Assessing the Impact of Control Algorithms in Direct Evaporative Cooling Systems in Mixed-mode Buildings

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Abstract

Direct evaporative cooling (DEC) is one of the most commonly used cooling systems in many parts of the world with mainly hot and dry climatic conditions. Various simulation-based studies have been conducted to explore the potential of direct evaporative cooling in buildings. However, current dynamic thermal simulation tools use a simplified on/off control approach and do not allow modelling of situations where advanced algorithms are used in controlling DEC units. This paper couples EnergyPlus with Dymola® to simulate and assess the benefits of sophisticated control strategies for DEC units in mixed-mode buildings. This is a novel simulation approach for investigating control of DEC units in buildings that provides great flexibility for investigating future advanced control algorithms. The simulated results suggested that using the proposed sophisticated control algorithms for DEC units it is possible to achieve energy savings up to 35% compared to the base-case scenario and achieve up to 92% comfort hours for Ahmedabad, India. Similar results were predicted for Gatwick, UK.

Introduction

Evaporative cooling operation is based on the processes of heat and mass transfer (José Rui Camargo, Ebinuma, & Silveira, 2005). The two fluids that are used are water and air: when the water evaporates it absorbs energy from the air resulting in a cooling effect (Jain & Hindoliya, 2014). Direct evaporative cooling (DEC) occurs when the water and the air come into direct contact, and the transfer of energy from the air to the water takes place when the air has relative humidity less the 100% (Jain & Hindoliya, 2014). In a DEC system a fan forces the air through a wet surface for evaporation. The heat and mass transfer between air and water results in a decrease of the air dry-bulb temperature and increase of its humidity levels, and in an ideal case, this process is adiabatic (Watt & Brown, 1997). The minimum temperature that can be reached is determined by thermodynamics and is the wet–bulb temperature of the incoming air. Consequently, this process is more efficient when the levels of the relative humidity of the incoming air to the evaporative cooler are low. The effectiveness of a DEC is defined as (Jain & Hindoliya, 2014):

$$\varepsilon_{satur,effic} = \frac{T_{db}^{in} - T_{db}^{out}}{T_{db}^{out} - T_{wb}^{out}} \qquad (1)$$

Based on its characteristics, DEC is most suited to regions with hot and dry climatic conditions but it can be used in other climatic conditions too (J. R. Camargo, Godoy Jr, & Ebinuma, 2005; José Rui Camargo et al., 2005; Jain & Hindoliya, 2014). In countries with high demand for cooling, such as India, alternative cooling systems can provide thermal comfort that consume less energy compared to vapour compression mechanical cooling systems, such as split air-conditioning units.

The design of a DEC will depend on the material of the cooling pad. Common materials that are used are grass, aspen and khus (Jain & Hindoliya, 2014). Previous studies have examined the performance of DEC systems based on different pad materials. Barzegar, et al., (2012) used pad materials made by kraft and nssc corrugated papers and evaluated their performance experimentally. They concluded that cooling/saturation efficiencies can be improved by decreasing air velocity at the inlet of the cooling pad. Similarly, Jain & Hindoliya, (2014) examined different cooling pad materials, typically used in the Indian context, and found the performance of the DEC is inversely proportional to the mass flow rate of the inlet air. Depending on the pad material, the increase of the flow rate can result in up to 15% reduction on the performance of the DEC. Al-Sulaiman, (2002) predicted maximum efficiency for air velocities of 2.4m/s, whilst for higher air velocities the drop in the efficiency was substantial. Similarly, Wu, Huang, & Zhang, (2009) using a theoretical model based on the frontal air velocity and the thickness of the cooling pad, concluded that the most important parameter to determine the efficiency is the air velocity with the optimum value 2.5m/s.

Although several studies have highlighted the importance of optimum air velocity, there are no studies, to the authors' knowledge, assessing the impact of sophisticated control strategies for a DEC system for simulation purposes. The use of sophisticated control strategies is important for controlling the air velocity and hence improving the efficiency of the DEC unit. Dynamic thermal modelling (DTM) tools, such as EnergyPlus, use a simplified On/Off control approach and often assume constant saturation efficiency of direct evaporative coolers. However, since the saturation efficiency varies with the mass flow, it is not accurate to assume constant saturation efficiency in the simulations (Jain & Hindoliya, 2014). The innovation of this research presented here lies in the proposed control strategies that utilise a variety of control algorithms that control the fan speed and hence control the air velocity at the inlet of the cooling pad. The variation of the saturation efficiency also improves on the control approach currently being used by a wide range of DTM tools.

Using a co-simulation approach, this paper evaluates the benefits of using advanced control algorithms for DEC units in mixed-mode buildings, which are buildings operating in both mechanical and passive modes. To address this task, the following objective was followed: use of constant and variable fan flow to examine the impact of the variation of mass flow on the saturation efficiency and hence on the performance of the DEC unit. The benefits of advanced control algorithms are also assessed for two geographic location and climate zones.

Methods

Computer simulations were carried out to evaluate the performance of the different control strategies. EnergyPlus with Dymola® were used for the co-simulations and to assess the benefits of advanced control strategies for DEC systems in mixed-mode buildings. These were considered to be located in both Ahmedabad, India and London Gatwick, UK to represent different climates. EnergyPlus is used to design the building envelope, while Dymola is used to develop the control strategies. The focus of this paper is to evaluate and quantify the benefits of using more advanced control strategies for DEC systems compared to those that can be found in the majority of DTM tools. To eliminate the uncertainties associated with the building envelope, the BESTEST Case 600 (Henninger & Witte, 2011) was used to represent a single thermal zone building.

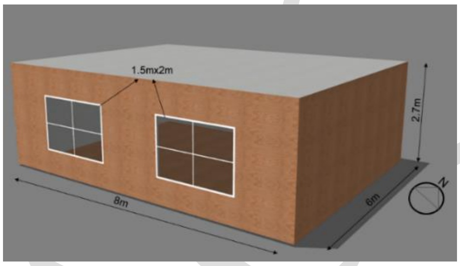

Figure 1: Layout of the single thermal zone building:

Table 1: Envelope characteristics and DEC input parameters

Element	U-value $\left[\frac{W}{m^2K}\right]$
Wall	0.514
Roof	0.318
Floor	0.039
Window	2.721
DEC Unit	
Cooling pad area [m^2]	0.18
Cooling pad depth [m]	0.1
Maximum air flow [m^3/s]	0.25

The floor area of the building is 48 m^2 and has two south facing windows 3m^2 each (see Figure 1). The occupancy density was assumed to be 16 m^2/occupant and the total internal electrical gains were 19.3W/m^2 as used in previous work investigating the performance of dynamic cooling setpoints for mixed-mode buildings (Angelopoulos et al., 2018). Table 1 summarizes the envelope characteristics employed and the input parameters for the DEC unit. Default weather files provided by EnergyPlus were used for this study (EnergyPlus WeatherData, 2018).

Co-simulations

As mentioned in the Introduction, the majority of DTM tools use a simplistic On/Off approach to control a DEC. The reason for this is that the main focus of DTM tools is to perform annual energy performance simulations and not to design advanced control strategies for mechanical or passive systems (Nouidui, Wetter, & Zuo, 2014). Therefore, to improve the performance of the DTM tools, co-simulations have recently attracted great attention. The coupling of two or more simulation tools can be achieved using the Functional Mock-up Interface (FMI), which is a standardised method to couple different simulation tools (MODELISAR, 2017). The use of the co-simulations has the advantage of combining the strengths of each simulation tool.

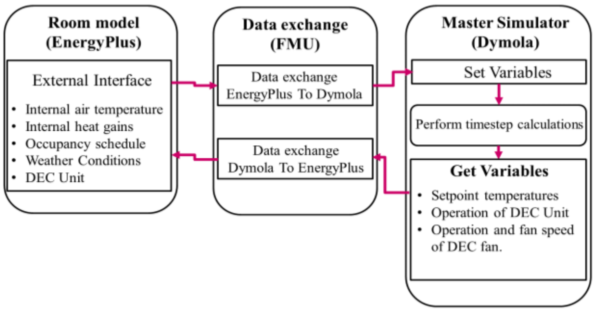

Figure 2: Variable exchange between the two simulation tools

For this reason, the building envelope, the evaporative cooler (AIRLOOPHVAC object) and the cooling pad, as well as the schedules for the occupants and the electrical equipment usage, were developed in EnergyPlus (DOE, 2018), see figure 2. The control algorithms for the DEC system were developed in Dymola which is a commercial tool based on the Modelica language (DYMOLA, 2018). The EnergyPlus model was then exported in a Functional Mock-up Unit (FMU) and imported into Dymola. The exchange of variables occurred between the two simulation tools at each timestep (300 sec). Dymola handled the co-simulations and it was responsible for "calling" EnergyPlus at each timestep and to exchange the required information. This process is completely automated and occurred at each timestep throughout the simulation period. This simulation technique provides great flexibility since the same control algorithms can be used in different cases, if the case is imported to Dymola via the FMU.

Control algorithms

To fully examine the effect of the variation of the fan speed, as well as the variation of the saturation efficiency based on the airflow rate, different control algorithms were developed and simulated. Since the focus of this paper is to examine the benefits of using advanced control algorithms for DEC systems and not to investigate the actual performance of mixed-mode buildings, it is assumed that the windows will remain closed throughout the simulation period, which is from January to December (inclusive). The design of the control algorithms has focused solely on the control of the evaporative cooler and its components.

In the literature, there is not a common approach on how to operate or control a DEC unit. In EnergyPlus, you cannot assign directly a cooling setpoint temperature to the AIRLOOPHVAC system. For this reason, the cases that were simulated on EnergyPlus did not have a direct control of the temperature and the control of the DEC unit was based on the occupancy schedule. For the co-simulations, the adaptive comfort model from ASHRAE Adaptive Standard 55 (ASHRAE-Standard-55, 2013) was used to determine the heating and cooling setpoint. A 30-day running mean for the outdoor temperature $(T_{out})$was used to calculate the heating and cooling setpoint temperatures for the 90% acceptability limits:

$$T_{HSP} = 0.31 * T_{out} + 15.3 \tag{2}$$

$$T_{CSP} = 0.31 * T_{out} + 20.3 \tag{3}$$

Variation of control algorithms for co-simulations

The design of the control algorithms has a gradually increasing complexity. The “basic” control algorithms use a similar methodology to the majority of the DTM tools. The control of the DEC systems is based on the On/Off approach of the evaporative cooler and the fan. When there is a need for cooling, the control algorithms turn on the evaporative cooler without any extra control over the fan speed. The fan operates at its maximum airflow, see table 1. The decision to operate or not the DEC takes place at the beginning of each timestep. When the unit operates, it runs at the full design air flow rate regardless of the required amount for cooling. This control method might not be optimal but it is similar to how most thermostats operate in real applications. To eliminate the short cycling of the DEC unit, a deadband of 0.5°C is used. The value of the deadband was selected by carefully adjusting it in trial simulations to ensure the maximum comfort conditions. The control algorithm, see figure 3A, uses as inputs the most recent value of the zone air temperature $(T_{int,aver})$ and the current cooling setpoint(T_{CSP}). This approach has a disadvantage of operating the DEC unit at full load at periods when there is no need for this amount of cooling. However, this is the most common control approach found in DTM tools.

The “advanced” control algorithms used a more detailed approach to control the DEC unit and the fan. For the “advanced” control algorithms a variable speed fan, with 3 fan speed levels (33%, 66% and 100% of its maximum air flow), was used instead of a constant volume fan that was used in the previous cases. This control method uses a more sophisticated approach to modulate the fan speed based on the required cooling load at each timestep. At each timestep,part load fraction (PLF) is calculated. PLF is the cooling load that is required for the zone is calculated in Dymola, divided by the maximum value of the cooling load that the DEC unit is capable of providing. To avoid running the DEC unit at periods when there is no need for cooling, a deadband 0.5°C value for the temperature is used. This control approach eliminates the cases where the unit is turned on and off constantly. Then the sensible cooling provided by the unit $\dot{Q}_{FULL,OUTPUT}$ is calculated and compared against the cooling load of the zone $\dot{Q}_{COOLING\ LOAD}$ as presented in figure 3B.

The power consumption of the variable speed fan was calculated by calculating the required mass flow for each timestep,$\dot{m}_{timestep}$, and then calculating the flow fraction $f_{flow} = \frac{\dot{m}_{timestep}}{\dot{m}_{design}}$, where $\dot{m}_{design}$ is the maximum flow. Then the total power consumption was calculated by using the formula: $P_{total} = RTF\left[\frac{\dot{m}_{timestep}\Delta P}{\varepsilon_{total}\rho_{air}}\right]$

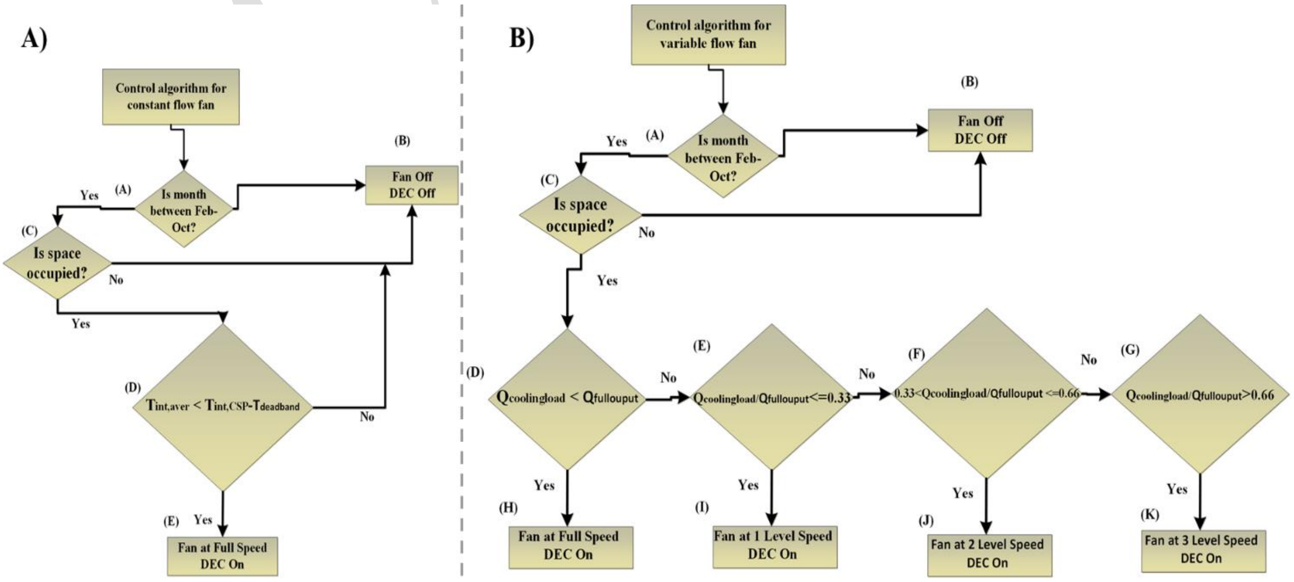

Figure 3: Control algorithms for constant(left) and variable fan flow(right)

where $RTF = \frac{f_{flow}}{PLF}$ and ΔP is the fan design pressure increase in Pascals.

Detailed modelling of saturation efficiency

The default selection for most DTM tools is to use a cooling pad with a constant saturation efficiency. The efficiency is determined by manufacturers' data and the modeller can only decide what would be the area and the thickness of the pad.

Then by using equation (1) the dry-bulb temperature of the outlet air can be calculated. As equation (1) shows, the calculation of the outlet temperature is not related to the mass flow of the inlet air which contradicts findings from the literature suggesting, that the saturation efficiency is highly affected by the air frontal velocity (Jain & Hindoliya, 2014; Sheng & Nnanna, 2011). EnergyPlus has also an object that provides the flexibility to the user to include an equation to vary the saturation efficiency based on the frontal air velocity. Jain & Hindoliya, (2014) examined a variety of pad materials that are typically used in the Indian context. For the purpose of this research it was assumed that palash fibers were used as the cooling pad material and based on experimental observations by Jain & Hindoliya, (2014) the correlation between the saturation efficiency and the frontal air velocity for this material is given by equation (4):

$$\varepsilon_{satur,effic} = 1 - e^{-\frac{4.606}{{m_a}^{0.2}}} \qquad (4)$$

where m_a [kg/h] is the mass flow of the air entering the cooling pad.

For this paper, both cases, with constant and variable saturation efficiency, were used to compare whether this influences the total thermal performance of the DEC unit.

Control Strategies

The simulations are divided into the base case scenarios, where only EnergyPlus was used (scenario 1& 2) and to the cases where co-simulations were performed to incorporate the advanced control strategies proposed in this paper, see table 2.

For all the simulation scenarios (1-10) it was assumed the DEC unit is available between March-October (inclusive) and only when the house was occupied. For the base case scenarios (scenario 1 & 2), the operation of the DEC unit was based on the occupancy schedule. When occupants were present between March-October, DEC was modelled to turn on without any extra control algorithm whilst for the rest of the scenarios the advanced control algorithms were used, see table 2.

Table 2: Simulation scenarios

<table>
<tr><th colspan="4">Base Case scenarios – DTM simulations</th></tr>
<tr><th>Scenario</th><th>Saturation efficiency</th><th>Fan speed</th><th>Control parameter</th></tr>
<tr><td>1</td><td>Constant</td><td>Constant</td><td>-</td></tr>
<tr><td>2</td><td>Variable</td><td>Constant</td><td>-</td></tr>
<tr><th colspan="4">Co-simulations</th></tr>
<tr><th>Scenario</th><th>Saturation efficiency</th><th>Fan speed</th><th>Control parameter</th></tr>
<tr><td>3</td><td>Constant</td><td>Constant</td><td>Zone air temperature</td></tr>
<tr><td>4</td><td>Constant</td><td>Constant</td><td>Zone air temperature and RH</td></tr>
<tr><td>5</td><td>Variable</td><td>Constant</td><td>Zone air temperature</td></tr>
<tr><td>6</td><td>Variable</td><td>Constant</td><td>Zone air temperature and RH</td></tr>
<tr><td>7</td><td>Constant</td><td>Variable</td><td>Zone air temperature</td></tr>
<tr><td>8</td><td>Constant</td><td>Variable</td><td>Zone air temperature and RH</td></tr>
<tr><td>9</td><td>Variable</td><td>Variable</td><td>Zone air temperature</td></tr>
<tr><td>10</td><td>Variable</td><td>Variable</td><td>Zone air temperature and RH</td></tr>
</table>

Results analysis and Discussion

This section presents whether there is any impact as a result of i) different control strategies and ii) different methods to model the evaporative cooler, constant or variable saturation efficiency, on the thermal performance of the DEC unit and hence on the overall energy consumption. Additionally, it analyses the comfort hours that could be achieved under the different simulation scenarios.

Figure 4 illustrates the annual predictions for internal air temperature for the scenario 1 and 3 for Ahmedabad.

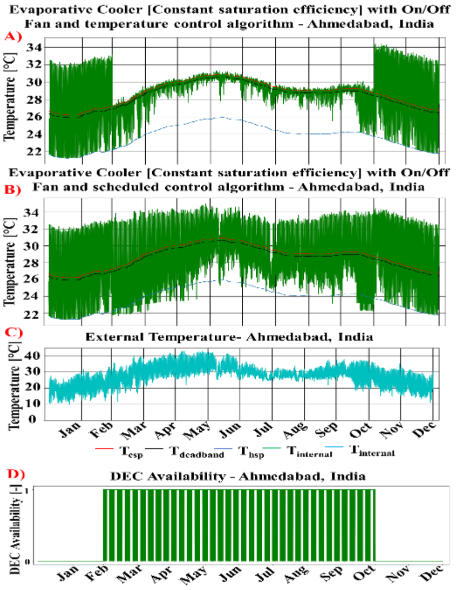

Figure 4:Predicted internal air temperature for Ahmedabad for scenario 3 (fig 4A), and scenario 1 (fig 4B); outdoor air temperature (fig 4C) and DEC availability (fig 4D).

As expected, the absence of sophisticated control algorithms, figure 4B, resulted in internal temperature outside the comfort limits. Specifically, on average the internal air temperature was 2~4°C higher than that recommended by the thermal comfort models. The lack of a control algorithm to maintain the air temperature within the comfort limits affected the performance of the DEC unit even during periods when the external temperature was low. As figure 4B shows, during February and September, the internal air temperature was lower than the lowest acceptable comfort limit. The reason for this is that the external temperature (figure 4C) was low at these periods and the control logic did not include temperature control hence the heating system was not able to meet the heating demand. As these results suggested, the use of very simplistic control algorithms, base case, results in uncomfortable internal conditions. It is essential therefore to include more advanced control algorithms that incorporate temperature control in their logic (co-simulation scenarios 3-10). By incorporating the temperature control logic, the thermal performance of the DEC unit was improved significantly compared to the base case scenarios, figure 4A. The use of a deadband temperature was deemed important to improve the performance of the DEC unit. The periods of the year that the DEC unit is available can be seen, as indicated in figure 4D. The inclusion of temperature control logic into the control algorithms had a positive impact on both cooling and heating energy consumption. As it can be observed, the predicted air temperature is always equal to or higher than the lower band for thermal comfort in contrast with the base case where the uncontrolled operation of the fan resulted in internal air temperatures lower than that suggested by the thermal comfort model.

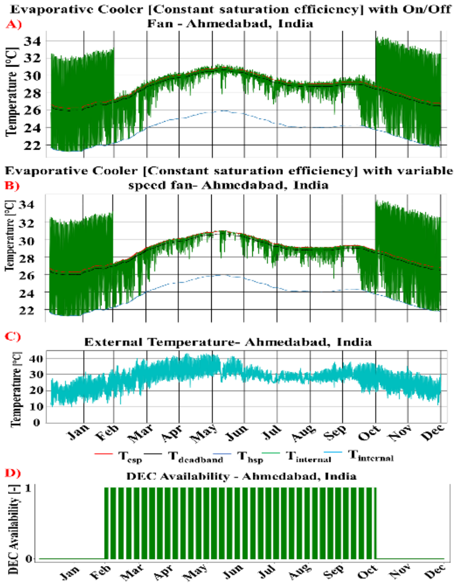

Figure 5: Predicted internal air temperature for Ahmedabad for scenario 3 (fig 5A), and scenario 7 (fig 5B); outdoor air temperature (fig 5C) and DEC availability (fig 5D).

The use of a variable fan speed improved the thermal performance of the DEC unit over the use of a constant volume fan (figure 5B and figure 5A respectively). By calculating the required cooling load and modulating the fan speed based on this, it was possible to improve further upon the overall improved thermal performance. The fluctuations of the predicted temperature were smaller compared to the case of the constant volume fan due to the operation of the fan at different speeds. As figure 5 suggests, the control of the variable fan speed based on the sophisticated control algorithms suggested in this research (figure 5B) could ensure that the internal air temperature will be maintained within the comfort limits for most of the period.

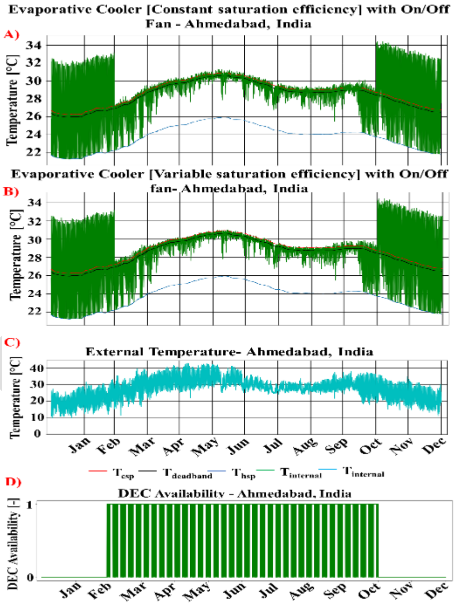

Figure 6: Predicted internal air temperature for Ahmedabad for scenario 3 (fig 6A), and scenario 5 (fig 6B); outdoor air temperature (fig 6C) and DEC availability (fig 6D).

The variation of the saturation efficiency based on the mass flow of the air had a higher positive impact on the On/Off fan, see figure 6B. As suggested in figure 6B, the thermal performance of the DEC unit improved substantially between April to September compared to the constant saturation efficiency scenario (figure 6A). For the variable speed fan, the improvement of the thermal performance based on the temperature predictions is less because, even with the constant saturation efficiency, the DEC unit was still very effective.

DEC units can increase the levels of relative humidity (RH). Hence, it was important to examine how each scenario impacts the levels of RH in the zone. The levels of RH inside the zone are high, especially during the months of the year that the DEC unit operates. An additional check was made in the control algorithm regarding the level of the internal RH. When RH was equal to or less than 70%, the DEC unit was available, otherwise it remained off. Figure 7 shows the variation of the internal air temperature when the RH was used as a control parameter (figure 7B). The inclusion of the RH as the control parameter slightly improved the levels of the internal RH but it resulted in less hours of operation of the DEC unit and, as a result, the internal air temperature was higher. Furthermore, due to high internal air temperature when the DEC unit was turned off, the system could not reach the setpoint temperature when it was in operation.

Due to the high levels of external RH in addition to the internal RH, it is not feasible to maintain the internal RH or the internal air temperature within the limits without the use of mechanical systems.

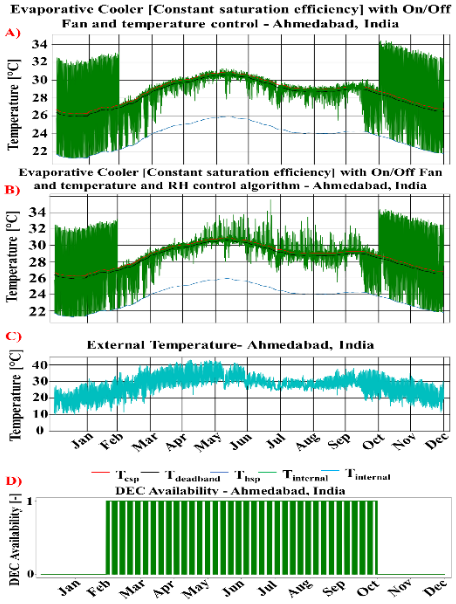

Figure 7: Predicted internal air temperature for Ahmedabad for scenario 3 (fig 7A), and scenario 4 (fig 7B); outdoor air temperature (fig 7C) and DEC availability (fig 7D)

The inclusion of the RH as part of the control logic is important for all the cases when DEC units are used. As the analysis showed however, during the periods of the year that the levels of outside RH were high, the internal RH was found to be high as well. Hence, from a practical point of view, mechanical systems to maintain the RH within the desirable limits throughout the year deem essential. However, the purpose of this paper is not to include any additional mechanical systems, but to investigate how intelligent control algorithms can improve the thermal performance of the DEC unit.

It is very important to present the hours of the year that the proposed control algorithms could maintain a thermally comfortable internal environment. To calculate the comfortable hours, two different approaches were used. In this research the comfortable hours were measured i) firstly using the operative temperature (ASHRAE-Standard-55, 2013), and ii) secondly using the operative temperature and the levels of RH. For RH values above 70%, irrespective of the internal operative temperatures, these periods did not count as comfortable hour. Table 3 summarizes the results for the comfortable hours for each scenario. It should be mentioned that the percentages are referring to the periods when the space was occupied between March-October (both months included) and not to the whole year.

Table 3: Summary table for percentage of comfortable hours. In the brackets are the numbers of comfortable hours.

				Ahmedabad		**Gatwick**	
Scenarios	**Saturation efficiency**	**Volume fan**	**Control parameters**	**Operative temperature as parameter**	**Operative temperature and RH as parameter**	**Operative temperature as parameter**	**Operative temperature and RH as parameter**
1.	Constant	Constant	--	50.2% [2161]	47.6% [2049]	89.4% [3848]	69.2% [2978]
2.	Variable	Constant	--	48.1% [2070]	45.3% [1950]	77.3% [3327]	64.3% [2806]
3.	Constant	Constant	$T_{zone,air}$	82.6% [3555]	61.5% [2647]	85.7% [3689]	64.8% [2789]
4.	Constant	Constant	$T_{zone,air}$ &RH	77.1% [3318]	57.2% [2462]	79.6% [3426]	59.8% [2473]
5.	Variable	Constant	$T_{zone,air}$	87.6% [3770]	66.2% [2849]	89.7% [3861]	74.6% [3211]
6.	Variable	Constant	$T_{zone,air}$ &RH	80.2% [3452]	62.4% [2686]	83.5% [3594]	69.7% [3000]
7.	Constant	Variable	$T_{zone,air}$	85.2% [3667]	65.2% [2806]	87.6% [3770]	72.5% [3120]
8.	Constant	Variable	$T_{zone,air}$ &RH	82.1% [3534]	61.2% [2634]	85.2% [3667]	68.5% [2948]
9.	Variable	Variable	$T_{zone,air}$	92.3% [3973]	72.1% [3103]	95.4% [4106]	79.8% [3435]
10.	Variable	Variable	$T_{zone,air}$ &RH	85.6% [3684]	67.8% [2918]	90.2% [3882]	72.2% [3108]

The inclusion of the RH as a parameter resulted in less comfortable hours which is expected as the levels of RH were very high, but it does not overestimate the comfortable hours as in the case where only the operative temperature is used. In Gatwick, the simulations predicted overall higher hours of comfortable internal conditions compared to Ahmedabad. This is due to the lower levels of RH in Gatwick in addition to the relatively smaller demand for cooling. Hence the DEC unit was able to meet the demand for cooling for longer periods compared to Ahmedabad. Significant differences were predicted in the energy consumption for the different scenarios (Figure 8).

To calculate the energy consumption, the consumption of the fan and the evaporative cooler (AIRLOOPHVAC object). As expected, the base case scenarios resulted in the higher energy demand predictions among the rest of the scenarios. The use of the very simplistic control algorithms for the DEC unit, based on the occupancy schedule (scenario 1-2), resulted not only in very high internal air temperatures and hence in thermally uncomfortable internal environments, but also in very high energy consumption. The control of the fan based on the On/Off approach (scenario 3-6) resulted in higher energy saving potentials for both Ahmedabad and

Gatwick compared to the variable fan speed (scenario 7-10). This can be explained because the On/Off fan operated for fewer hours compared to the variable fan speed. In instances where the On/Off fan was off, the variable fan speed operated at lower speed to meet the setpoint temperature. This resulted in slightly higher energy consumption, but also a higher percentage of thermally comfortable hours.

Table 4: Summary table of energy savings and comfort hours

Algorithms	**Ahmedabad**		**Gatwick**	
	Comfort Hours	**Energy Demand (cooling)**	**Comfort Hours**	**Energy Demand (cooling)**
Fan speed control	61.2-92.3%	25.0-30.9%	68.5-95.4%	117-120.8%
Temp control	57.2-82.6%	30.5-35.2%	59.8-89.7%	117.9-129.7%

When using both the air temperature and RH as a control parameter in the control algorithms, the co-simulations predicted higher energy saving potential compared to the rest of the scenarios. This can be explained because the DEC was turned off when the internal RH was above the limit. However, in those scenarios the analysis showed that the percentages of the comfortable hours were significantly smaller. Table 4 summarizes the energy savings and comfort hours for the different scenarios.

Conclusions

The research presented in this paper aims to develop and test control algorithms for DEC units for mixed-mode buildings in different climatic conditions and to quantify their energy saving potential using co-simulations. The development of improved simulation tools to achieve this is also described and presented. The most important findings are:

- The use of co-simulations can improve the thermal performance of DEC systems over the
- use of DTM tools and the proposed control algorithms can be used for co-simulations with any software that has the FMU import function;
- The use of advanced control algorithms in conjunction with constant fan speed and constant saturation efficiency cooling pad increased the number of comfortable hours by approximately
- 1000h in Ahmedabad compared to the basic control algorithms used by the DTM tools;
- The use of variable saturation efficiency cooling pads improved the thermal performance for energy consumption of the DEC unit between 2-8% for all the scenarios.
- The use of RH in the control logic of the control algorithms resulted in 2-5% lower internal RH compared to the scenarios without RH control.
- The DEC unit in combination with the proposed control algorithms can be used as the sole cooling system to maintain comfortable internal conditions for almost 95% of the time that was available in moderate climates such as Gatwick.
- The use of the internal RH to assess the comfortable hours is essential to enable more accurate predictions of the comfortable hours when a DEC unit is used.
- Current DEC units, in the residential market primarily, rely on the users to adjust fan speed as well as water pump operations. Further, these DEC units do not modify their operations automatically, based on the prevalent temperature or relative humidity in the space. As this research highlighted, the proposed control strategies have the potential to reduce the energy consumption of DECs while achieving better comfort in the space.

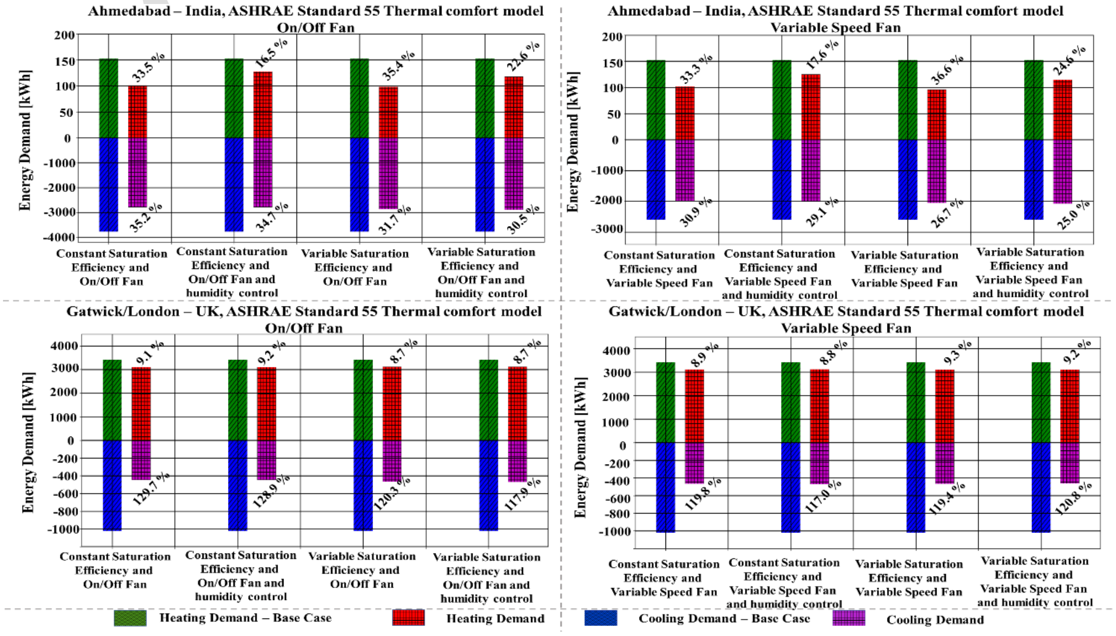

Figure 8: Predictions of the cooling and heating consumption for the different scenarios

- In real applications, many DEC units (cost-effective one) use plastic fibres and/or paper fibres coated with melamine. These fibres are worn out within time and age, ultimately affecting saturation efficiency. Other products do use corrugated boards, which does not get deteriorate quickly, so these materials should be used to maintain the thermal performance of the DEC unit. Additionally, the efficiency of the DEC unit is affected by the direct sunlight which results in lower performance. So, the DEC unit should not be exposed to direct sunlight for better performance.

Future work

The following work is proposed to improve even further the current study:

- Expand the control algorithm to include the control of the windows/dampers and ceiling fan.
- Include a dehumidifier as part of the control algorithm to mitigate the risk of uncomfortable internal conditions due to high levels of RH; and
- Validate the thermal performance of the proposed control algorithms using a full-scale environmental chamber.
- The cost implications of incorporating sophisticated controls and variable speed fan may also need to be studied further for real implementation.

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