INFLUENCE OF CONTROL STRATEGIES AND OCCUPANT BEHAVIOR ON ENERGY CONSUMPTION OF A DIRECT EVAPORATIVE COOLER IN TEHRAN

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ABSTRACT

This paper looks into the influence of occupant behavior on the electricity consumption of a manually controlled DEC and comparing it with one that is controlled automatically by a thermostat. Based on the adaptive thermal comfort theory, an algorithm for manual control of windows and DECs is proposed and it is integrated in the EnergyPlus software by its Energy Management System (EMS) feature. The results show that the electricity consumption of a thermostat controlled DEC is strongly related to setpoint temperature; for instance, at the setpoint temperature below 26 ºC a thermostat controlled DEC consumes more electricity than a manually controlled one. However, at setpoint temperature 29 ºC -which it provides the same amount of thermal comfort as a manually controlled one- the electricity saving is about 60%.

INTRODUCTION

Tehran, the capital and the most populated city of Iran, is located in longitude 35.4º E, latitude 51.19º N with elevation 1190 m. Tehran's climate is generally described as mild in spring and autumn, cold in winter and hot and dry in summer. This means the buildings in Tehran should be heated in winter, can be free-running in mid-seasons and should be cooled in summer. Direct Evaporative Coolers (DECs) are the most common cooling system for residential buildings in Tehran. About 80% of new buildings in Tehran are designed to use DEC as cooling system (Heidarinejad; et al., 2008).

In a Direct Evaporative Cooler, outside air is blown by a fan through a water-saturated medium and cooled by evaporation. During this Process, the dry bulb temperature of air is reduced, while its wet bulb temperature stays the same (Delfani et al., 2010). This system can be considered as a passive technique while the dry bulb temperature of air is decreased only by water evaporation (Steeman et al., 2009).

One of the weaknesses of conventional DECs in Iran is the lack of an automatic temperature control. Occupants control the indoor temperature manually by turning the whole system ON or OFF, or by adjusting the fan speed of DEC to LOW or HIGH. It means that the energy consumption of this system as well as the indoor thermal comfort are completely dependent on occupant behavior. Occupant behavior also greatly influences building energy consumption by occupation patterns, the way they use equipment, lighting systems and how often they open or close windows (Peng et al., 2012).

Several studies have been done to recognize the most influential parameters on occupant behavior, in order to prepare a mathematical model and to integrate it into simulation software. Nicol (2001) by analyzing the data from UK, Pakistan and throughout Europe proposed some probability algorithms relating occupant behavior to outdoor temperature. Lightswitch-2002 is another model which predicts the lighting energy performance of manually and automatically controlled electric lighting and blind systems in offices (Bourgeois et al., 2006). Tanimoto et al. (2008), based on their measurement, concluded that the probability of turning on an air conditioning system in a residential building is related to the indoor globe temperature while the probability of ongoing air conditioning is related to outdoor temperature. Some equations are proposed by Rijal et al. (2008) which show the relation of the probability of using the various controls (windows, fans, heating and cooling) to the indoor and outdoor temperature in 'mixed mode' buildings. Rijal et al. (2011) added the term "constraints" to their algorithms in order to quantify the accessibility, usability and desirability of available controls, and to incorporate any non-thermal benefits or adverse effects. Another model for occupant behavior is proposed based on stochastic Markov models by Virote and Neves-Silva (2012). Wilke et al. (2013) presented a bottom-up modelling approach together with a set of calibration methodologies to predict residential building occupants' time-dependent activities, for use in dynamic building simulations.

Due to the strong influence of occupant window-opening behavior on building air change rate (Howard-Reed et al., 2002) and respectively energy consumption, some studies focused in particular on this subject. Their aim was to recognize the most influential parameters on opening and closing the windows by occupants. Herkel et al. (2008) proposed a preliminary user model to simulate and predict window status in office buildings with varying outdoor temperature and occupancy. The stochastic models that are developed by Yun and Steemers (2008) predict window-opening behavior patterns as a function of indoor temperature, time of day and the previous window state. The strong influence of previous state of a window on the current window state is also revealed by Yun et al. (2009). A hybridized model is recommended by Haldi and Robinson (2009), (Haldi and Robinson, 2010) which combines the accuracy of the discrete-time Markov process with the efficiency of the continuous-time model for opening window durations. The results of a study on a naturally ventilated office building in Sheffield, UK shows that manual window control has a strong correlation with: outdoor air temperature, the season of year, time of a day and occupancy pattern (Zhang and Barrett, 2012). However, a study on Japanese houses indicated that the window opening correlated better with the indoor temperature than with the outdoor temperature (Rijal and Nakaya, 2012). On the other hand, measurements of occupant's window opening behavior in Denmark indicated that the CO_2 concentration (indoor quality) had an impact on the window opening probability while the outdoor temperature affected the closing probability (Andersen et al., 2013).

Thermostat setpoint temperature is another parameter that can lead to wide variations in energy consumption and peak demand (Parker; et al., 1996, Peffer et al., 2011). A sensitivity analysis on 9 different occupancy behavioral parameters of typical office buildings of different size and in different weather zones of USA revealed that the highest sensitivity was obtained when varying the 'heating temperature set point' parameter in small-size buildings located in cold and dry area (Azar and Menassa, 2012).

When the results of all these field studies and proposed models regarding occupant behavior are considered, it can be concluded that there is still no single shared approach to identify the driving forces for occupant behavior (Fabi et al., 2012). Moreover, because of the important role of different variables like climate, culture, building structure, space typology on occupant behavior (e.g. residential or office building), the results of these studies cannot be generally applied to other buildings (Herkel et al., 2008, Rijal and Nakaya, 2012). The existence of many uncertainties (Rijal et al., 2011) and over-simplification in data collection and analysis (Zhang and Barrett, 2012) are other reasons that emphasize the need for more research to fully understand human behavior in buildings (Peng et al., 2012).

This paper investigates the influence of occupant behavior on the electricity consumption of a manually controlled DEC and comparing it with one which is controlled automatically by a thermostat. The indoor operative temperature is considered as an independent variable for taking an adaptive action by occupants, because it is the outcome of several parameters such as building orientation, its envelope properties (insulation and thermal mass), internal heat gains, etc. (Yun and Steemers, 2008). Based on the adaptive thermal comfort theory, an algorithm for manual control of widows and DECs is proposed and it is integrated in the EnergyPlus software with its EMS feature.

METHODOLOGY

The aim of this study is to investigate the influence of the control strategy and occupant behavior on energy consumption of a DEC in a residential building in Tehran. To achieve this goal, a hypothetical room in a residential complex is simulated by EnergyPlus v. 8.0. This software is a dynamic thermal simulation engine and has been validated under the analytical and comparative tests (EnergyPlus, 2013b). In order to apply the defined algorithms for different control strategies into the software, the Energy Management System (EMS) feature in EnergyPlus is used. EMS provides a high-level, supervisory control to override selected aspects of EnergyPlus modeling by its special programming language called EnergyPlus Runtime Language (Erl) (ENERGYPLUS, 2013a). The annual hourly weather data of Tehran-Mehrabad is used in these simulations. This data is downloaded from the EnergyPlus website (EnergyPlus, 2013c).

Test room specifications

All simulations are carried out for a hypothetical room in a residential complex, which is prevalent in a compact urban area like Tehran. In this paper, this room is called "*test room*'' and its size is considered to be 3m (W) × 3m (H) ×4m (D). The test room has one external wall which is exposed to outdoor environment. A two-leaf double glazing window, which one of its leaves can be opened and closed by occupants, is considered in the external wall. The other three walls, floor, and roof of this room are exposed to rooms with similar temperature. Therefore, there is no heat loss/gain through these surfaces and they can be considered as adiabatic surfaces. However, these surfaces act as thermal mass, because they can store and release the thermal energy when the indoor temperature fluctuates (Yang and Li, 2008). Figure 1 shows a schematic of the test room.

Conventional materials in the local area are considered for the test room. Table 1 shows the material properties. Figure 2 shows the internal loads of the room which are based on a multifamily residential building according to ASHRAE 2005 HOF (EnergyPlus, 2013b).

Table 1: Construction and material properties of test room, ASHRAE 2005 HOF (EnergyPlus, 2013b)

CONSTRUCTION NAME	MATERIAL CODE	THICKNESS (MM)	CONDUCTIVITY (W/M.K)	DENSITY (KG/M3)	SPECIFIC HEAT (J/KG.K)
External Wall	F10 stone	25.4	3.17	2560	790
	Brick M19	200	0.51	600	790
	G01 gypsum	19	0.16	800	1090
Interior Wall	Brick M19	100	0.51	600	790
	G01 gypsum	19	0.16	800	1090
Ceiling and Floor	Concrete M19	100	1.75	2300	900

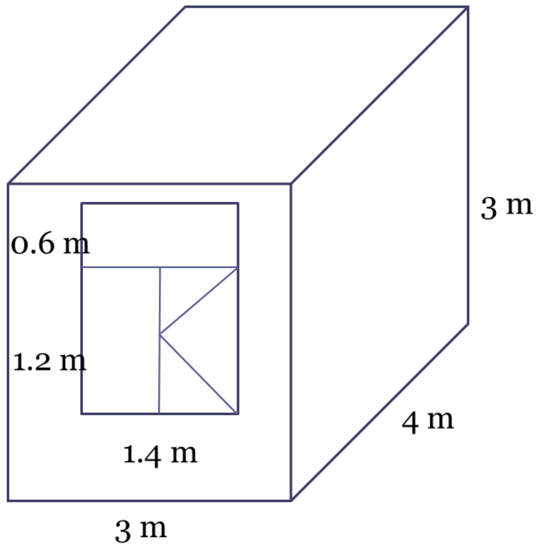

Figure 1: Schematic of the test room

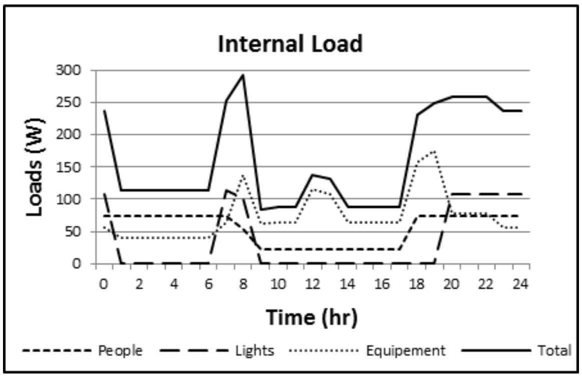

Figure 2: Internal loads for a multifamily residential building, according to ASHRAE 2005 HOF (EnergyPlus, 2013b)

Table 2: Specifications of assumed Direct Evaporative Cooler (DEC)

PARAMETERS	LOW FAN SPEED	HIGH FAN SPEED
Outdoor air flow rate (Kg/s)	0.1333	0.2000
Fan pressure (pa)	44.44	100
Circulating pump power (W)	10	10
Pad Area (m2)	0.15	0.15
Pad Depth (m)	0.1	0.1
Fresh air (%)	100	100

The algorithm of manual control for window and DEC

In manual control mode, occupants can adjust the window situation to OPEN (open factor of = 1.0), TILT (open factor of = 0.3) and CLOSE (open factor of = 0.0). They can also turn on the DEC and set its fan speed to LOW or HIGH. We assumed that manual action of occupants is based on the adaptive thermal comfort theory which means "occupants exercise adaptive actions in response to discomforting environmental stimuli in an attempt to restore their comfort" (Haldi and Robinson, 2010). Moreover, we considered the findings of Rijal et al. (2011) which concluded "if several controls are available people will use those that are more user-friendly, effective and free from undesirable consequences".

During the cooling period, which starts from 1st May and lasts until 31st October, the occupants can prepare their thermal comfort by opening the window to benefit from the natural cooling ventilation or by turning on a Direct Evaporative Cooler (DEC) which supplies cooled air to the test room. The specifications of assumed DEC are shown in Table 2.

According to the mentioned assumptions, the following algorithm is defined for the manual control mode. In manual control mode, when occupants feel warm, they set the window situation to OPEN and it will be open until they feel cold and change the window situation to CLOSE. When the outdoor temperature is below 15 ºC occupants change the window situation to TILT instead of OPEN (Zhang and Barrett, 2012, Raja et al., 2001). When the outdoor temperature is higher than indoor temperature the window situation is always CLOSE. If after opening the window occupants still feel warm, they will close the window and turn the DEC on and set the fan speed to LOW and the fan runs until occupants feel cold. If the occupants cannot reach comfort in LOW fan speed and they feel warm, they change it to HIGH speed. We assumed that when the fan is ON, the window is CLOSE and there is no natural ventilation through the window. This assumption is very close to reality, because when the fan is on and there is no return air duct, indoor pressure is adequately positive to prevent the air flow through the window from outside to inside. A sleep phase is defined between midnight and 7:00 AM. During this phase residents are sleeping and they do not take an adaptive action to change the window and DEC situation.

We assess the thermal feeling of residents toward their environment, based on BS-EN-15251 (2007) which defines a neutral thermal comfort temperature according the following equations:

$$T_{Op,Neu} = 0.33\, T_{rm} + 18.8 \quad (1)$$

$$T_{rm} = (1-\alpha).\{T_{ed-1} + \alpha\, T_{ed-2} + \alpha^2\, T_{ed-3\ldots\ldots}\} \quad (2)$$

Which:

$T_{Op,Neu}$	Neutral operative temperature
T_{rm}	External running mean temperature
T_{ed-1}	Daily mean external temperature for the previous day
T_{ed-2}	Daily mean external temperature for the day before and so on
α	A constant between 0.0 and 1.0, Recommended to use 0.8

Occupants take an adaptive action when the indoor operative temperature is a specific amount (ΔT) higher or lower than the neutral operative temperature (Rijal et al., 2011). The amount of ΔT is related to occupant behavior which varies in different people (Yun et al., 2009). Therefore, three groups of people are defined based on how much they are sensitive to temperature in order to take an adaptive action. They are named as, high sensitive (H.S.), normal (N.), and low sensitive (L.S.) people. Table 3 shows various ΔT, in which each group of people takes different type of adaptive action.

The algorithm of thermostat control of DEC

In thermostat control mode, occupants can adjust a setpoint temperature for a thermostat that controls the DEC automatically. In order to make the calculations closer to reality, a thermostat response time is considered by defining a 1.5 ºC dead-band from setpoint temperature (Moon and Han, 2011). It means that the thermostat turns the DEC on and sets the fan speed to LOW when the indoor temperature is 1.5 ºC higher than setpoint temperature. The fan runs until the indoor temperature decreases to 1.5 ºC lower than setpoint temperature. When the indoor temperature is 2.0 ºC higher than setpoint temperature, the thermostat changes the fan speed to HIGH speed and it changes only to OFF when the indoor temperature is 2.0 ºC lower than setpoint temperature. We assumed that when the fan is ON, the window is CLOSE and there is no natural ventilation through the window.

Table 3: Deviation from neutral operative temperature (ΔT) for taking an adaptive action by occupants in various groups of people

PEOPLE GROUP NAME	CHANGE WINDOW SITUATION (ºC)	CHANGE DEC TO LOW FAN SPEED (ºC)	CHANGE DEC TO HIGH FAN SPEED (ºC)
High Sensitive (H.S.)	2.0	3.0	3.5
Normal (N.)	3.0	4.0	4.5
Low Sensitive (L.S.)	4.0	5.0	5.5

Occupant thermal comfort

As occupants in the test room can take adaptive actions to achieve thermal comfort (such as adjusting the window situation and turning the DEC on or off), their thermal comfort situation -during the cooling period- is calculated based on adaptive thermal comfort according to standard BS-EN-15251 (2007). In this standard thermal comfort is classified in four categories as follows:

Category I: Indoor operative temperature is in the range of ± 2.0 ºC of Neutral operative temperature. It is a high level of comfort and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.

Category II: Indoor operative temperature is in the range of ± 3.0 ºC of Neutral operative temperature. It is a normal level of comfort and should be used for new buildings and renovations.

Category III: Indoor operative temperature is in the range of ± 4.0 ºC of Neutral operative temperature. It is an acceptable, moderate level of comfort and may be used for existing buildings.

Category IV: Indoor operative temperature is out of the criteria mentioned in the above categories. This category should only be accepted for a limited part of the year.

An Erl is written in EMS of EnergyPlus to calculate the percentage of time (during the cooling period) that each category of thermal comfort is met in the test room.

RESULTS AND DISCUSSION

In this section, the results of simulations for different types of control strategy are presented and they are compared based on the electricity consumption of DEC and occupant thermal comfort during the cooling period (1st May – 31st October).

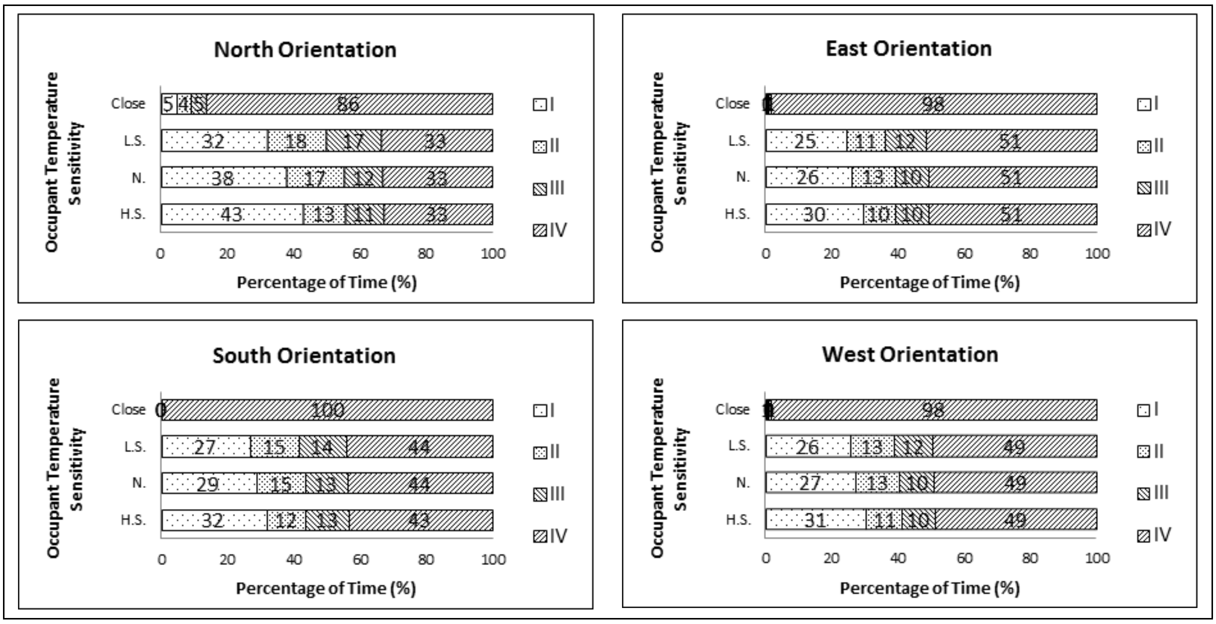

Figure 3: Time percentage of different categories of thermal comfort during the cooling period in the test room for various types of occupant temperature sensitivity (DEC: OFF, Window: Adjustable or Close)

Natural cooling ventilation without DEC

At the first step, occupants' thermal comfort during the cooling period is investigated when the DEC is OFF and they can reach their comfort only by adjusting the window situation. The simulations are performed during the whole cooling period for three groups of people with different temperature sensitivity. The simulation is also carried out when occupants are not allowed to open the window. They are also repeated for four main orientations of the test room (the external wall orientation of test room). The results are shown in Figure 3.

This figure shows that when occupants are not allowed to open the window (Data with the label of 'Close') 86%, 98%, 98% and 100% of the time, respectively for the North, East, West and South orientated test room the thermal comfort is not acceptable (Category IV). When the occupants are allowed to open the window, the percentage of time for unacceptable thermal comfort decreases to 33%, 51%, 49% and 44% respectively for the North, East, West and South orientated test room. These data show that natural cooling ventilation through window cannot prepare acceptable thermal comfort during the whole cooling period and using a mechanically cooling system is necessary.

The East oriented test room has the maximum time of unacceptable thermal comfort, because the sunrise increases the indoor temperature before 7:00 am but occupants do not open the window since they are asleep.

Manually controlled DEC without natural cooling ventilation

In this section the electricity consumption of a manually controlled DEC and the thermal comfort of occupants during the cooling period is investigated when the window is CLOSE and occupants can reach their comfort only by turning on the DEC and adjusting its fan speed to LOW or HIGH. The simulations are done during the whole cooling period for three groups of people with different thermal sensitivity to adjust the DEC and they are repeated for four main orientations of the test room. The results for electricity consumption of fan and water circulation pump of DEC are shown in Figure 4. It shows that the East oriented test room has the highest and the North oriented test room has the lowest electricity consumption.

Manually controlled DEC combined with natural cooling ventilation

The influence of benefiting from natural cooling ventilation (through window adjustment) on the electricity consumption of a manually controlled DEC is investigated during the cooling period. The simulations are done during the whole cooling period for three groups of people with different temperature sensitivity to adjust the DEC and window. They are repeated for four main orientations of the test room.

The percentage of decrease in the total electricity consumption of DEC due to the use of natural cooling ventilation is shown in Figure 5. This figure indicates that in all situations using the natural cooling ventilation decreases the electricity consumption of DEC; although its amount depends on the people's

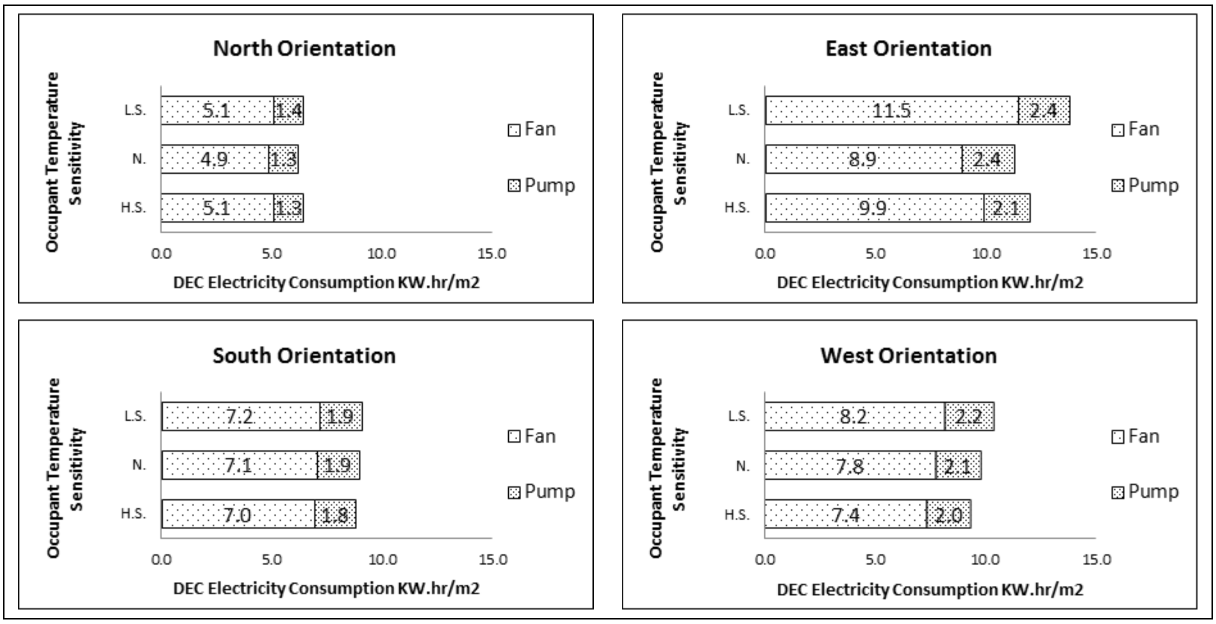

Figure 4: Electricity consumption of DEC during cooling period for various types of occupant's temperature sensitivity (DEC: Manual control, Window: Close)

temperature sensitivities and test room orientation. It varies from 7% for High sensitive people in west orientated test room to 36% for Low sensitive people

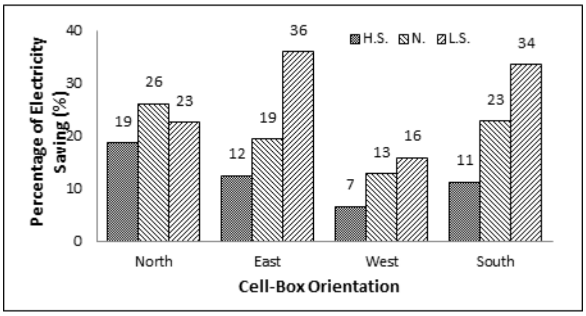

Figure 5: Percentage of decrease in the electricity consumption of DEC due to benefitting from natural cooling ventilation for various types of occupant temperature sensitivity in four orientations of test room (DEC: Manual control, Window: Adjustable)

in the East orientated test room.

The influence of using a thermostat control on energy consumption of a DEC

In this section, the electricity consumption of a Manually controlled DEC is compared with one which is controlled automatically by a thermostat. In both situations the window can be adjusted manually to benefit from natural cooling ventilation. The percentage of changes in the total electricity consumption of DEC due to the use of a thermostat with different setpoint temperature for four orientations of test room is shown in Figure 6. The results are for occupants with a normal thermal sensitivity (N.). Needless to mention that negative values in this figure mean that the electricity consumption is increased in thermostat controlled DEC . It shows that for all orientations of test room, the amount of electricity consumption strongly

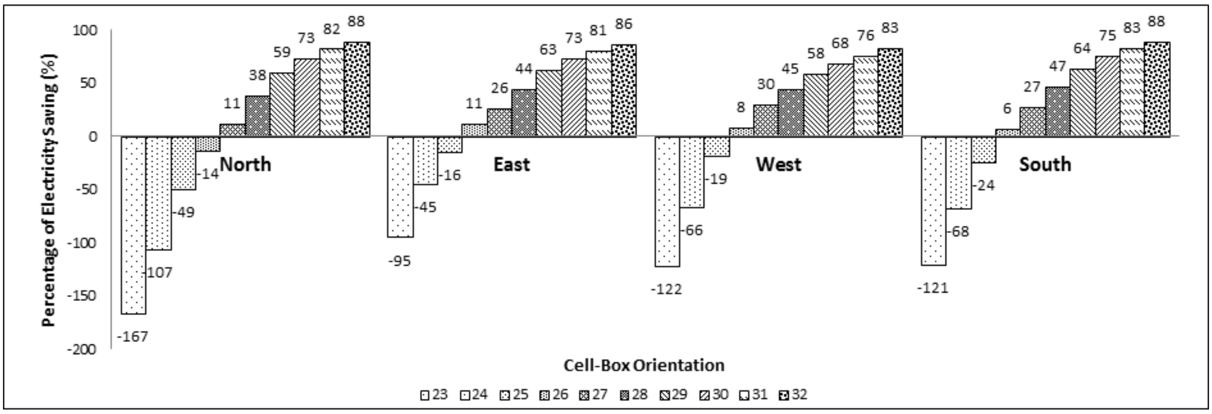

Figure 6: Percentage of decrease in the total electricity consumption of a DEC due to using a thermostat in different setpoint temperature, for four orientations of test room (Window: Adjustable, People thermal sensitivity group: Normal Sensitivity)

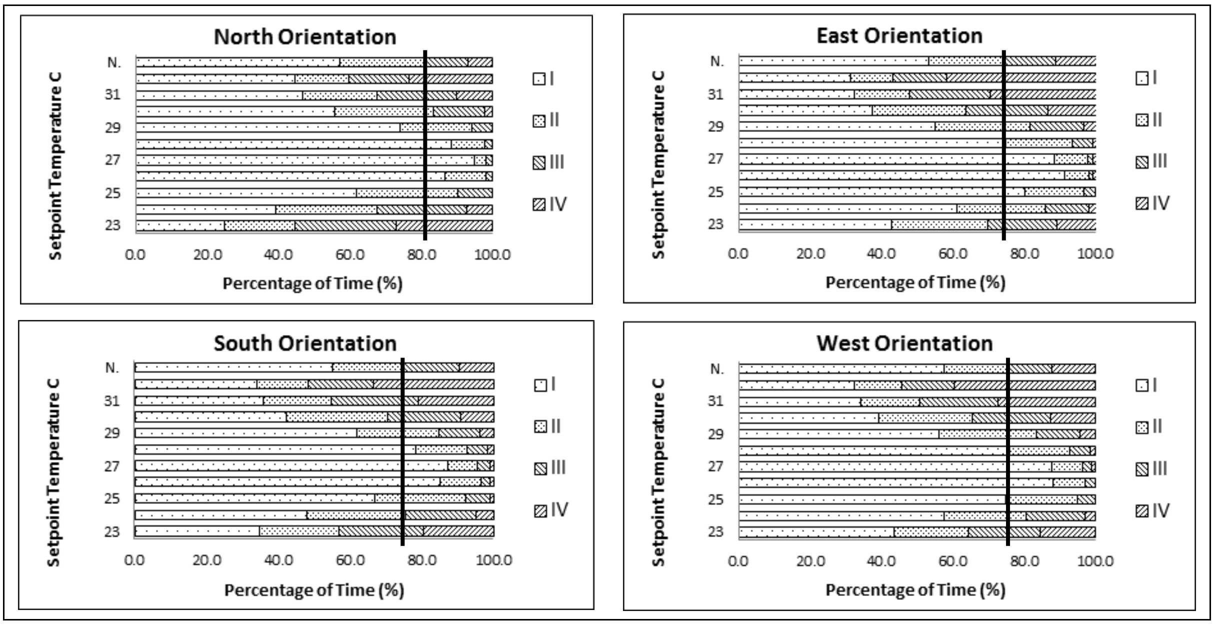

Figure 7: Time percentage of different categories of thermal comfort during the cooling period in the test room for a manually and thermostat controlled DEC (Window: Adjustable, People thermal sensitivity group: Normal Sensitivity)

depends on thermostat setpoint temperature. In setpoint temperature below 26 ºC a thermostat controlled DEC consumes more electricity than a manually controlled one. However, with increasing the setpoint temperature, the amount of electricity saving by a thermostat controlled DEC will increase and it will consume less energy than manually controlled one. This result proves the finding of Toftum (2010) that using a thermostat controlled DEC cannot decrease the energy consumption unless the occupants are educated to choose a correct setpoint temperature

Figure 7 shows the indoor thermal comfort situation of a thermostat controlled DEC in different setpoint temperatures. Results are based on occupants with a normal thermal sensitivity to benefit from natural cooling ventilation (adjusting the window). It shows that for all orientations, by increasing the setpoint temperature from 23 ºC up to 26 ºC the thermal comfort situation improves, but above this temperature the thermal comfort decreases. It means that -during the cooling period - the maximum time of thermal comfort can be achieved in the setpoint temperature of 26 ºC.

Electricity consumption of a thermostat controlled DEC should be compared with a manually controlled one at the setpoint temperature that they prepare the same thermal comfort. Category II of thermal comfort is considered as a reference level for acceptable thermal comfort, as it is the normal level of comfort for new buildings and renovations (BS EN-15251, 2007). In Figure 7, the percentage of time that a manually controlled DEC can prepare the category II of thermal comfort is specified with a black line.

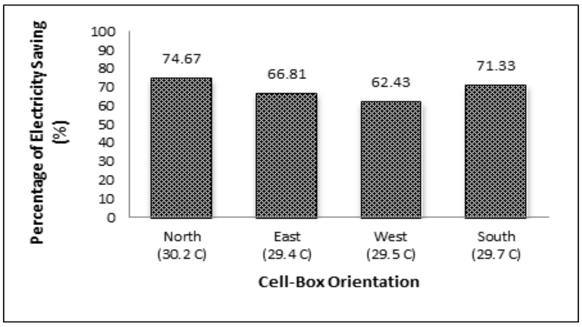

Figure 8: Percentage of decrease in the total electricity consumption of a DEC due to use of a thermostat in the setpoint temperatures that creates similar thermal comfort as a manually controlled DEC, for four orientations of test room (Window: Adjustable, People thermal sensitivity group: Normal Sensitivity)

According to this, and with a linear interpolation, the setpoint temperatures for a thermostat controlled DEC that prepare the same thermal comfort as a manually controlled DEC is calculated for different orientations of the test room.

Figure 8 shows the Percentage of decrease in the total electricity consumptions of DEC due to use of a thermostat in these setpoint temperatures. This figure shows that installing a thermostat on DEC and adjusting the setpoint temperature so that it prepares the same thermal comfort as a manually controlled DEC can considerably decrease the electricity consumption. The energy saving is between 62.43% in the West oriented test room and 74.67% in the North oriented test room.

CONCLUSIONS

In this paper the electricity consumption of a manually controlled direct evaporative cooler (DEC) is compared with a thermostat controlled one. Moreover, the significance of adjusting the window to benefit from natural cooling ventilation is investigated. To achieve these goals, a test room with a two-leaf double glazing window and conventional material is assumed. Three groups of occupant temperature sensitivity are defined and based on adaptive thermal comfort theory, three algorithms for adjusting the window by occupants, and manual and thermostat control of DEC are proposed. After integrating these algorithms in EnergyPlus software with its EMS feature and simulating the energy performance of test room during the cooling period in four main orientations, following results are concluded:

- In Tehran, for all four orientations of the test room, although natural cooling ventilation improves the thermal comfort situation, it cannot prepare acceptable thermal comfort during the whole cooling period on its own and a mechanically cooling system is required.

- Benefitting from natural cooling ventilation by adjusting the window can reduce7-36% the cooling electricity consumption. It depends on occupant temperature sensitivities and room orientation.

- The amount of electricity consumption of a thermostat controlled DEC strongly depends on thermostat setpoint temperature so that in setpoint temperature below 26 ºC it consumes more electricity than a manually controlled DEC. However, with increasing the setpoint temperature the amount of electricity saving increases and it consumes less energy than manually controlled one. This shows that using a thermostat cannot decrease the energy consumption unless occupants are educated to choose a correct setpoint temperature.

- In a thermostat controlled DEC, during cooling period, the maximum time of thermal comfort (based on adaptive comfort of EN 15251) can be achieved in the setpoint temperature of 26 ºC.

- In a thermostat controlled DEC, the setpoint temperature of 29 ºC can prepare the same thermal comfort as a manually controlled one. In this setpoint temperature the electricity consumption decreases about 60%.

Finally, it should be mentioned that the results and conclusions are limited to considered assumptions in this paper and may change for different climate, occupant behavior, internal loads and building structure.

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