The Acceptability of Different Types of Evaporative Cooling System across India

V. Venkateswara Rao
Birla Institute of Technology and Science Pilani—Hyderabad Campus, 500078, India, venkat4523@gmail.com

Santanu Prasad Datta
Birla Institute of Technology and Science Pilani—Hyderabad Campus, 500078, India, spdatta@hyderabad.bits-pilani.ac.in

Follow this and additional works at: https://docs.lib.purdue.edu/ihpbc

https://docs.lib.purdue.edu/ihpbc/283

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html
The Acceptability of Different Types of Evaporative Cooling Systems across India

V. Venkateswara RAO¹, Santanu P. DATTA*¹

¹ Department of Mechanical Engineering,
Birla Institute of Technology and Science Pilani— Hyderabad Campus, Hyderabad, Telangana, 500078, India

venkat4523@gmail.com
spdatta@hyderabad.bits-pilani.ac.in

* Corresponding Author

ABSTRACT

In present days, building energy consumption for cooling and heating purposes accounts for about 40% of entire energy consumption. The conventional air conditioning system based on vapour compression cycle is energy intensive and influences the environment through leakage of hydrofluorocarbons, significantly. Therefore, there is an immediate need for development of energy efficient air conditioning systems. It is a well-known fact that evaporative cooling mechanism is natural, eco-friendly and involves minimal energy consumption for air conditioning purpose. In addition, evaporating cooling systems are inexpensive, and involve minimum initial and running costs compared to conventional vapour compression systems. In this work, a comparative study among direct evaporative cooling (DEC), indirect evaporative cooling (IEC) and hybrid system (two stage DEC-IEC) has been done to estimate the potentiality of evaporative cooling in terms of energy savings and wet bulb effectiveness with a commercial software DesignBuilder followed by simulation in EnergyPlus with a constant cooling load for major cities namely Hyderabad, Delhi, Mumbai, Chennai, Kolkata and Jodhpur in India for various time scales i.e., annually, monthly and daily basis. Based on the study, it can be concluded that cooling energy consumption is maximum when two stage DEC-IEC based systems are used compared to DEC or IEC alone irrespective of the region and simulation period. The indoor air temperature comparison results indicate that Jodhpur has highest indoor temperature with the evaporative cooling system. The indoor relative humidity results reveal that New Delhi has highest indoor air relative humidity with evaporative cooling system and zone sensible cooling is maximum for Jodhpur from February-April.

1. INTRODUCTION

Buildings contribute to around 30-40% of entire energy consumption and are responsible for greenhouse gas emissions to a significant extent (Cao, Dai, & Liu, 2016; Cuce & Riffat, 2016; Duan et al., 2012). Major part of this consumption can be attributed to Heating, ventilation and air conditioning(HVAC) equipment accounting for about 50% of the total received energy (Cao et al., 2016; Cuce & Riffat, 2016; Duan et al., 2012). For the air conditioning purpose, vapor compression-based systems are widely used, and they dominate today’s market. But it has to be noted that vapor compression based systems (VCS) are energy intensive and are not eco-friendly (Duan et al., 2012; Mahmood et al., 2016; Nunes et al., 2015). Therefore, an evaporative cooling system can be an alternative option to VCS and is energy efficient and eco-friendly subject to proper design. Evaporative cooling systems consume only one quarter of the energy consumed by vapor compression based air conditioning system (Chen, Zhu, & Bai, 2017). In addition, traditional evaporative cooling systems can decrease the supply air temperature to its wet bulb temperature ideally. Due to this, now-a-days an evaporative cooling system is utilized as non-energy intensive device for cooling and air conditioning in industrial, farming and housing sectors for low temperature fluid requirement (air, water etc.) (Lacour et al., 2018; Tejero-González et al., 2016).

The widely used evaporative coolers are mostly Direct Evaporative Cooling (DEC) and Indirect Evaporative Cooling (IEC) (Cuce, 2017). DEC involves cooling and humidification of intake air to inlet air wet-bulb temperature, theoretically. From Figure 1(a), it is understandable that in case of a DEC, the temperature of intake air
reduces from $T_1$ to $T_2$ and humidity ratio increases from $W_1$ to $W_2$ (Riangvilaikul & Kumar, 2010). Whereas, the IEC involves heat transfer between dry channel and wet channel separated by a wall. The intake ambient air undergoes sensible cooling and its temperature decreases from $T_1$ to $T_2$ as can be seen from psychrometric chart of Figure 1(b). Simultaneously, the air in the wet channel undergoes cooling and humidification from point (1) to point (3) (Figure 1(b)). Ideally, from IEC, one can achieve the outlet air temperature equivalent to ambient wet-bulb temperature (Riangvilaikul & Kumar, 2010). However, the DEC is suitable for hot and dry climates while the IEC is suitable for humid climate (Cuce & Riffat, 2016).

Therefore, it is understandable that DEC or IEC alone cannot meet the desired human comfort conditions. So, multi-staging is becoming inevitable for better comfort. Here multi-staging refers to DEC and IEC working in conjunction to each other to meet the human comfort condition. These types of multi-stage systems are advantageous in a country like India where diverse climatic conditions are visible.

The performance of a hybrid system consisting of DEC and IEC with 100% outdoor air has been studied by (Kim & Jeong, 2013). The results indicated that the combined system working in hybrid mode provides 51% energy saving over the usual variable air volume system. However, the developed system required higher operating energy due to the restricted performance of the IEC in hot and humid climate. In another investigation, the potential of an IEC as pre-cooler to vapor compression has been investigated for different regions in Iran (Delfani et al., 2010). The results indicated decreased cooling load up to 75% with a significant reduction in electrical energy consumption in the cool climatic condition.

Another study has been reported in which evaporative-vapor compression-based air conditioning system has been developed and evaluated in hot and dry climate. Interestingly, the reduction in energy consumption by cooling coil has been found to be maximum up to 64.2% for the month of March (Chauhan & Rajput, 2015). A hybrid system constituting IEC and vapor compression system has been developed and evaluated. The results indicated that the temperature of intake air from the ambient can be reduced to dew point temperature when the wet bulb temperature of the outgoing air is lesser than the dewpoint temperature of intake ambient air (Cui, Chua, & Yang, 2014). Economic analysis of a hybrid system containing DEC and vapor compression system has been carried out to determine the cost effectiveness associated with addition of DEC to the conventional system (Jain, Mullick, & Kandpal, 2013). Evaluation of effectiveness associated with the usage of evaporative cooled condenser in terms of COP has been done. All psychrometric properties were measured to evaluate the effectiveness of IEC included in the system (Wang, Sheng, & Nnanna, 2014). Comparative study of different pad materials of evaporative cooler has also been studied. The results indicate a reduction in saturation efficiency with increased mass flow rate of air (Kulkarni & Rajput, 2013). An energy recovery system containing IEC in conjunction with cooling unit has been proposed and evaluated (Cianfrini et al., 2014).

The above-mentioned studies indicate the increasing research interest in multi-stage systems due to their advantages. But there are limited studies reported in the literature where a comparative analysis of a multi-stage evaporative cooling system evaluated for different regions representative of different climatic conditions has been conducted.

In this work, a comparative analysis of different systems involving direct and indirect evaporative coolers has been done to gauge the potential of evaporative cooling in terms of energy saving potential and efficiency for major cities namely Hyderabad, New Delhi, Mumbai, Chennai, Kolkata and Jodhpur in India. The analysis involved DEC, IEC and DEC-IEC based systems evaluated independently for their performance theoretically by integrating them to a 10*10 room modeled in DesignBuilder followed by simulation using EnergyPlus at various time scales i.e., annual, monthly and for one day for each city mentioned and the results were compared.
2. METHODOLOGY

The details of the model and the corresponding simulation algorithm are discussed in this section. The variation of climatic conditions for different major cities across India and the corresponding suitable cooling systems are discussed.

2.1 Building Details

A test building using the ‘generic office area template’ has been modeled in DesignBuilder for integrating different types of evaporative cooling systems into it. The building has one room with dimensions (3.048m*3.048m) indicating a floor area of 9.2903 m². The building with one room is enclosed by a pitched roof. Each wall of the room has window for exterior heat gains. It is assumed that the window to wall percentage is 30%. The window width is 3.0 m and the corresponding window height is 1.50 m. Each window is enclosed by a frame of width 0.040 m on a wall with a surface area of 10.668 m². The thermal conductivity of the glass used for windows is 0.9 W/mK. The model of the building as built in DesignBuilder can be seen in Figure 2. This building is divided into two zones using DesignBuilder with each zone connected with the corresponding evaporative cooling system i.e., DEC, IEC or DEC-IEC.

![Figure 2: Building Model created in DesignBuilder](image)

2.2 Description of Climatic Conditions of Cities Considered for Simulation

Six cities namely Hyderabad, New Delhi, Mumbai, Chennai, Kolkata and Jodhpur in India are considered for simulation of the three different evaporative cooling systems connected to building for each city one at a time. These cities represent all types of climatic conditions in India. All the cities considered for simulation in this study are marked in the map as can be seen in the Figure 3 in the India map.

Hyderabad (78°28'12"E, 17°27'0"N) is in the southern part of India. This city lies in the Deccan Plateau and is at a mean height of 536m above sea level. Hyderabad has tropical wet and dry climate. The maximum and minimum temperatures recorded till date in this city are 42°C and 12°C respectively.

New Delhi (77°7'12"E, 28°34'12"N), the capital city of India has a combination of humid subtropical climate and semi-arid climate. Summers commence from April and reach maximum in the month of May. The monsoon commences from mid-June till mid-September. The maximum and minimum temperatures recorded in this city till date are -2.2°C and 48.4°C respectively.

Mumbai (72°51'0"E, 19°7'12"N) is in the Western Ghats of India. It has a tropical wet and dry climate. The city being present at the coast experiences high humidity and high temperatures, but the temperature variations are minimal in the entire year. The maximum and minimum temperatures recorded in this city till date are 42°C and 7.7°C respectively.

Chennai (80°10'48"E, 13°0'0"N) is located on the eastern coastal plain of Indian peninsula. It has hot and humid climate. The temperature variations in this city are minimal as it is present in the coastal region and it lies on the thermal equator. The maximum and minimum temperatures recorded for the city are 45°C and 13.9°C respectively.

Kolkata (88°27'0"E, 22°39'0"N) is in the eastern part of India. It has a tropical wet and dry climate. It has hot and humid climate and the temperature exceeds 40°C in summer. Winters last for two and half months and the temperature ranges from 9°C to 11°C. The maximum and minimum temperatures experienced by habitants in the city are 43.9°C and 5°C respectively.

Jodhpur (73°1'12"E, 26°18'0"N) is in the Thar desert of India. It has hot and semi-arid climate and it is a dry region. But the region experiences rainfall from mid-June to September. The highest temperature recorded in this region is 53.2°C. The details pertaining to average high temperature and relative humidity for all cities considered for simulation can be found in Table 1.
Table 1: Climatic details of the cities considered

<table>
<thead>
<tr>
<th>City</th>
<th>Average Ambient high temperature</th>
<th>Relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyderabad</td>
<td>32.2°C</td>
<td>56%</td>
</tr>
<tr>
<td>New Delhi</td>
<td>31.7°C</td>
<td>54%</td>
</tr>
<tr>
<td>Mumbai</td>
<td>31.8°C</td>
<td>75%</td>
</tr>
<tr>
<td>Chennai</td>
<td>33.1°C</td>
<td>70%</td>
</tr>
<tr>
<td>Kolkata</td>
<td>31.7°C</td>
<td>71%</td>
</tr>
<tr>
<td>Jodhpur</td>
<td>33.55°C</td>
<td>26%</td>
</tr>
</tbody>
</table>

Figure 3: India Map with the locations of all the cities considered for simulation highlighted in green color

2.3 Simulation Details

The test building to which the evaporative cooler based system is attached is modeled in DesignBuilder 4.5 version. DesignBuilder integrated with EnergyPlus has a user friendly graphical user interface for modeling building followed by simulation in EnergyPlus. EnergyPlus is a building performance evaluation tool capable of modeling heating, ventilation, cooling, lighting, etc. In this work, a test building is built, and it is connected with an air handling unit without recirculation of air. The air handling unit is tailored to have evaporative cooler (DEC or IEC or DEC-IEC (two stage DEC-IEC) included in it. The combined unit attached to the building is simulated at different time scales i.e., the simulation is running for different periods (annual, for a month and for one day) for all the locations considered to conclude upon the effectiveness of evaporative cooler for cooling purpose.

The air handling unit consists of two fans i.e., supply fan and extraction fan. The supply fan supplies the outdoor air after it is pretreated in the evaporative cooler (DEC, IEC or DEC-IEC) for temperature reduction. In the case of direct evaporative cooler and DEC-IEC multi-stage unit, the humidity ratio of the outdoor air gets changed. The air handling unit has been used with no recirculation of air to the supply side i.e., 100% outdoor air is used in the supply side. The air from supply side is distributed in the room by using a direct air distribution unit without any zone level control or tempering. The extraction fan picks up the air from the room or the conditioned space and is exhausted from the system.

For the above described customized HVAC design, Detailed HVAC module of EnergyPlus has been utilized. The above described system has been set to run for six-time steps per hour. The solution algorithm used by EnergyPlus to calculate surface heat fluxes is conduction transfer function. This function calculates the surface heat fluxes without any need to know the temperatures and fluxes within the surface. The weather data for each city considered was taken from EnergyPlus. The inside convection between zones in the test building is calculated using 6-TARP model and the outside convection was solved using 6-DOE-2 model available in EnergyPlus. These are surface convection models.

EnergyPlus based Direct CelDek Pad is used as DEC. In the air handling unit this DEC is placed as pretreatment unit. The pad area of this DEC is 0.6 m² and the pad depth is 0.2 m. The DEC effectiveness is 0.7. When the effect of IEC was investigated, the EnergyPlus based Indirect CelDek Pad was used with a pad area of 0.6 m² and pad depth of 0.2 m. The effectiveness of IEC was 0.7. This IEC was placed as a pretreatment unit in air handling unit when its cooling effect was only investigated. When DEC-IEC based multi-stage unit was investigated, DEC was placed as pretreatment unit and the IEC was placed into the air handling unit followed by DEC.

3. RESULTS AND DISCUSSION

The results to follow include interior air temperature comparison for various cities considered followed by comparison of indoor air relative humidity variation for all the cities considered and then followed by cooling energy consumption details and the zone sensible cooling results for various cities considered. This type of comparative study helps in acquiring an understanding about the applicability of evaporative cooling-based system as an alternative to conventional vapor compression-based air conditioning system. The simulations are conducted for three different time periods i.e., annually, monthly and for a 24-hour period.
3.1 Variation of indoor air temperatures with DEC, IEC and DEC-IEC

The variation of the air temperature shown in Figures 4-6, is the temperature averaged over a zone of the room in the test building. Figure 4 represents the variation of indoor air temperature for a simulation period of one year (1st January-31st December) for different cities representative of the climatic conditions prevalent in India. It can be seen from Fig.4 that the indoor air temperature increased with the changing months for almost half of the year. Afterwards, a decreasing trend in the temperature variation can be observed. These temperatures represent the climatic condition of a tropical country like India. Moreover, the dry-bulb temperature is maximum for the month of May for all the cities considered. It can be observed that the air temperatures are maximum with IEC included in the air handling unit. This increase in temperature in the case of IEC is due to the sensible heat gain from the supply air fan in the air handling unit. But in the case of DEC and two stage DEC-IEC, the temperatures are almost identical due to the presence of moisture in the supplied air to the intake air fan of the AHU. This fan in the case of DEC and DEC-IEC absorbed the moisture from the air in the form of latent heat load. Similar variations in the indoor air temperature for DEC, IEC and DEC-IEC can be observed from Figure 5 and Figure 6. The indoor air temperature reached maximum in case of Jodhpur as can be seen from Figure 4(f) due to the adverse climatic conditions.

Figure 4: Variation of indoor air temperatures with different evaporative cooling systems for various cities ((a)-(f)) simulated annually (1st January-31st December)

Figure 5: Variation of indoor air temperatures with different evaporative cooling systems for various cities ((a)-(f)) simulated for a month (1st May-31st May)
3.2 Variation of Indoor Air Relative Humidity with DEC, IEC and DEC-IEC

The variation of relative humidity shown in Figures 7-9, represents the calculated average relative humidity of indoor air of the room of the test building. This property has been calculated using EnergyPlus. It can be seen from all the figures that relative humidity of indoor air is highest in the case of DEC attached to the building through air handling unit. This can be expected since air in the DEC undergoes cooling and humidification. Again, it can be observed from these figures that indoor air has lowest relative humidity when IEC is attached to test building. This is due to the air in IEC undergoes sensible cooling only by exchanging heat with air in the wet channel. The relative humidity variations for building attached with two stage DEC-IEC and only with DEC are almost identical with minimal variation. The minor reduction in the relative humidity in the case of DEC-IEC is observed comparing to DEC or IEC. The air from DEC is cooled and humidified. This air when passes through IEC gets further cooled and the humidity ratio remains constant. When this air meets the supply air fan of the AHU, there will be latent heat transfer. This latent heat transfer will be higher in case of DEC-IEC when compared with DEC only case leading to decrease in humidity ratio of indoor air. The indoor air relative humidity is maximum in the case of New Delhi as can be seen from Figure 7(b).

Figure 7: Variation of indoor air relative humidity with different evaporative cooling systems for various cities ((a)-(f)) simulated annually (1st January-31st December)
3.3 Zone Sensible Cooling with DEC, IEC and DEC-IEC

Zone sensible cooling is the overall sensible cooling effect on the zone air of the test building due to the air introduced by the attached HVAC system containing DEC, IEC or DEC-IEC as can be seen from Figures 10-12. The zone sensible cooling is minimal for all the cities and for all the systems from July to September. Zone sensible cooling is highest for the city of Jodhpur with DEC from February-April. Zone sensible cooling gets reflected in the heat balance calculated for the indoor air due to the outdoor air admitted because of the HVAC system. As can be seen from Figure 10, the zone sensible cooling has higher value in the late winter and early summer, and lower in the early winter and late rainy season as could be witnessed in a country like India.
Figure 10: Zone sensible cooling variation with different evaporative cooling systems for various cities ((a)-(f)) simulated for one year (1st January-31st December)

Figure 11: Zone sensible cooling variation with different evaporative cooling systems for various cities ((a)-(f)) simulated for one month (1st May-31st May)

Figure 12: Zone sensible cooling variation with different evaporative cooling systems for various cities ((a)-(f)) simulated for one day (1st May)

3.4 Cooling Energy Consumption with DEC, IEC and DEC-IEC

Cooling energy consumption refers to the electrical energy consumed for conditioning the room according to the human comfort condition using cooling equipment. This consumption is almost constant for all the cities and
for the entire duration of simulation considered. This value varies only when there is a change in the cooling equipment. It can be understood from the following that two stage DEC-IEC consumes highest electrical energy for cooling purpose because of the additional auxiliaries associated with an additional evaporative cooler included in the AHU. The IEC consumes more electrical power for cooling purpose when compared to DEC because it handles two streams of air for cooling namely, primary and secondary air while DEC handles single stream of air which gets cooled and humidified.

![Image](72x596 to 216x650)

![Image](235x593 to 379x650)

![Image](392x591 to 536x650)

(a) Simulation Period: 1st January-31st December
(b) Simulation Period: 1st May-31st May
(c) Simulation Period: One Day (1st May)

**Figure 13:** Cooling energy consumption variation with different evaporative cooling systems (DEC/IEC/DEC-IEC) simulated for the cities considered

### 4. CONCLUSIONS

This comparative study involved utilization of DesignBuilder integrated with EnergyPlus for simulation of HVAC system containing DEC or IEC or DEC-IEC for different cities namely Hyderabad, New Delhi, Mumbai, Chennai, Kolkata and Jodhpur for different simulation periods i.e., annual simulation, monthly simulation and a 24-hour simulation in India. This kind of analysis is necessary to decide the applicability of evaporative cooling-based systems for various regions. Based on the study, it can be concluded that cooling energy consumption is maximum when two stage DEC-IEC based systems is used irrespective of the region and simulation period. Moreover, the utility of EnergyPlus as building performance tool for conducting this kind of analysis has been demonstrated. The indoor air temperature comparison results indicate that Jodhpur has highest indoor temperature with the evaporative cooling system. The indoor relative humidity results revealed that New Delhi has highest indoor air relative humidity with evaporative cooling system and zone sensible cooling is maximum for Jodhpur from February-April. Therefore, it can be concluded that DEC is suitable for Jodhpur, New Delhi, Hyderabad and Chennai whereas IEC is suitable for Jodhpur, New Delhi and Hyderabad. The cities like Jodhpur, Hyderabad, Chennai and New Delhi are ideal for a combined DEC-IEC system. Therefore, it can be concluded that DEC is mostly suitable for dry climates whereas, IEC is suitable for all climates. However to achieve similar cooling capacity, the size of IEC should be more comparing to DEC. Interestingly, the hybrid (DEC-IEC) system will have more acceptability for all climatic conditions due to higher cooling capacity in spite of marginally larger power consumption.

### NOMENCLATURE

- **DEC**: Direct Evaporative Cooling
- **IEC**: Indirect Evaporative Cooling
- **HVAC**: Heating, Ventilation and Air Conditioning
- **VCS**: Vapor Compression System
- **T**: Temperature (°C)
- **W**: Humidity Ratio (kg of water vapor/kg of dry air)
- **DBT**: Dry-bulb Temperature(°C)
- **WBT**: Wet-bulb Temperature(°C)
- **DPT**: Dew point Temperature(°C)
- **Subscript WB**: Wet-bulb temperature (°C)

### REFERENCES


**ACKNOWLEDGEMENT**

The authors gratefully acknowledge the financial support of BITS Pilani, Hyderabad Campus, India under the aegis of the Research Initiation Grant (RIG) to the corresponding author.