTS)

The experimental results showed the potential for a desiccant evaporative cooling to achieve better humidity control and comfort than the conventional HVAC system. However, experiments also demonstrated a much higher energy consumption of the DEC system compared to the conventional HVAC. On most days of the test period, the DEC system consumed more than twice the amount of electricity as the conventional system, and also required natural gas for the regeneration water heater (~6.5 to 23.4 m3/day), and water for the indirect evaporative cooler (~360 to 730 L/day). Several parameters affected the energy performance of the DEC system including regeneration temperature and fan motor efficiency. Additionally, the DEC system was located in the house basement and generated a substantial amount of heat, adding to the sensible heat load of the house. Thus, the DEC system has to deal with not only the existing house heat loads, but also its own additional heat. Heat sources of the DEC system included: fan motors; drive motors for the wheels, a water heater (providing heat for regeneration) and the circulation pump.

In order to improve the efficiency of the system, the system needs to be optimized, components with better electrical efficiency (for example electronically commutated motors) need to be introduced, and heat sources need to be minimized and/or isolated. One potential solution to minimizing heat gains is to install the system outside the house envelope, thus ensuring that all heat gains from the DEC system itself are lost to the exterior.

SIMULATION RESULTS

The simulation models are used with the TRNSYS software (Solar Energy Laboratory, 2006) to generate results for a house with the same characteristics as the CCHT house in Calgary, Halifax, Montreal, Ottawa, Saskatoon, Toronto, and Vancouver using actual weather data files for the year 2001 for the period June 1st – August 31st. These locations are chosen because they represent a good diversity in the fraction of the total load that is sensible. All the results are generated using a 5-minute time step.

Table 2 shows the sensible, latent, and total cooling demands predicted for all the seven cities using an ideal controller to maintain the first and second floor dry-bulb temperature below 25°C and relative humidity below 50%. These cooling demands do not include the contribution of the ventilation air and circulation fan heat toward the space cooling requirements. As expected, for a location such as Halifax, the latent loads represent a significant portion (25%) of the total cooling load. Whereas in the dryer climate of Calgary, latent loads represent only a small portion (6%) of the total cooling load. The average sensible heat ratio varies from a low of 0.714 for Vancouver to a high of 0.940 for Calgary.

TABLE 2: COOLING DEMAND USING IDEAL CONTROLLER FOR CCHT HOUSE

CITY	Q_s (KWH)	Q_l (KWH)	Q_t (KWH)	*SHR*
CALGARY	620.2	39.3	659.5	0.940
HALIFAX	695.4	226.9	922.3	0.754
MONTREAL	1511.9	276.5	1788.4	0.845
OTTAWA	1202.5	232.3	1434.8	0.838
SASKATOON	1033.2	139.5	1172.7	0.881
TORONTO	1736.8	176.5	1913.3	0.907
VANCOUVER	464.1	185.3	649.4	0.714

Figure 9 shows the variation of the second floor temperature (Operative, Dew-point, and Wet-bulb) for Ottawa when the house is cooled using a conventional air-conditioning system. In this case the wet-bulb temperature of the floor is continuously changing with the control of the dry-bulb temperature. This is similar to what was seen in the experiment results for the conventional system (Figure 8). The three temperatures in Figure 9 for the second floor are very close to those of the first floor due to the high mixing simulated between the two floors. The mean radiant temperature of the second floor is higher because of the high solar gains of this floor.

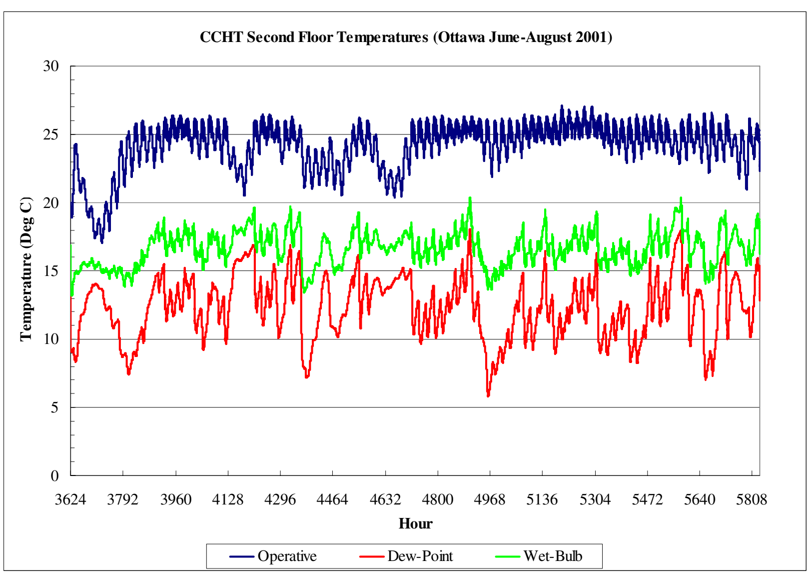


FIGURE 9: SIMULATION: SECOND FLOOR TEMPERATURES WITH CONVENTIONAL SYSTEM FOR OTTAWA

Figure 10 shows the variation of the second floor temperature when conditioned with a desiccant cooling system. In this case the controlled wet-bulb temperature is maintained around the set point of 18°C. In contrast to the conventional system, in the case of the desiccant cooling system, active dehumidification is triggered only when the wet-bulb temperature reaches a maximum threshold.

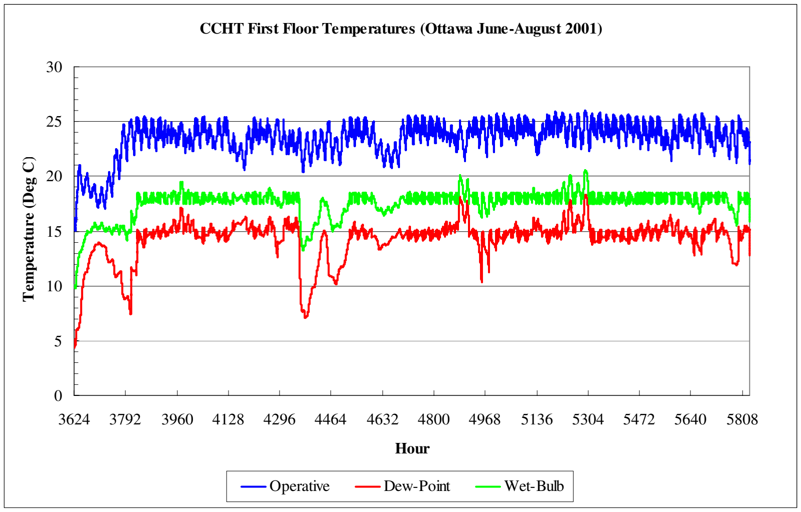


FIGURE 10: SIMULATION: SECOND FLOOR TEMPERATURES FOR SUMMER 2001 FOR OTTAWA USING DEC SYSTEM ($T_{G,I}$ = 70^{O}C; TOTAL FLOW = 0.64 M^3/S).

ASHRAE Cooling Comfort Zone

The ASHRAE comfort zone for cooling, as specified in the ASHRAE Handbook of Fundamentals (1997), is bounded at the top by the constant wet-bulb temperature line T_{wb} of 20°C and the bottom with the constant dew-point temperature line T_{dp} of 2°C. The maximum allowable operative temperature on the x-axis is 27°C at T_{dp} = 2°C and 26°C at T_{wb} = 20°C.

The operative temperature of 25°C and a relative humidity of 50% (T_{wb} = 18 °C) are right at the centre of the summer comfort zone. In this study it is assumed that discomfort inside the occupied space occurs when either of the following conditions is true:

- $T_{db} > 26.5$ °C
- ($T_{wb} > 18.5$ °C) and ($T_{op} > 23$ °C)
- ($T_{dp} < 2$ °C) and ($T_{op} > 23$ °C)

Figure 11 shows the predicted total hours of discomfort for the second floor of the house. The number of hours of discomfort for the first floor, not shown in the graph, is lower because of the lower solar gains and the cooling effect from the basement.

Figure 12 shows the predicted total number of hours of discomfort for the second floor with the desiccant system installed. For all the cities considered, with the exception of Calgary and Toronto, there is a substantial reduction in the predicted total number of hours of discomfort. This reduction is especially pronounced in Halifax, which has a high latent load ratio. It is evident that the desiccant system is especially well suited for areas where the latent loads are high. For Calgary and Toronto, the desiccant system results in fact in an increase in the total number of hours of discomfort. In these areas with relatively low latent loads, the operation of the indirect evaporative cooler leads to an increase in discomfort caused by a decreased ability to control temperature, and thus conditions are too hot (humidity is not much of an issue in these locations).

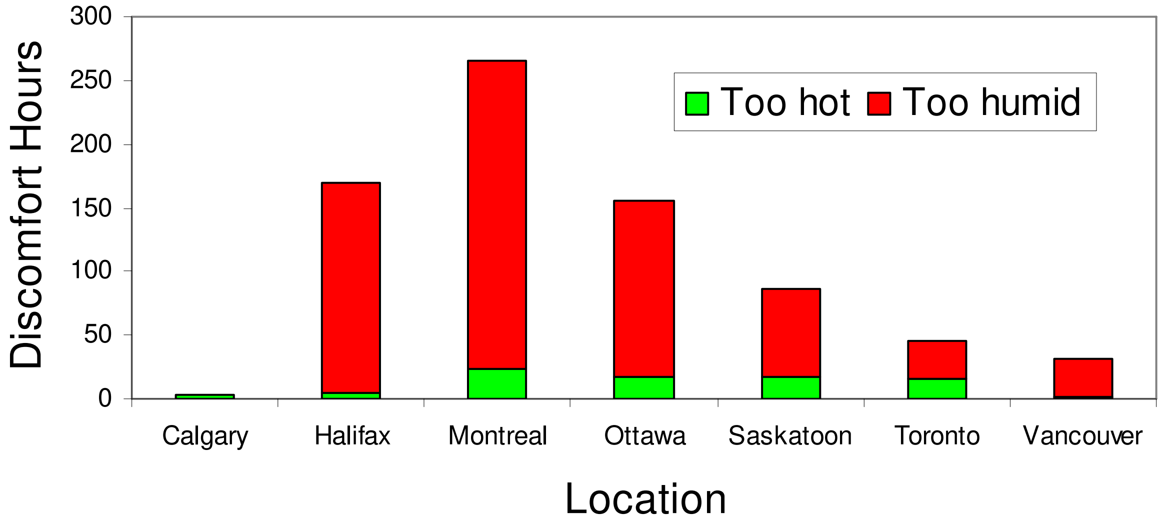


FIGURE 11: SECOND FLOOR TOTAL HOURS OF DISCOMFORT OF THE HOUSE WITH CONVENTIONAL SYSTEM

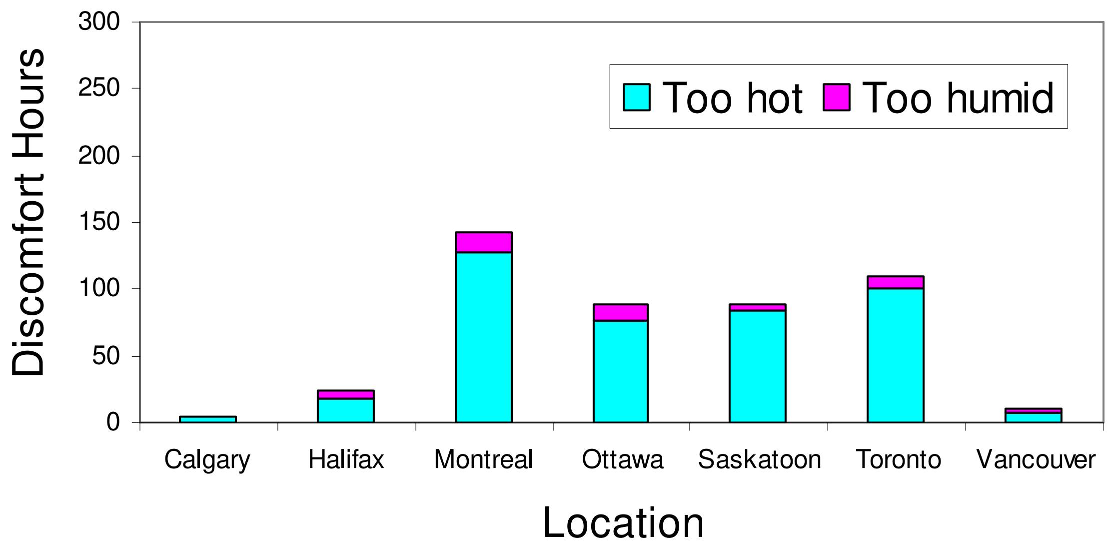


FIGURE 12: SECOND FLOOR TOTAL HOURS OF DISCOMFORT OF THE HOUSE WITH DEC SYSTEM

CONCLUSION

The desiccant based evaporative cooling system offers a promising alternative to conventional air-conditioning systems using vapour compression refrigeration especially under conditions involving high latent load.

Both simulation and experiments showed that the desiccant evaporative cooling system has significant potential for reducing the occurrence of uncomfortable high indoor humidity levels that tend to occur in humid weather.

In simulated areas with relatively low sensible heat ratios; the desiccant system is expected to be more effective at maintaining comfort levels than the conventional air conditioning system. In areas with high sensible heat ratios the use of the desiccant system with indirect evaporative coolers can potentially increase the total number of hours of discomfort.

The field experiments conducted using the twin CCHT houses showed higher energy consumption of the prototype Desiccant Evaporative Cooling system (DEC) compared to the Conventional HVAC. Potential measures to reduce the electrical consumption include: (1) higher and stable regeneration temperature (2) use of an advanced variable frequency drive, or an ECM motors (3) improve the Indirect Evaporative Cooler performance and (4) minimize or isolate heat gains from the system components.

ACNOWLEDGEMENTS

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