CHAPTER 6

PERFORMANCE FORECASTING OF DUAL-MODE EVAPORATIVE COOLER

6.1. Introduction

India can be divided into six different climatic zones, namely, hot and dry, warm and humid, moderate, cold and cloudy, cold and sunny, and composite (Bishoyia et al., 2017). Most of the central regions of India come under the composite zone, where climatic conditions significantly vary. Furthermore, ASHRAE divides the world into eight different international climatic zones: four are hot, and four are cold zones (ASHRAE Handbook, 2009).DEC is best applied during hot and dry seasons, and it is widely used due to its high cooling capacity, low equipment cost, and eco-friendly technology; however, the REC can be applicable in relatively humid seasons and has the potential of sub wet cooling. Hence, to abstain from the use of two coolers for the same purpose, a dual-mode evaporative cooler is proposed that can operate in dual mode (direct as well as a regenerative-indirect mode). However, further detailed analysis of this novel device is required for various world climate zones (cities) for global acceptability. Hence, in this study, exergy and economic analyses of this novel device are performed to check its exergy and economic feasibilities. Its performance (both modes) for four different international climatic hot zones is also investigated to check worldwide acceptability. Performance forecasting is also needed by considering the climatic change effect to check the future acceptability of dual-mode cooling devices.The exergy analysis of the evaporative cooler helps to identify the inefficiency of both heat and mass transfer processes. The forms of exergy involved in evaporative cooling are thermal exergy, chemical exergy, and mechanical exergy. DEC cools air at the cost of increased humidity and hence the chemical exergy losses to obtain the thermal exergy. REC cools the air by preserving the chemical exergy; that's why it can be further cooled below the wet-bulb temperature. This preserved exergy is utilized in the wet air channel and transferred to dry air. The evaporative cooling process utilizes humidity potential (chemical exergy) to obtain cool air (thermal exergy). However, in this conversion process, total exergy (sum of thermal, mechanical, and chemical exergies) deteriorates due to irreversibility, which is calculated in terms of exergy destruction. The ratio of useful output exergy to total exergy incoming is called exergy efficiency. The exergy analysis helps to compare the performance of the evaporative coolers, identify the inefficiencies and improvement measures.

The proposed dual-mode evaporative cooler has been developed and experimented. When the device operates in indirect mode, outdoor air enters the device at point 1, as shown in Fig. 6.1. While passing through the dry channels, air gets cooled sensibly by exchanging heat with the non-permeable separating plate. At the end of the dry channel, a fraction of air is supplied to the conditioning space at point 2, and the rest is redirected to the wet channel. This extraction ratio is controlled by the vanes located at the top of the device. This extracted air, while passing through the wet channel, gets humidified and exhausted to the atmosphere at point 3. A water circulating pump is used to recirculate the water in cooling pads of the wet channels. In this mode, the additional Vane located at the end of dry channels remains fully open, and the device operates in regenerative mode. When the device operates in direct mode, the vanes at the exit of dry channels remain fully closed. The flow of air in the dry channels is blocked, and it remains unfunctional. The valve located at the top of the device remains in a fully open state. The outdoor air enters the device at point 1, as shown in Fig.6.2. This air, while flowing over

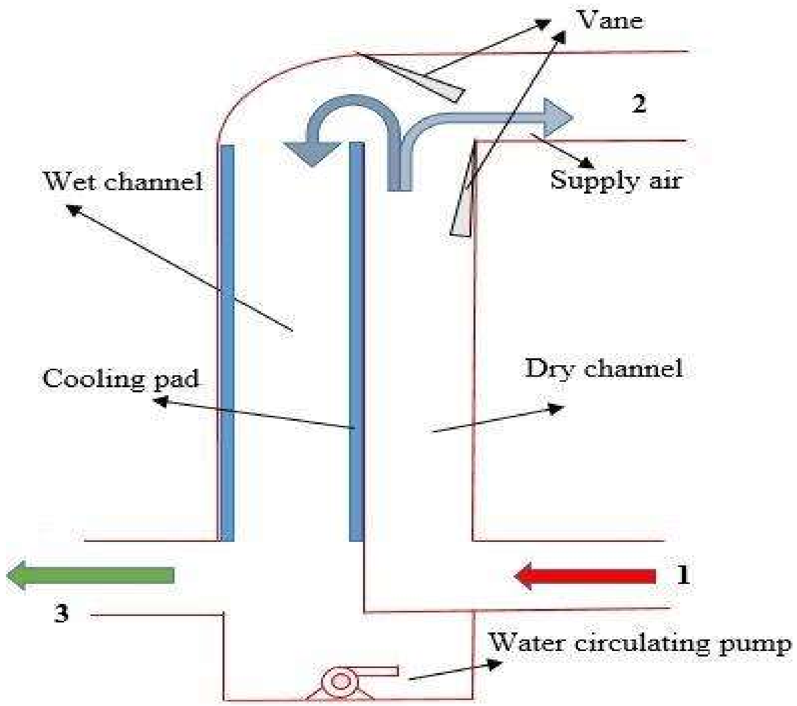

Fig. 6.1 Proposed evaporative cooler in indirect regenerative mode (REC)

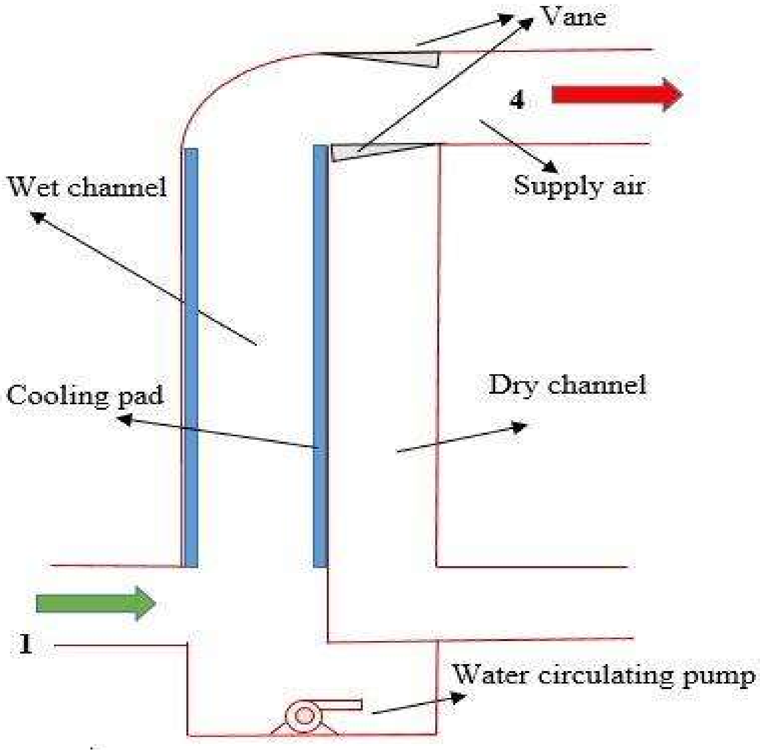

Fig. 6.2 Proposed evaporative cooler in direct mode (DEC)

the cooling pads, gets cooled and humidified and supplied to the conditioning space at point 4. Water is reached to the distributor (located at the top of the cooling pad) by the water circulating pump and collected in a tank at the bottom of the device.The flow process of air inside a dry channel and wet channel for indirect mode is shown on the psychrometric chart in Fig. 6.3. Outdoor air sensibly cools in the dry channel during processes 1-2, and the flow process of redirected air in the wet channel is shown by 2-3. The flow process of air in the direct mode is also represented on the psychrometric chart by processes 1-4 in Fig. 3. Control over the two different modes is achieved by controlling the vanes. Side Vane remains fully opened in REC mode and remains fully closed in DEC mode. Top Vane remains partially opened (depending upon extraction ratio) in REC mode while remaining fully opened in DEC mode. Hence by controlling the top Vane and side vane, the dual-mode evaporative cooler can be switched from DEC mode to REC mode or vice-versa depending on the outdoor air condition change.

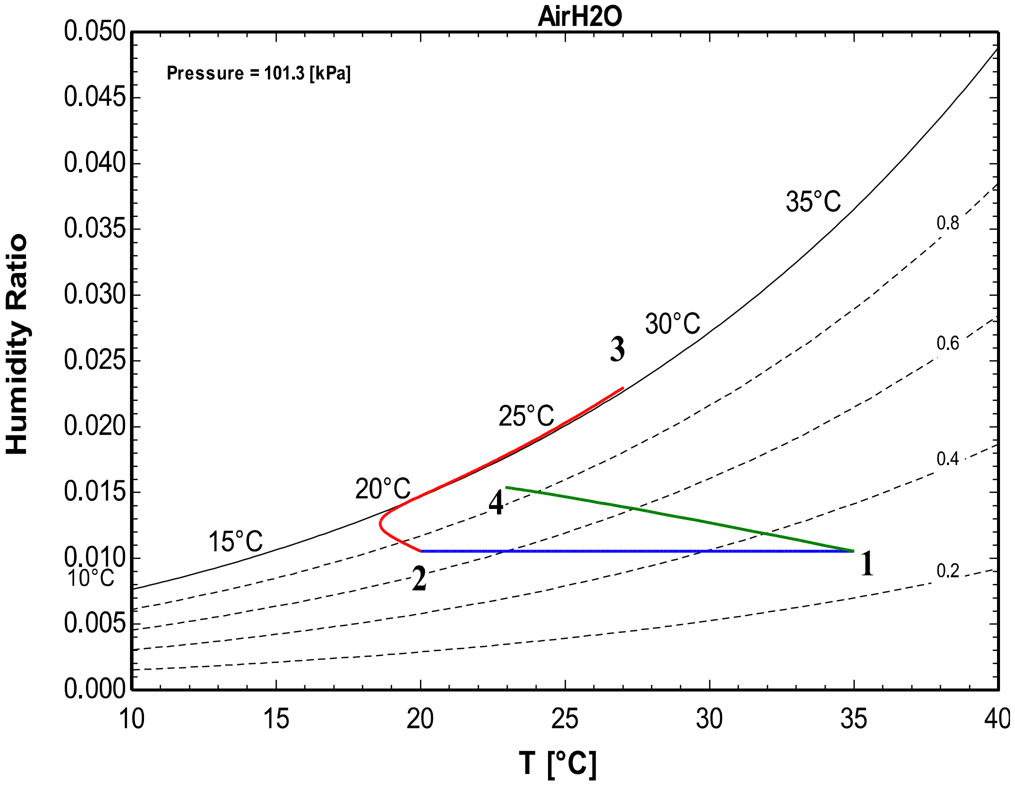

Fig. 6.3 Flow processes in both DEC and REC modes on the psychrometric chart

Dual mode evaporative cooler can be operated in either regenerative or direct mode by controlling the movement of two vanes which give it the flexibility to have the advantage of both modes depending upon the suitability of weather or outdoor conditions.

6.2. Numerical modelling and simulation

The mathematical model presented here is based on the steady-state energy conservation in both dry and wet channels and mass conservation in the wet channel. The x coordinate is taken in upwards direction for modelling (Fig. 6.4). The model consists of a layer of dry and wet channel with channel walls in between. The primary air (the sum of supply and secondary air) of dry channel is cooled through exchanging heat with the working air in the adjacent wet channel. The control volume is also shown in the figure 6.4. Some assumptions are used to simplify and develop the model:

(viii) The outer walls of the evaporative cooler are assumed to be adiabatic by considering proper insulation, so there is only heat exchange inside the device.

(ix) The air flow inside both channels is considered laminar as the flow rate is taken as very small (high velocity is not desirable).

(x) The gap between the two channels is very small, and the gap to width ratio is very less, so it is treated as a 1D problem.

(xi) Airflow inside the dry and wet channel is assumed to be incompressible and steady.

(xii) Thermal and physical properties of water vapor and flowing air are assumed to be temperature-dependent.

(xiii) Properties of water are temperature-dependent, and there is no axial conduction in the water film.

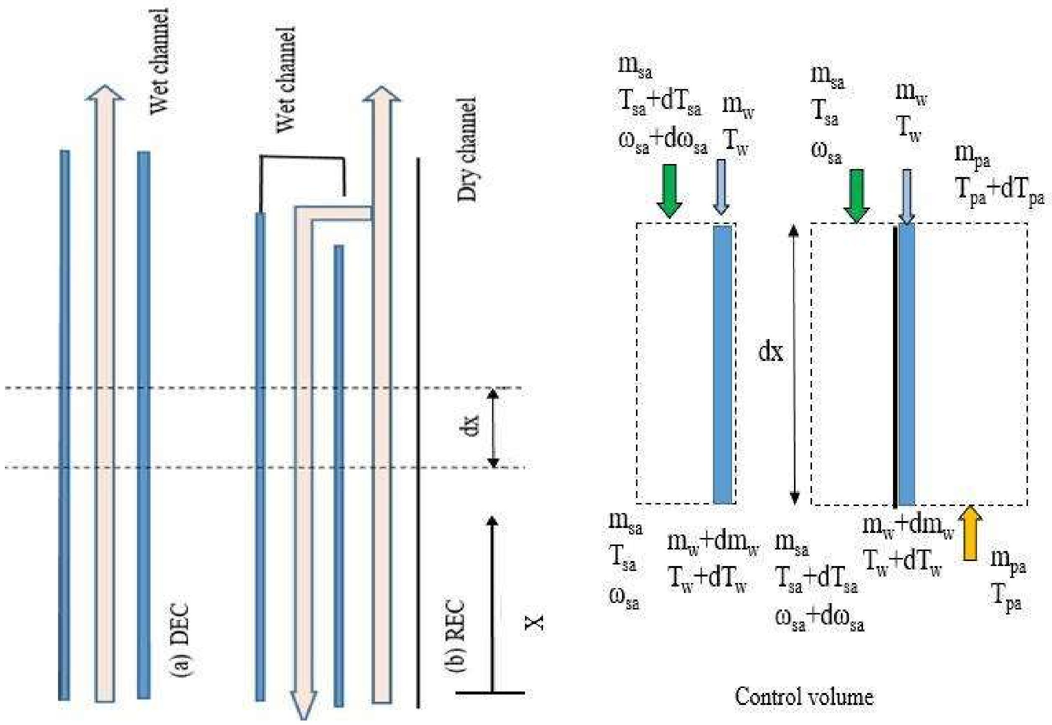

Fig. 6.4 Schematic and control volume of direct and indirect mode heat and mass exchangers

6.2.1 Governing equations

The device is same for both modes of operation but cooling process differ in DEC and REC. The flow direction and heat exchange process differ in wet channels in REC mode while dry channels remain unutilised in DEC mode. That's why two set of equations are used in the performance prediction. The mass and energy balances for DEC mode are given by, respectively,

$$m_{sa}\frac{d\omega_{sa}}{dx}=\kappa_m W(\omega_{ws}-\omega_{sa}) \tag{6.1}$$

$$m_{sa}c_{p,sa}\frac{dT_{sa}}{dx}=\alpha_{sa}(T_w-T_{sa})W \tag{6.2}$$

The conservation of energy for the water film for DEC mode is given by,

$$m_w c_{p,w}\frac{dT_w}{dx}=\alpha_{sa}(T_w-T_{sa})W+h_{fg}\kappa_m(\omega_{ws}-\omega_{sa})W \tag{6.3}$$

The differential equation for energy conservation in the dry channels for REC mode is given by,

$$m_{pa}c_{p,pa}\frac{dT_{pa}}{dx}=U(T_w-T_{pa})W \tag{6.4}$$

Where the overall heat transfer coefficient between dry air and water (U) is obtained by,

$$\frac{1}{U}=\frac{1}{\alpha_{pa}}+\frac{t_{plate}}{k_{plate}}+\frac{1}{\alpha_w} \tag{6.5}$$

The mass and energy balance equations in the wet channel is given by, respectively,

$$m_{sa}\frac{d\omega_{sa}}{dx}=-\kappa_m W(\omega_{ws}-\omega_{sa}) \tag{6.6}$$

$$m_{sa}c_{p,sa}\frac{dT_{sa}}{dx}=-\alpha_{sa}(T_w-T_{sa})W \tag{6.7}$$

The conservation of energy at the water film is given by,

$$m_w C_{p,w}\frac{\partial T_w}{\partial x}=-U(T_{pa}-T_w)W+\alpha_{sa}(T_w-T_{sa})W+h_{fg}\kappa_m(\omega_{ws}-\omega_{sa})W \tag{6.8}$$

The small channels gap results in a small hydraulic diameter and hence the low velocity and small hydraulic diameter make air flow laminar. The correlation used to calculate the Nusselt number for flow inside the primary and secondary air channels is given by (Zhan et al., 2011),

$$Nu=2+0.6Re^{0.5}Pr^{0.33} \tag{6.9}$$

Where, $Re=\frac{\rho_{pa}d_h u_{pa}}{\mu_{pa}}$ (for primary air) and $Re=\frac{\rho_{sa}d_h u_{sa}}{\mu_{sa}}$ (for secondary air).

$$\alpha_{pa}=Nu\left(k_{pa}/d_{h,pa}\right) \tag{6.10}$$

$$\alpha_{sa}=Nu\left(k_{sa}/d_{h,sa}\right) \tag{6.11}$$

For air flowing in both dry and wet channels, $d_h = 2g$.

The Nusselt number correlation used for downward flowing water film is Nu = 1.88 (Liu et al., 2019), and hence the heat transfer coefficient of the water film is determined as,

$$\alpha_w = Nu_w \left(k_w / \delta_w\right) \tag{6.12}$$

Where, $\delta_w = \dfrac{3\nu_w \Gamma}{\rho_w g}$ and $\Gamma = \dfrac{m_w}{(n+1)W}$

The mass transfer coefficient is calculated as $\kappa_m = \alpha_{sa} / (c_{p,sa} Le)$ (6.13)

Where Le is the Lewis factor. The Lewis factor of the air-water mixture is $(0.87)^{2/3}$ at standard atmosphere conditions.

6.2.2 Boundary conditions

For DEC mode, Inlet temperature and specific humidity are known and specified as,

$T_{sa} = T_{in}$ at $x = 0$ (6.14)

$\omega_{sa} = \omega_{in}$ at $x = 0$ (6.15)

$T_w = T_{w,in}$ at $x = L$ (6.16)

Similarly for REC mode, inlet temperature and specific humidity are specified as :

$T_{pa} = T_{in}$ at $x = 0$ (6.17)

$\omega_{pa} = \omega_{in}$ at $x = 0$ (6.18)

$T_{sa} = T_{pa}$ at $x = L$ (6.19)

$\omega_{sa} = \omega_{pa}$ at $x = L$ (6.20)

$T_w = T_{w,in}$ at $x = L$ (6.21)

6.2.3 Numerical simulation

The above-presented differential equations are solved simultaneously by iterative methods. The Equations are discretized by finite-difference. The grid cell size is decreased to minimize the error. The engineering equation solver (EES) (Klein et al., 2017) is used to solve these equations. The inbuilt functions are used to calculate the properties used in the simulations. The system of equations is solved by variation of the

Newton method until the absolute residual is reached to 10^{-6}. The computer algorithm used to develop the code is shown in Fig. 6.5. The grid independence test was performed, and that independent grid is further used for simulations.

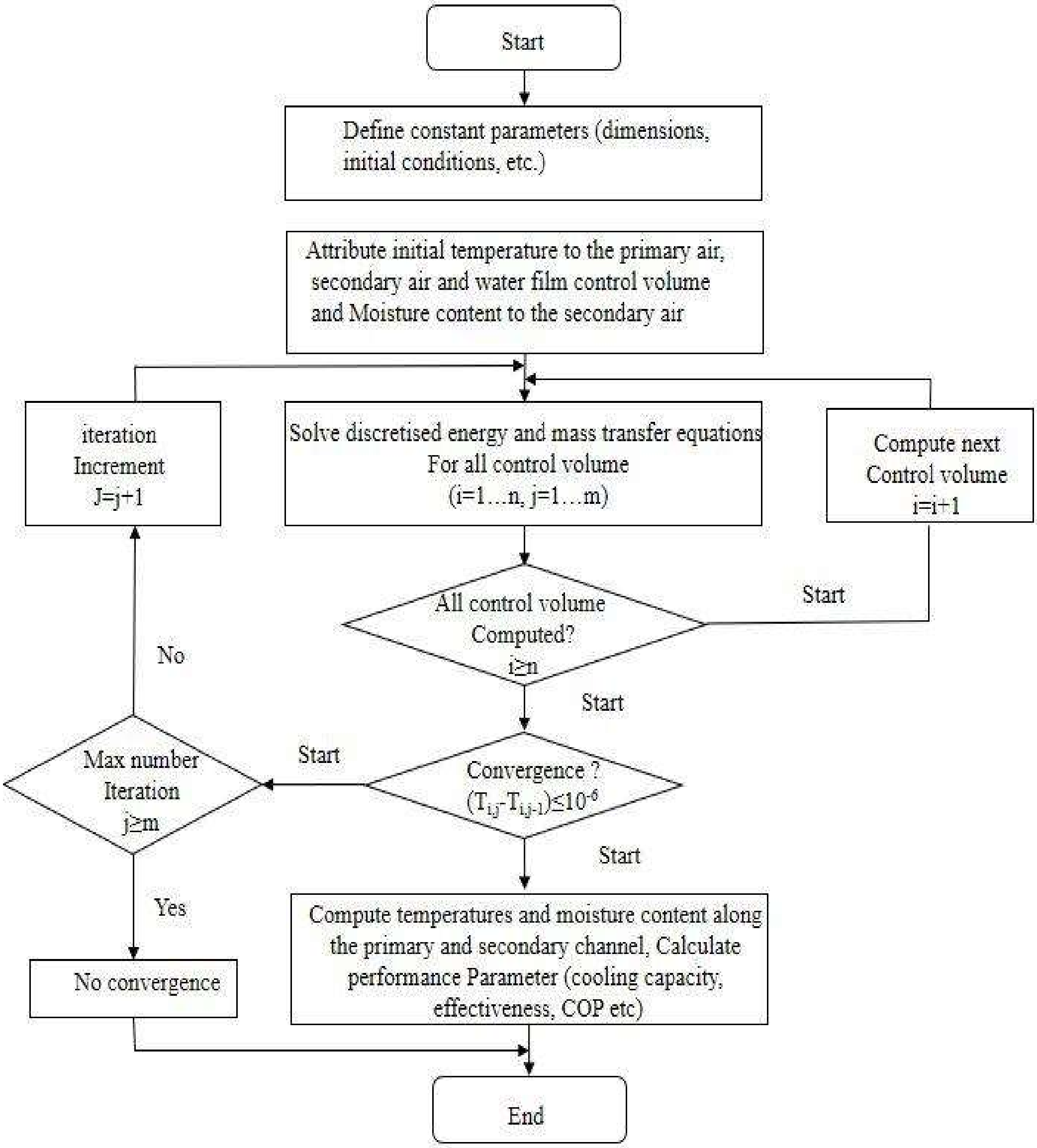

Fig. 6.5 The computer model flow chart

6.2.4 Performance parameters

The effectiveness and cooling energy produced (cooling capacity) are important factors in evaporative cooling technology. The effectiveness evaluates the actual temperature drop with reference to the maximum possible (dew point) temperature drop. The quantitative cooling potential of the device is measured by the cooling capacity. The pressure drop of REC mode consists of pressure loss in the dry channel and pressure loss in the working channel. The pressure drop of dry air consists of sudden contraction loss, frictional loss, line flow loss, and outlet sudden expansion loss. The pressure drop of REC mode consists of pressure loss in the dry channel and pressure loss in the working channel (Duan, 2011). The pressure drop of dry air consists of sudden contraction loss, frictional loss, line flow loss, and outlet sudden expansion loss. COP is calculated with the help of the cooling capacity and power consumption. The power consumption is numerically calculated for the fan and pump power. The equation for numerical calculations is discussed in chapter 3 (equations 3.12 to 3.18). The total flow exergy of the humid air is the summation of the thermal exergy, mechanical exergy, and chemical exergy. The total flow exergy of the humid air per kg of dry air is expressed as (Chengqin et al., 2006).

$$\psi = c_p T_0\left(\frac{T}{T_0} - 1 - \ln\frac{T}{T_0}\right) + (1+1.608\omega)R_a T_0 \ln\frac{p}{p_0} + R_a T_0\left\{(1+1.608\omega)\ln\frac{1+1.608\omega_0}{1+1.608\omega} + 1.608\omega\ln\frac{\omega}{\omega_0}\right\} \tag{6.22}$$

Where T_0, p_0, ω_0 are the temperature, pressure, and humidity at the reference state. R_a is the dry air-specific gas constant. Exergy destruction for the direct and regenerative mode is calculated by exergy balance, as discussed in chapter 5 (equations 5.6 and 5.7). The exergy efficiency of both modes is calculated by equations 5.8 and 5.9.

The total cost is the sum of the operating cost and the capital cost (initial cost) of the device. The main components of the evaporative cooling device are a fan, pump, heat and mass exchanger, etc. Hence, the capital cost is given by,

$$C_{Capital} = C_{fan} + C_{pump} + C_{HMX} + C_{casing} + C_{Upper\ tank} + C_{Lower\ tank} + C_{piping} \tag{6.23}$$

Where C denotes the cost. The cost of components is given in Table 3.2. Hence, the total cost for the evaporative cooling device is given by,

$$C_{Total} = C_{Capital} + C_{Operating} \tag{6.24}$$

The operating cost (running cost) of the cooler is obtained by the power consumption of the fan and water pump. The electricity consumption charges vary for different countries. The electricity charge for all the five different countries (five cities) are listed in Table 6.1. It is assumed that, on average, coolers are required for six months in a year. The operating cost of the device is calculated for eight working hours in a day and 183 days for six months (April to June) working days. The specific total cost (STC) is defined as the cost per unit cooling energy produced of the device, and hence it is given by,

$$STC = \frac{C_{Total}}{Q_{system}} \tag{6.25}$$

Table 6.1: Electricity cost of countries in USD

ASHRAE Climatic zone	Considered City	Country	Electricity prices, 2019
1	Delhi	India	0.08 USD/kWh
2	Brisbane	Australia	0.25 USD/kWh
2	Brazilia	Brazil	0.15 USD/kWh
3	Shanghai	China	0.08 USD/kWh
4	Seoul	South Korea	0.11 USD/kWh

6.2.5 Validation of simulation code

The experimental result of the testing unit is verified by the numerical model. The numerical model is based on the energy and mass conservation equations. In REC modelling, four unknown parameters (dry air temperature, wet air temperature, water film temperature, and wet air humidity) were solved iteratively. The DEC mode modelling solves three parameters (wet air temperature, wet air humidity, and water film temperature) which are derived from energy and mass conservation in the wet channels and energy conservation of water film. The evaporative cooling device operated at the inlet specific humidity of 10 g/kg, inlet velocity of 1.2 m/s, water temperature is 20 ºC, and water flow rate is 11.6 lph, and extraction ratio of 0.5 (in regenerative mode). The inlet temperate is varied with the help of variac attached to the air heater. The variation of supply air temperature with the inlet temperature is plotted in Fig. 6.6. The numerical model predicts lower supply air temperature as compared to the experimental result obtained. The discrepancy between numerical and experimental result is higher at the lower inlet air temperature conditions in both modes of testing. The comparative result shows the maximum deviation of 5.5 % in the direct mode at the inlet temperature of 28.3 ºC.

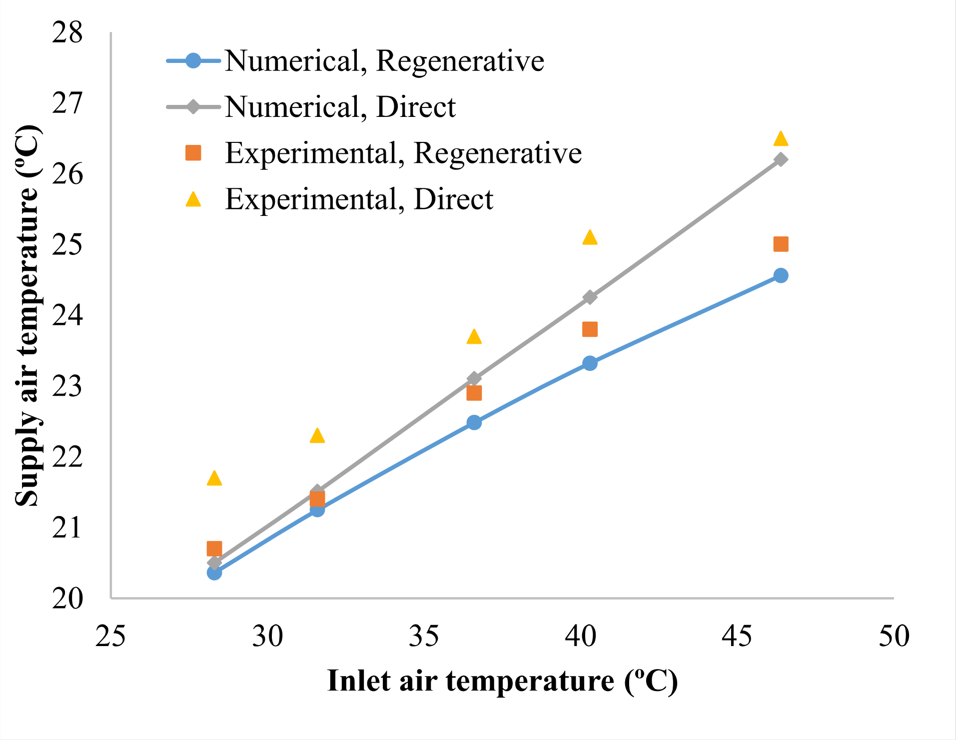

Fig. 6.6 Validation of the experimental result

6.2.6 Comparison of both modes

Table 6.2 compares the results of REC and DEC modes for the air inlet temperature of 35°C and inlet wet bulb temperature of 20 °C. The direct mode shows more cooling energy produced and coefficient of performance as compared to the regenerative mode operation. The regenerative mode shows higher wet bulb effectiveness and exergy efficiency. The pressure drop is more in the regenerative mode, so more fan power is required in REC mode leading to lower COP. The exergy efficiency of REC mode is higher due to less exergy destruction. The total exergy at a point includes the thermal (due to temperature difference), chemical (humidity difference) and mechanical (due to pressure difference) exergies. The inlet air is at the dead state (outdoor air) temperature, so thermal exergy is zero at the inlet of the device in both modes. The inlet air is not saturated, so it contains only chemical and mechanical exergies. Chemical exergy contribution at the inlet of REC mode is 97.8 %, while in DEC mode, it is 98.9 %. The chemical exergy contributes to the maximum percentage of the total exergy. The chemical exergy of the air is sacrificed to obtain thermal exergy. The pressure difference between the inlet and exhaust is higher in REC mode as compared to DEC mode. Hence, the mechanical exergy contribution at the inlet is higher for REC mode (2.1 %) as compared to that for DEC mode (1.05 %), which causes higher air inlet exergy for REC mode.

Table 6.2: Comparisons of results of both modes of evaporative cooler

Parameters	REC mode	DEC mode
Cooling energy produced (W)	4614	5312
Fan power (W)	46.72	15.26
COP	98.52	251.1
Wet-bulb effectiveness	1.127	0.8690
Exergy (W)	127.8 (inlet), 104.5 (supply), 17.0 (exhaust)	120.7 (inlet), 89.83 (supply)

Irreversibility (W)	96.52	251.1
Exergy efficiency	0.7635	0.7138
Vane position	Vane 1 = Partially open Vane 2 = Fully open	Vane 1 = Fully open Vane 2 = Fully closed

6.3. Performance in Indian climatic conditions

The performance of the dual-mode evaporative cooler has been assessed for various climatic conditions. The cooling capacity of the experimented dual-mode cooler is very low. To get the standard cooling capacity, a large number of channels have been used in present numerical investigations. Hence the following specifications have been used for the dual mode evaporative cooler: length of cooling plate or channel = 1.2 m, the width of cooling plate or channel = 0.4 m, and the total number of channels = 60 (30 dry channels and 30 wet channels). The intake velocity has been taken as 1m/s, and the extraction ratio has been taken as 0.4. A wide range of channel gaps was used in literature for the regenerative evaporative cooler. Zhao et al. (2008) recommended that the channel gap should be 6 mm or below. Lee et al. (2013) used channel gaps of dry and wet channels of 20 mm and 10 mm, respectively, and achieved wet-bulb effectiveness ranging between 1.18 to 1.22. Riangvilaikul and Kumar (2010) recommended that the channel gap should be less than 5 mm.

Figs. 6.7 show the effect of wet channel gap on the system cooling capacity and dew point effectiveness for indirect mode and direct mode operations, respectively. As shown, the dew point effectiveness improves, and outlet temperature drops as the channel height decreases. This behavior is due to the increase in convective heat transfer coefficient as the channel spacing between the dry channel and wet channel decreases. In direct mode, for the fixed dry channel height of 0.004m, the maximum cooling capacity is obtained at the wet channel height of 0.0064m due to an increase in mass flow rate in wet channels. Wet-bulb effectiveness decreases as wet channel height increases. When the device operates in the regenerative mode, cooling capacity and wet bulb effectiveness both decrease with an increase in the channel height. Hence depending upon the outlet temperature zone (with respect to thermal comfort), cooling capacity required, and suitability of direct and regenerative mode channel height should be selected judiciously. Based on this discussion and literature data, the height of both dry and wet channels has been taken as 5mm.

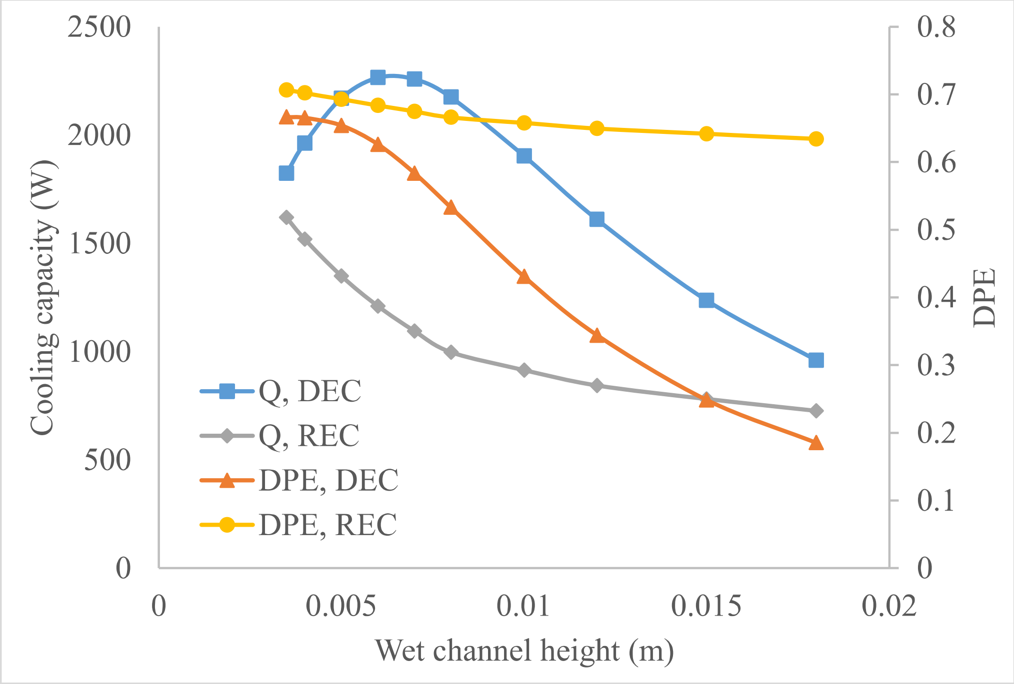

Fig. 6.7 Performance variation with a height of wet channel in DEC and REC mode

The inlet dry bulb temperature and humidity for the proposed cooler are the monthly climatic design data of 2017 for studied cities available in ASHRAE Handbook. Out of the six different climatic zones, the major region of India comes under a composite climatic zone. Hence, three cities (Bhopal, Lucknow, and Varanasi) of the composite climatic zone, one city (Ahmedabad) of the hot and dry climatic zone, and one city

(Kolkata) of a hot and humid climatic zone is selected in this study for performance assessment.

Results for considered Indian cities and hot months are summarized in Table 6.3. The table shows the final output relative humidity. The cooling process inside the channel reached this final state by passing through different states that may be in the thermal comfort zone. The outlet conditions can be easily restricted to the thermal comfort but just varying the operating parameter (like inlet velocity). So table concludes suitability by just observing its passing states in the Psychrometric chart. As indicated in the table, the proposed dual-mode evaporative cooler can be effectively used for the Indian cities of hot-dry and composite climate zones, where this cooler will be operated in direct mode for relatively lower humidity conditions and in the indirect regenerative mode for medium humidity condition. However, this evaporative cooler (or any evaporative cooler) cannot be used for high humidity conditions (e.g. Kolkata). For this case, the hybrid evaporative cooler with the desiccant system can be used, although that is a costly, bulky, and complex solution. In this respect, the proposed evaporative cooler is a simple and cost-effective solution for composite and hot-dry climate zones in the World.

Table 6.3: Summary of results of both modes of the proposed cooler for five cities in India

	Outdoor condition		DEC mode result		REC mode result		Remark
	T_{in} (°C)	RH_{in} (%)	T_{out} (°C)	RH_{out} (%)	T_{out} (°C)	RH_{out} (%)	
Bhopal							
April May	30.9 33.6	30.0 31.0	18.8 21.0	97.7 97.7	18.4 20.3	63.2 67.4	DEC mode for April and

June	31.1	57.0	24.3	98.7	23.9	86.4	May, REC mode for June and September.
July	27.0	83.0	24.7	99.5	24.6	95.5	
August	25.9	87.0	24.2	99.6	24.1	96.5	
September	26.7	77.0	23.6	99.3	23.4	93.3	
Lucknow							
April	29.8	39.0	19.9	98.1	19.5	72.0	DEC mode for April and May, REC mode for June and September
May	32.5	46.0	23.4	98.3	22.9	80.4	
June	32.5	59.0	25.9	98.8	25.5	88.3	
July	30.1	81.0	27.4	99.4	27.2	95.6	
August	29.7	83.0	27.3	99.4	27.1	96.1	
September	29.0	78.0	25.9	99.3	25.7	94.4	
Varanasi							
April	31.0	36.0	20.2	97.9	19.7	70.2	DEC mode for April and May, REC mode for June and September
May	33.3	43.0	23.4	98.2	22.8	78.8	
June	32.8	56.0	25.6	98.7	25.1	86.9	
July	30.3	78.0	27.1	99.3	26.9	94.8	
August	29.9	81.0	27.2	99.4	27.0	95.5	
September	29.5	78.0	26.4	99.3	26.2	94.5	
Ahmedabad							
April	32.1	35.0	20.8	97.9	20.2	70.3	DEC mode for April and May,
May	34.4	42.0	24.1	98.1	23.4	79.0	
June	33.2	58.0	26.3	98.7	25.9	88.2	

July	29.7	76.0	26.2	99.3	26.0	93.9	REC mode for June and September
August	28.8	79.0	25.8	99.3	25.7	94.6	
September	29.3	74.0	25.6	99.2	25.3	93.1	
Kolkata							
April	30.3	70.0	25.8	99.1	25.6	92.0	Evaporative cooler is not effective
May	30.8	73.0	26.8	99.2	26.5	93.3	
June	30.3	80.0	27.4	99.4	27.2	95.4	
July	29.5	84.0	27.2	99.5	27.1	96.3	
August	29.4	84.0	27.1	99.5	27.0	96.3	
September	29.2	84.0	27.0	99.5	26.8	96.2	

6.3.1 Month wise performance in the composite climatic zone

As shown in Fig. 6.8, regenerative mode performance of the evaporative cooler for Bhopal is satisfactory for four months (April, May, June, and September) since its outlet condition is at the left of the thermal comfort zone. As the outlet air enters the conditioning space, it gets heated and humidified, hence supply air condition needs to be left and a little below the thermal comfort zone. In the direct evaporative cooling mode, the supply air condition for the same four months also passes through the thermal comfort zone, but its humidity increases near to saturation, as shown in Fig. 6.9. Hence, it is not as comfortable as REC mode conditioning. For the months of July and August, air humidity at inlet condition is already more than that of comfort level, and hence both modes of the evaporative cooler are not suitable for these two months.

As shown in Fig. 6.10, the regenerative mode performance of the evaporative cooler for the Lucknow is satisfactory for the three months (April, May, and June) since its inlet humidity is less (within comfort zone limit) and it gets cooled at a constant specific humidity. Whereas, for direct evaporative mode (Fig. 6.11), the air outlet condition passes through the comfort zone for only 2 months (April and May). For the rest of the months (July, August, and September), inlet humidity condition is already uncomfortable, and hence evaporative cooler is not comfortable.

Similar to the above cities, air outlet condition in the indirect regenerative mode is at the left of the comfort zone for four months (April, May, June, and September), as shown in Fig. 6.12 in the case of Varanasi. However, the air outlet condition in the direct evaporative mode passes through the comfort zone for two months (April and May) only, as shown in Fig. 6.13, and the cooled air is supplied at a higher humidity condition. In the months of June, July, August, and September, the humidity of outdoor air entering the evaporative cooler are high, which further increases, and hence the direct mode operation of an evaporative cooler is not suitable during this period.

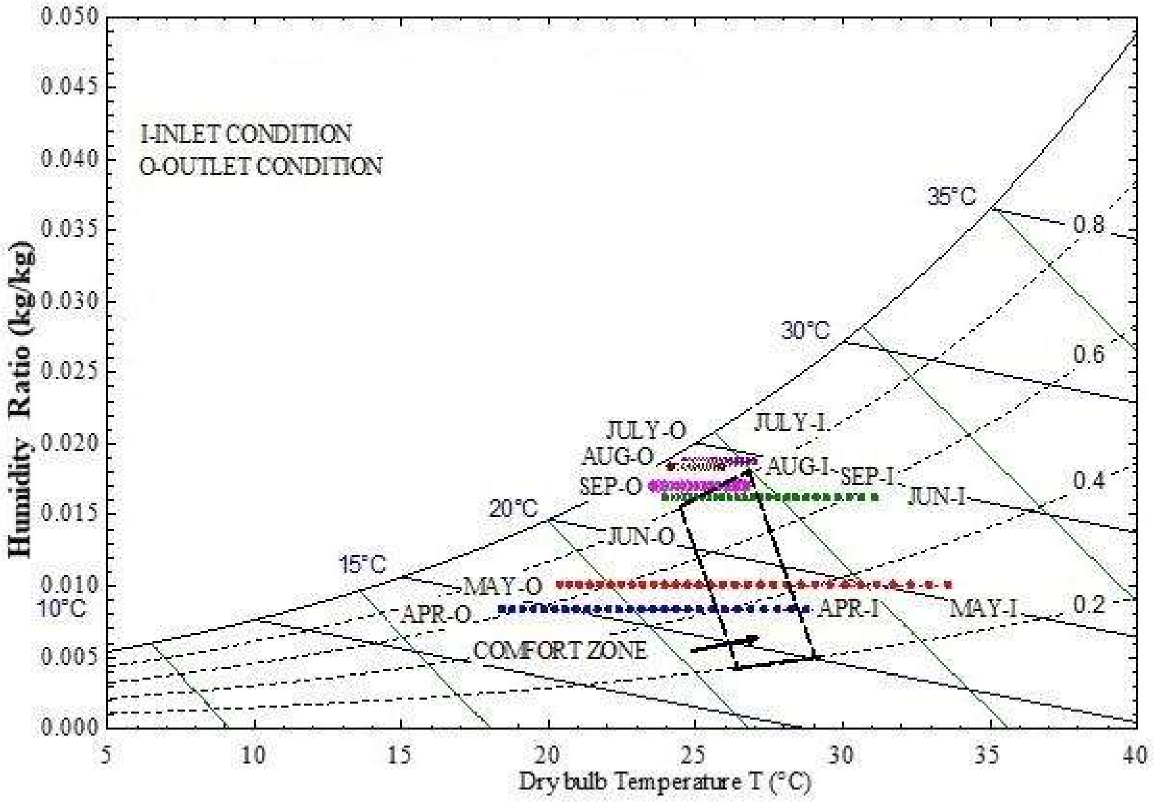

Fig. 6.8 Psychrometric chart showing REC mode results for Bhopal

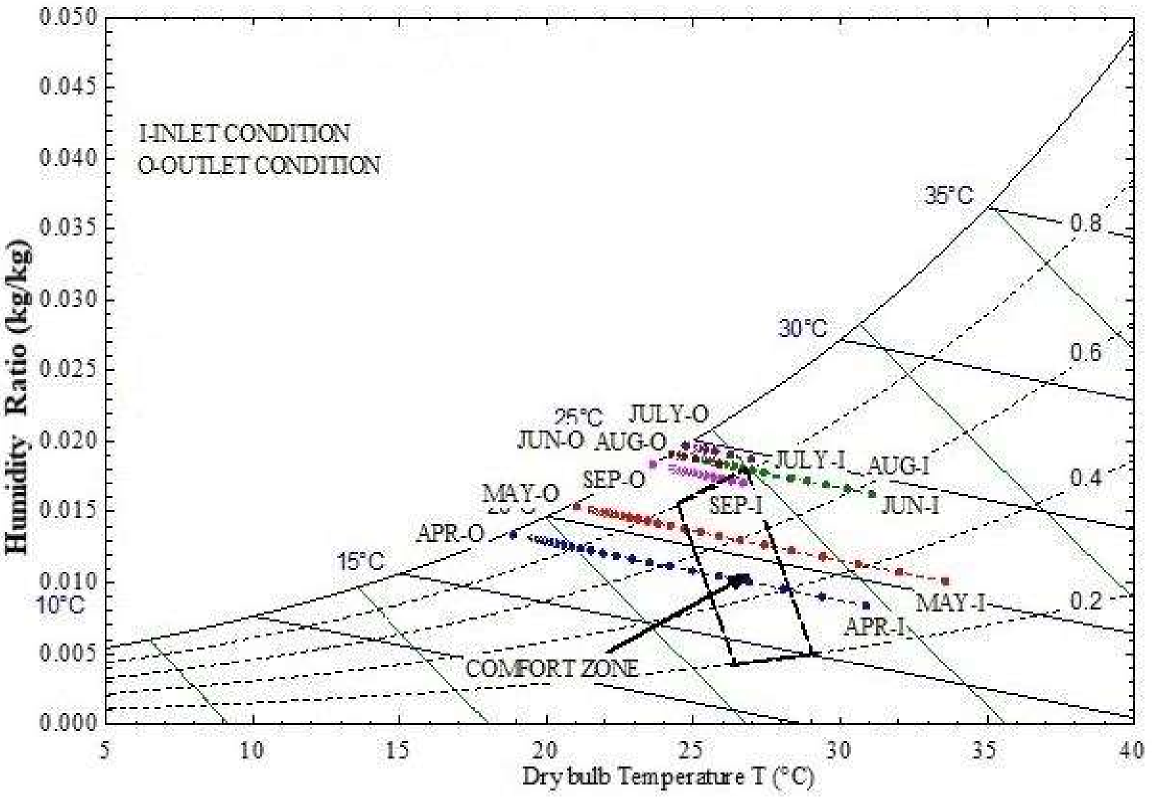

Fig. 6.9 Psychrometric chart showing DEC mode results for Bhopal

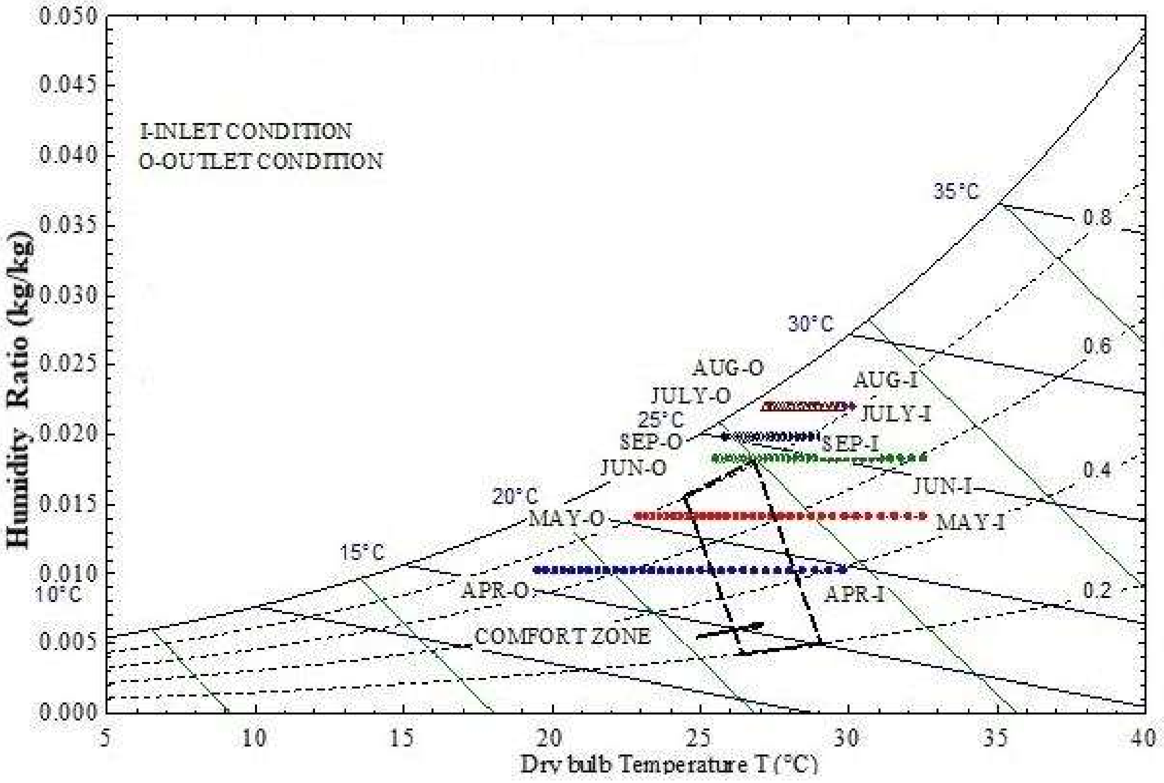

Fig. 6.10 Psychrometric chart showing REC mode results for Lucknow

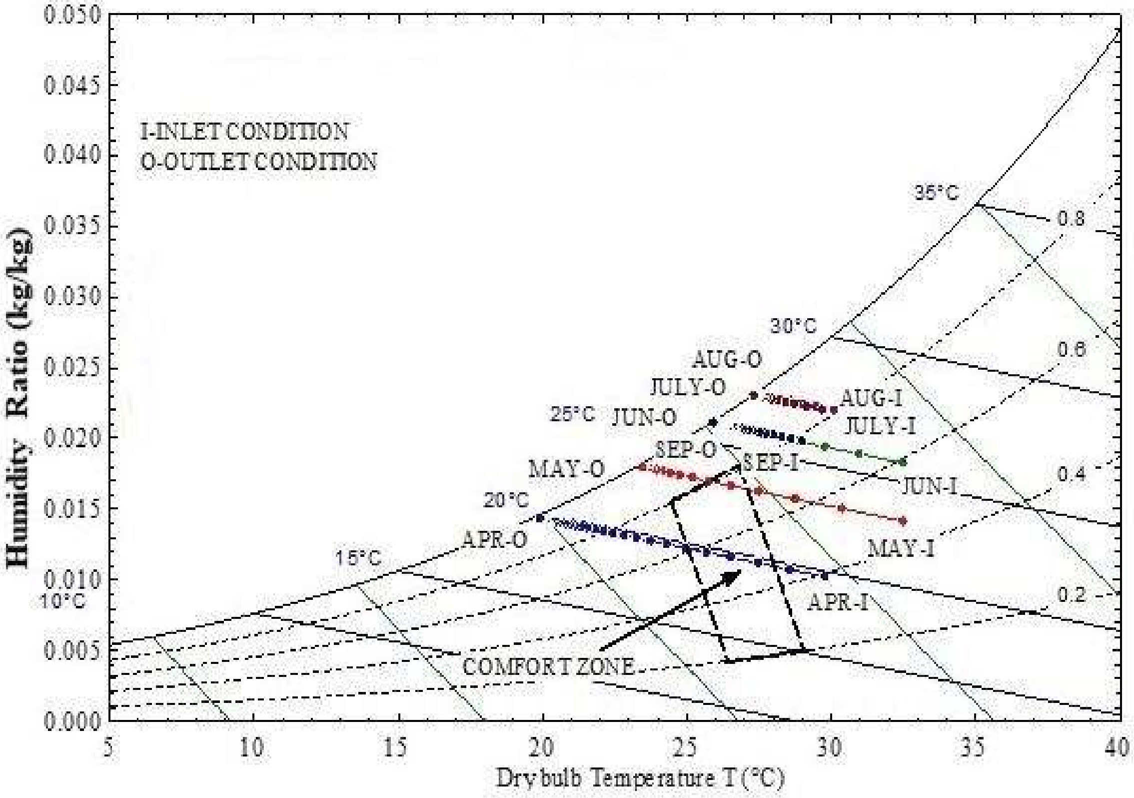

Fig. 6.11 Psychrometric chart showing DEC mode results for Lucknow

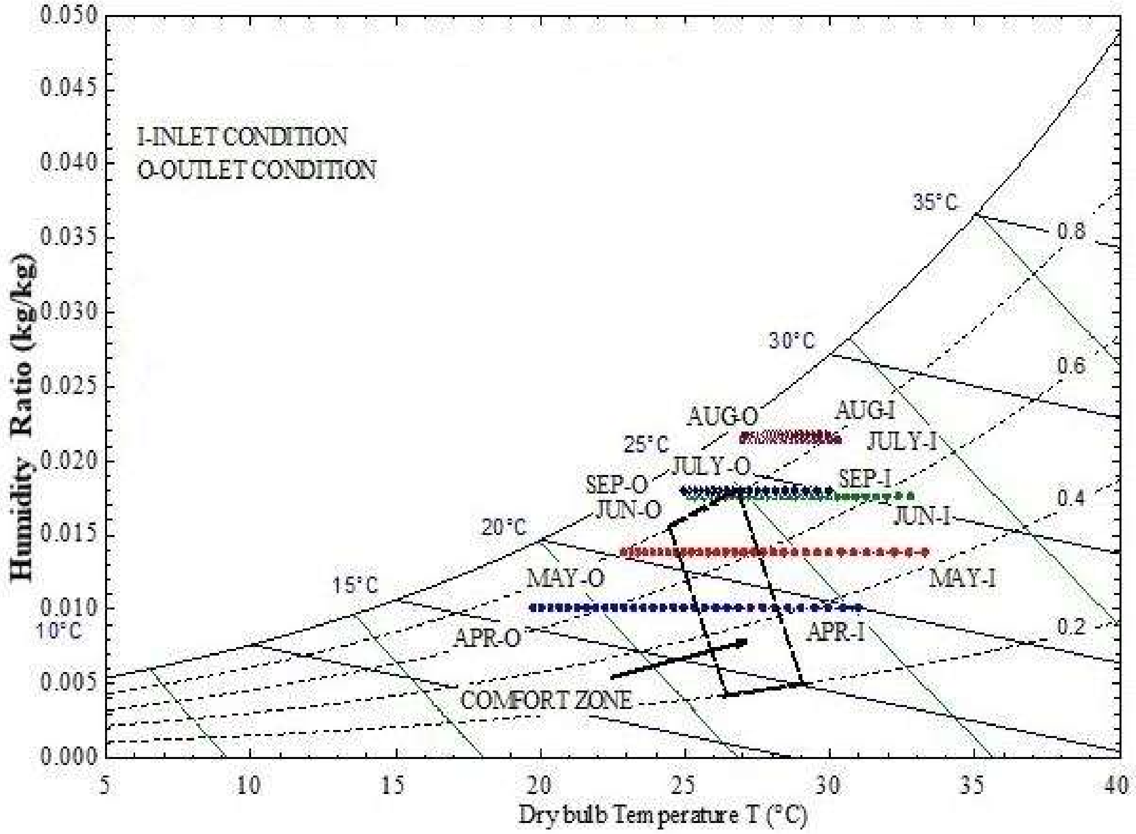

Fig. 6.12 Psychrometric chart showing REC mode results for Varanasi

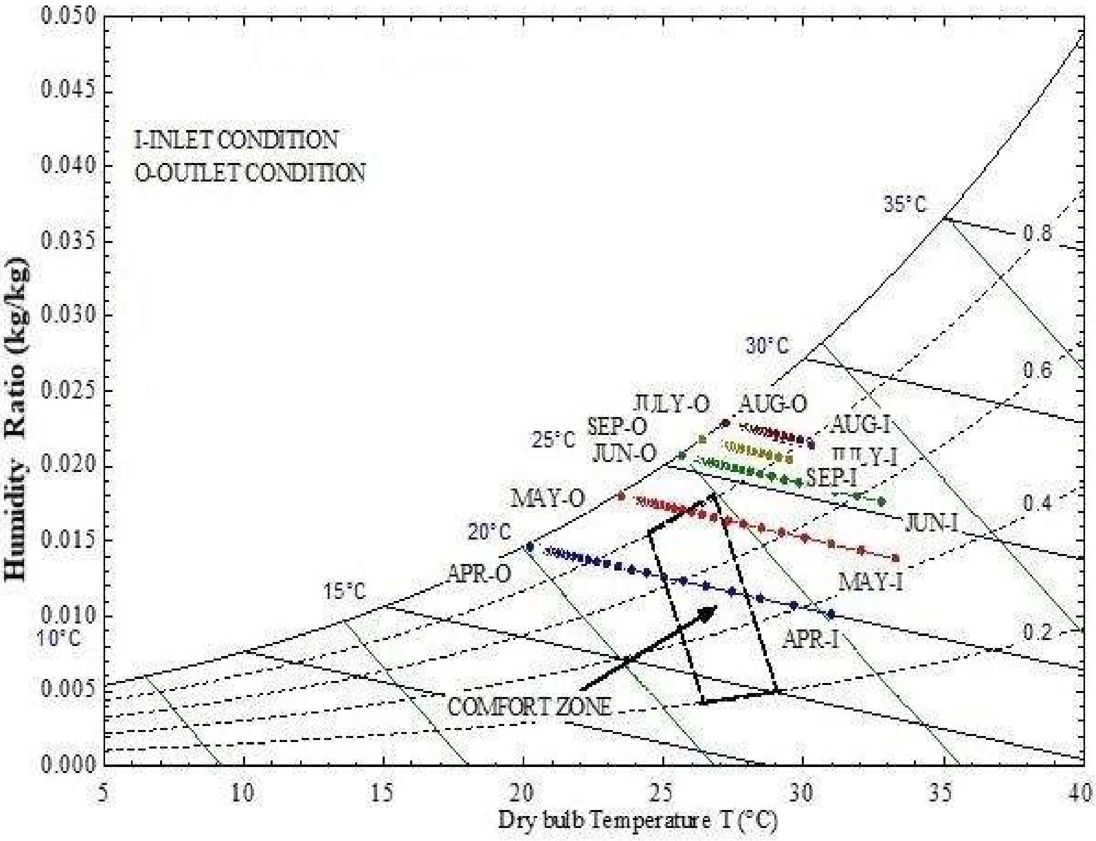

Fig. 6.13 Psychrometric chart showing DEC mode results for Varanasi

6.3.2 Month wise performance in the hot and dry climatic zone

Ahmedabad city comes under dry and hot weather conditions, and the outdoor humidity is low (within comfort range) for four months (April, May, June, and September). Hence, the indirect regenerative mode of the evaporative cooler performs satisfactorily for these four months, as shown in Fig. 6.14. The REC mode can drop the temperature to approximately 5°C, but initial humidity is still high enough to make it uncomfortable for occupants, and hence air flow rate needs to be controlled. The air outlet condition for direct evaporative mode for April and May passes through the comfort zone as shown in Fig. 6.15. For the months of June and September, the process line of direct mode operation is very closely passed through the comfort zone but has high humidity at the outlet. For the months of July and August, both the modes of the evaporative cooler are not suitable because its initial humidity condition is above the comfort zone.

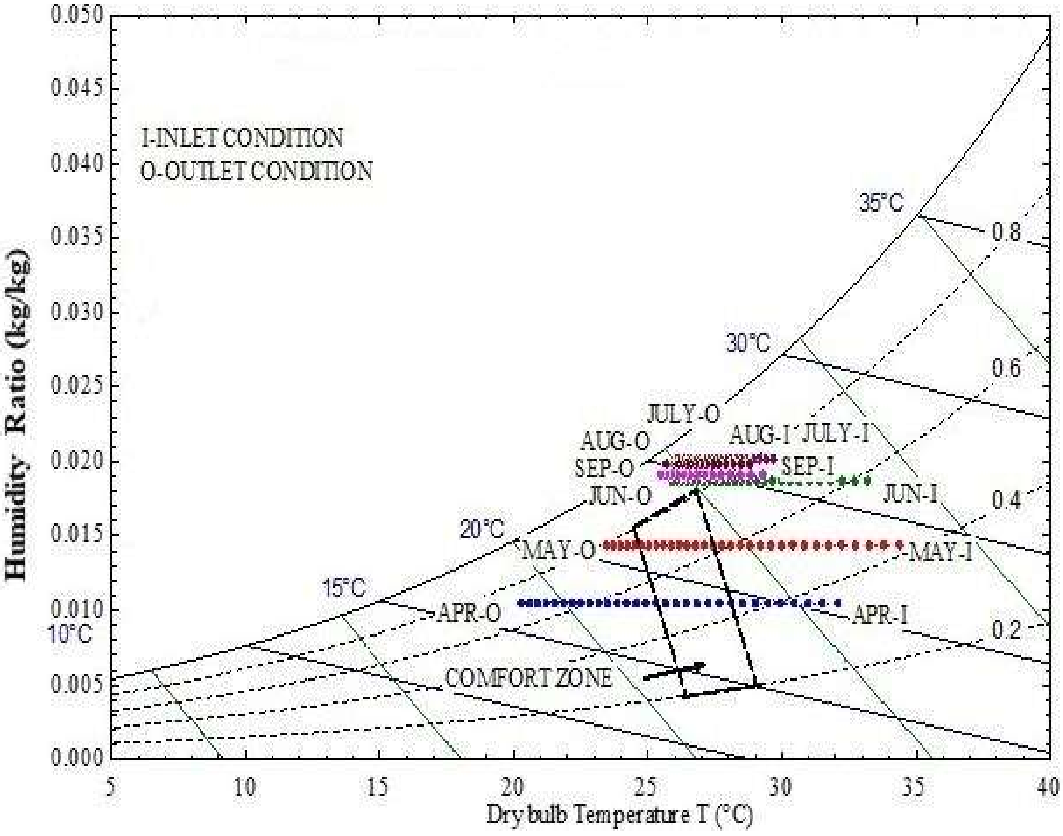

Fig. 6.14 Psychrometric chart showing REC mode results for Ahemedabad

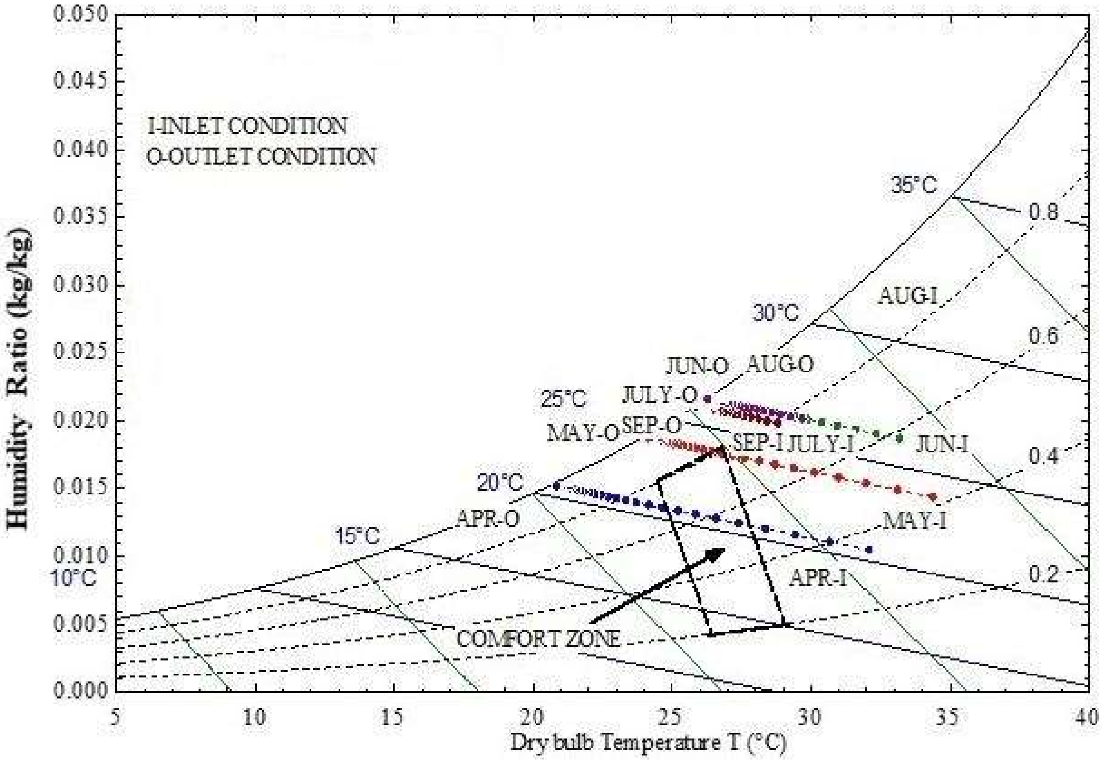

Fig. 6.15 Psychrometric chart showing DEC mode results for Ahemedabad

6.3.3 Month wise performance in the hot and humid climatic zone

The Kolkata city comes under a hot and humid climate zone, and the inlet air humidity for all six months (April to September) is high enough (65-70% relative humidity), which makes it unsuitable for both the direct and indirect operation modes of the evaporative cooler. Both the modes drop the outlet air temperature by around 5°C due to much lower evaporation rate, but humidity condition lies much beyond the comfort zone, as shown in Figs. 6.16 and 6.17.

6.4. Performance in the global climatic conditions

ASHRAE provides climatic design data from different stations across the world (ASHRAE Handbook, 2009). There are two kinds of data: one is for annual cooling, dehumidification, and enthalpy design conditions, and the other for monthly climatic design conditions. Annual evaporation (wet bulb and mean coincident dry bulb temperature) data is recommended for the design of evaporative coolers. There are eight international climatic zones, classified by ASHRAE; out of which four zones are selected for analysis. The five cities, Delhi (India) from the very hot-humid zone (Zone number-1), Brisbane (Australia) and Brasilia (Brazil) from the hot-humid zone (Zone number-2), Shanghai (China) from the warm-humid zone (Zone number-3), Seoul (South Korea) from the mixed humid zone (Zone number-4) are selected for investigations from 1 to 4 climatic zones. The performance of the dual-mode evaporative cooler has been assessed for the various ASHRAE climatic conditions. The following geometrical specifications have been used for the dual-mode evaporative cooler: channel length = 1.2 m, the width of the channel = 0.5 m, channel gap = 5 mm (for both wet and dry channels), and the total number of channels = 140 (70 each dry and wet channels). The common operating conditions used are: air inlet velocity = 2 m/s and extraction ratio = 0.33. The exergy parameters are calculated by taking an atmospheric air saturation state as a dead state.

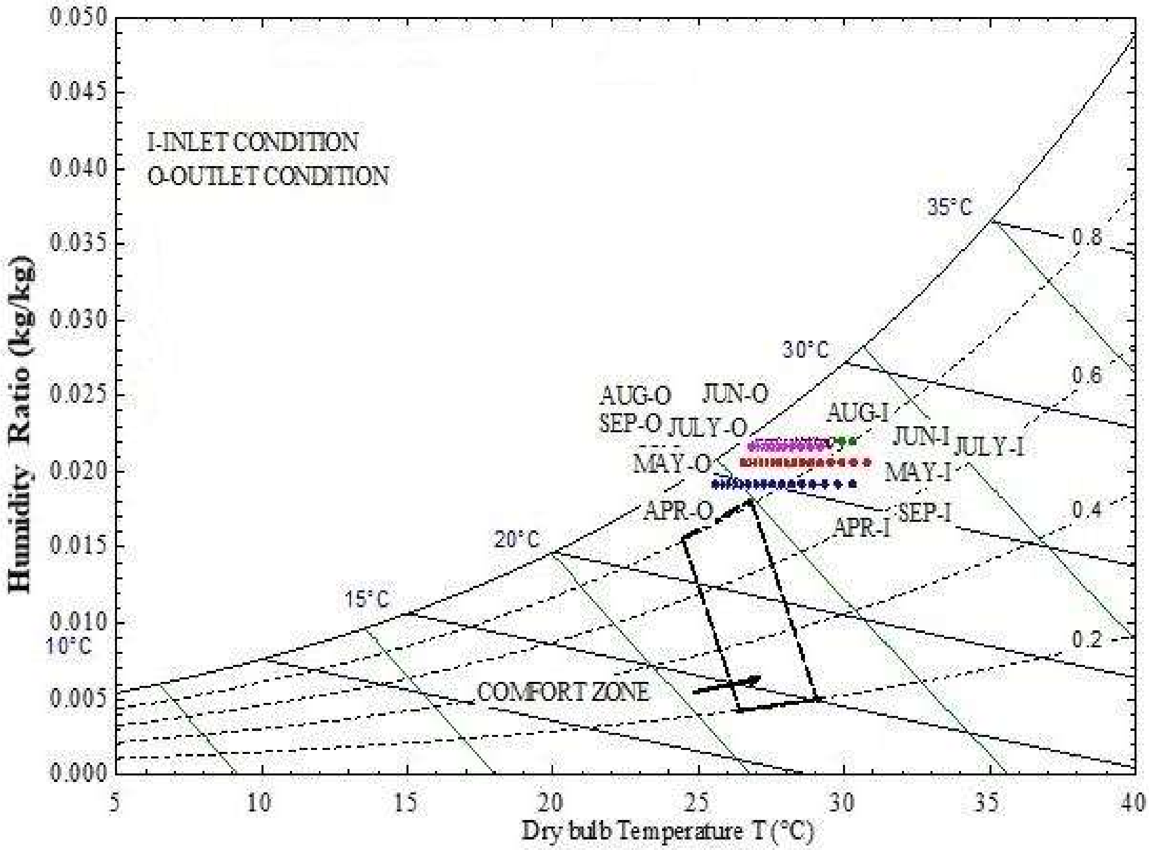

Fig. 6.16 Psychrometric chart showing REC mode results for Kolkata

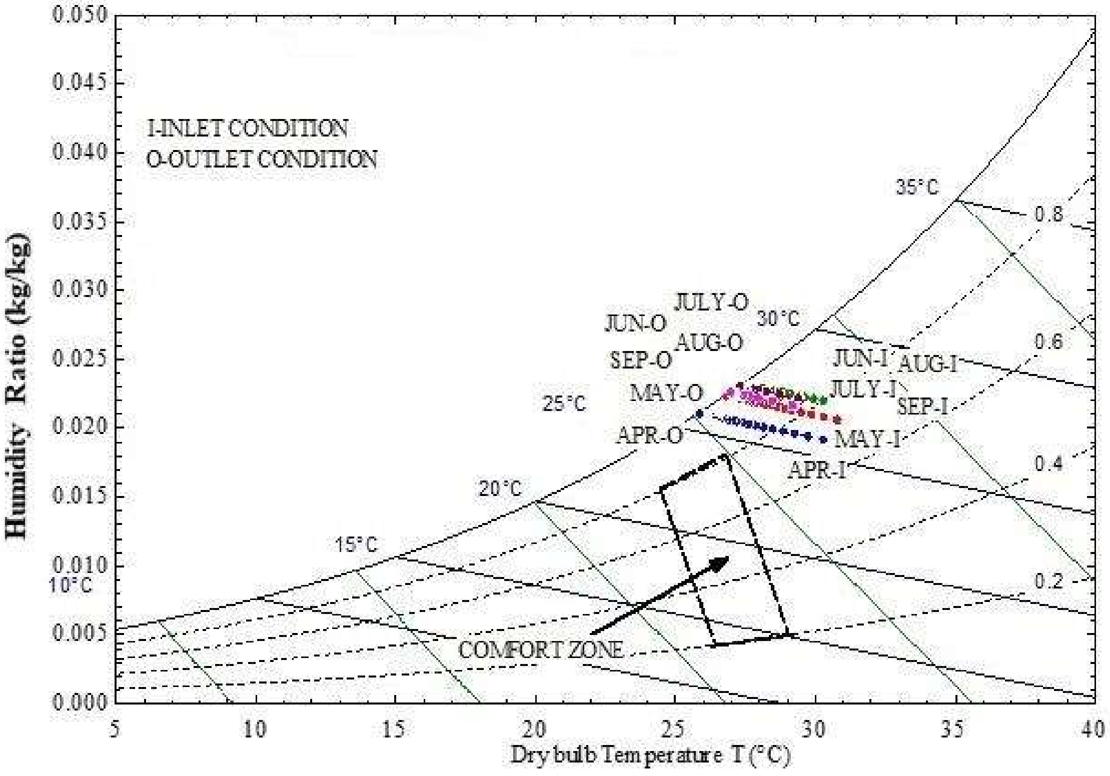

Fig. 6.17 Psychrometric chart showing DEC mode results for Kolkata

The annual climatic design data is used to compare the performance of both modes for all five cities. Month-wise climatic data are listed in Table 6.4. Cooling energy produced depends on the mass flow rate of air and temperature difference between inlet and outlet. In REC mode, the mass flow rate is reduced due to the extracted air, but it produces a lower outlet temperature than that of DEC mode. The Cooling energy produced of DEC mode is more as compared to REC mode for all the five different cities of the international climatic zones. The Cooling energy produced gets reduced when we move from climatic zone 1 to 4 for both modes (Table 6.4). The regenerative mode has the potential to cool air to a temperature between the wet bulb and dew point temperature. Direct mode delivers air in between 80-90% of the wet-bulb temperature. There is a possibility to restrict the outlet air up to the desired (comfort zone) relative humidity by governing the other parameters. In climatic zone 3, July and August months show higher cooling energy produced in both the modes. Similar results are also obtained for climatic zone 4, such as lower temperature by REC and higher cooling energy produced by DEC mode (Table 6.4). The specific cooling energy of the REC is higher due to more temperature drops obtained as compared to DEC. However, the total cooling energy (which includes the mass of supplied air) of the direct mode is higher as compared to the regenerative mode. The DEC mode supplies complete intake air to the conditioning space while REC mode wastes a large portion (depending upon extraction ratio) of the intake air as exhaust air in the environment. The climatic zone 1 shows the highest exergy destruction for DEC mode of operation. The exergy destruction is more for the direct mode of operation as compared to REC mode for all the five cities. The mixing of air and water vapor is an irreversible process, and irreversibility is more in DEC as compared to REC mode of operation. In REC mode, some exergy is recovered in sensible cooling from wet to dry channel heat exchange. Exergy destruction is directly related to the wet-bulb depression. The wet-bulb depression is less at the inlet of the wet channel in REC mode, and hence there is less destruction of exergy. The cities (Brisbane and Brazilia) of climatic zone 2 yield the highest exergy destruction in REC mode. The city of climatic zone 4 shows the lowest exergy destruction for DEC mode. The exergy destruction decreases from zone 1 to 4 in the direct mode of operation. The exergy destruction rate varies for all months depending upon inlet humidity and temperature conditions, as listed in Table 6.4.

The dew point effectiveness of the different cities in DEC mode is shown in Fig. 6.18. The climatic Zone-3 reached the highest effectiveness among the other zones for all months except April. The Brazilia city shows its lowest effectiveness from June to September months. The REC mode effectiveness of the device is shown in Fig. 6.19. The highest effectiveness of approx. 77% is obtained for the September month in climatic zone 3. The effectiveness increases from April to July for climatic zone 4, after it starts decreasing for the remaining two months. The climatic zone-1 shows increases in the effectiveness of the device from April to August. The COP of the DEC mode is highest in the dry months for climatic zone 1, as shown in Fig. 6.20. The COP of the Brazilia city increases continuously from April to September. The COP of the Brisbane and Shanghai follow the alternate increasing and decreasing pattern. The COP of the REC mode is shown in Fig.6.21. The lowest COP of 36 is obtained for the June month of Brisbane city. The COP of climatic zone 1 starts decreasing after June month due to an increase in the humidity conditions from June onwards. In the direct mode, only one exhaust fan is needed, and pressure drop is reduced. Hence, the coefficient of performance is much higher for DEC mode as compared to REC mode. The maximum COP is obtained for the direct mode of operation of the device in climatic zone 1. The averaged COP goes down from climatic zone 1 to 4 for both modes. The averaged exergy efficiency of DEC mode is 5.8 % lesser than that of REC mode. Brazilia city shows the lowest exergy efficiency in both modes. The month-wise exergy efficiency of REC mode is presented in Fig. 6.22. The exergy efficiency is highest for Shanghai and lowest for Brisbane in four months (June to September). The low exergy destruction rate ensures a high exergy efficiency of the device. The city of zone 1 shows marginal increases in the exergy efficiency from April to September in REC mode. The exergy efficiency of Brisbane and Brazilia is lowest in June and July. Delhi shows the highest exergy efficiency in DEC mode (Fig. 6.23) during dry months; however, its value decreases in July, August, and September.

Table 6.4: Results of dual-mode cooler for five cities of different climatic zones

			REC				**DEC**			
	T_{in} (°C)	RH_{in} (%)	T_{out} (°C)	RH_{out} (%)	Q (W)	$Exergy_{dest}$ (W)	T_{out} (°C)	RH_{out} (%)	Q (W)	$Exergy_{dest}$ (W)
Delhi										
April	41.6	15.05	22.33	44.8	5144	211.6	24.24	77.6	6924	449.1
May	44.1	12.9	22.82	42.4	5634	246.8	25.06	76.5	7533	532.7
June	44.2	15.77	23.77	49.3	5421	214.9	26.12	78.0	7166	464.6
July	40.2	32.32	25.95	71.9	3855	92.02	28.04	84.6	4914	200.8
Aug	37.1	43.07	26.18	80.0	2992	53.83	27.97	87.8	3736	116.5
Sept	36.4	39.92	25.09	76.1	3097	62.98	26.76	86.9	3945	131.7
Brisbane										
April	29.4	46.21	21.44	74.1	2220	47.77	22.17	88.6	3013	83.88
May	27.1	37.73	18.79	62.4	2326	65.94	18.93	86.3	3413	113
June	24.7	50.38	18.8	72.2	1667	40.60	18.83	89.8	2476	61.61
July	24.2	39.48	17.22	60.7	1971	59.97	16.89	86.9	3082	96.4
Aug	27.0	33.91	18.22	57.8	2457	75.93	18.24	85.2	3660	131.9

Sep	30.1	26.23	18.86	51.4	3110	106.4	19.19	82.5	4508	198.7
Brazilia										
April	30.8	37.22	21.01	66.4	2714	69.48	21.77	86.1	3736	128.1
May	30.0	32.48	19.78	59.7	2833	83.36	20.29	84.6	4021	152.9
June	28.8	26.64	18.21	50.4	2941	102.4	18.32	82.7	4346	187.8
July	29.2	22.69	17.82	45.0	3153	119.8	17.86	81.3	4692	223.7
Aug	32.0	18.18	18.48	40.6	3711	151.4	18.84	79.4	5392	295.4
Sep	33.2	16.18	18.68	38.2	3968	168.6	19.18	78.5	5724	334.5
Shanghai										
April	29.2	46.01	21.28	46.0	2210	48.18	21.97	88.6	3014	84.2
May	32.2	33.81	21.32	33.8	3003	80.94	22.23	85.0	4108	153.8
June	35.2	52.83	26.59	52.8	2378	33.32	28.21	90.4	2884	71.47
July	38.0	42.59	26.71	42.5	3087	54.91	28.61	87.7	3835	121.5
Aug	38.0	45.52	27.29	45.5	2933	47.08	29.2	88.5	3596	106.5
Sep	34.1	56.98	26.45	56.9	2120	27.54	27.96	91.4	2541	57.29
Seoul										
April	25.5	30.15	16.85	51.2	2426	85.01	16.48	84.0	3780	146.7
May	29.1	32.73	19.29	58.9	2727	81.60	19.65	84.7	3924	147.4
June	31.7	35.47	21.29	65.5	2878	75.20	22.16	85.6	3939	141.4
July	34.0	51.9	25.55	84.3	2339	35.68	27.01	90.2	2888	72.64
Aug	34.3	45.48	24.68	79.2	2654	48.58	26.12	88.5	3370	97.94
Sep	30.5	46.28	22.2	75.5	2310	47.56	23.1	88.7	3077	86.04

The exergy efficiency during July and August is highest for Seoul, while lowest for Brazilia and Brisbane. The climatic zone 4 shows the increase (12 %) in exergy efficiency from April to July, which further decreases up to September.

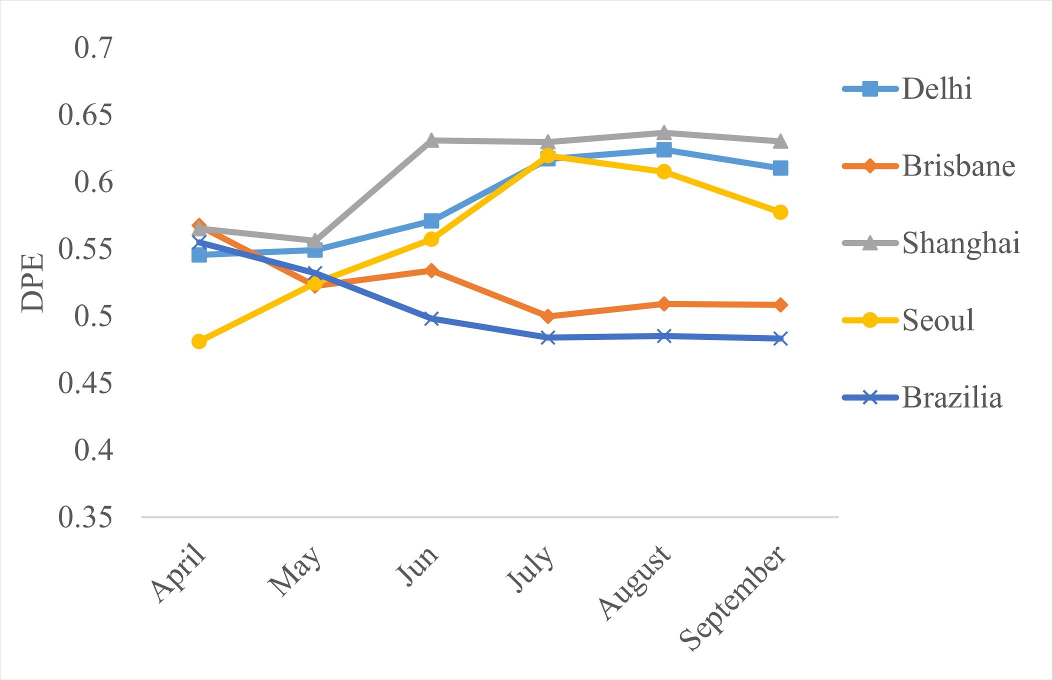

Fig. 6.18 Dew point effectiveness of DEC modes of evaporative cooler

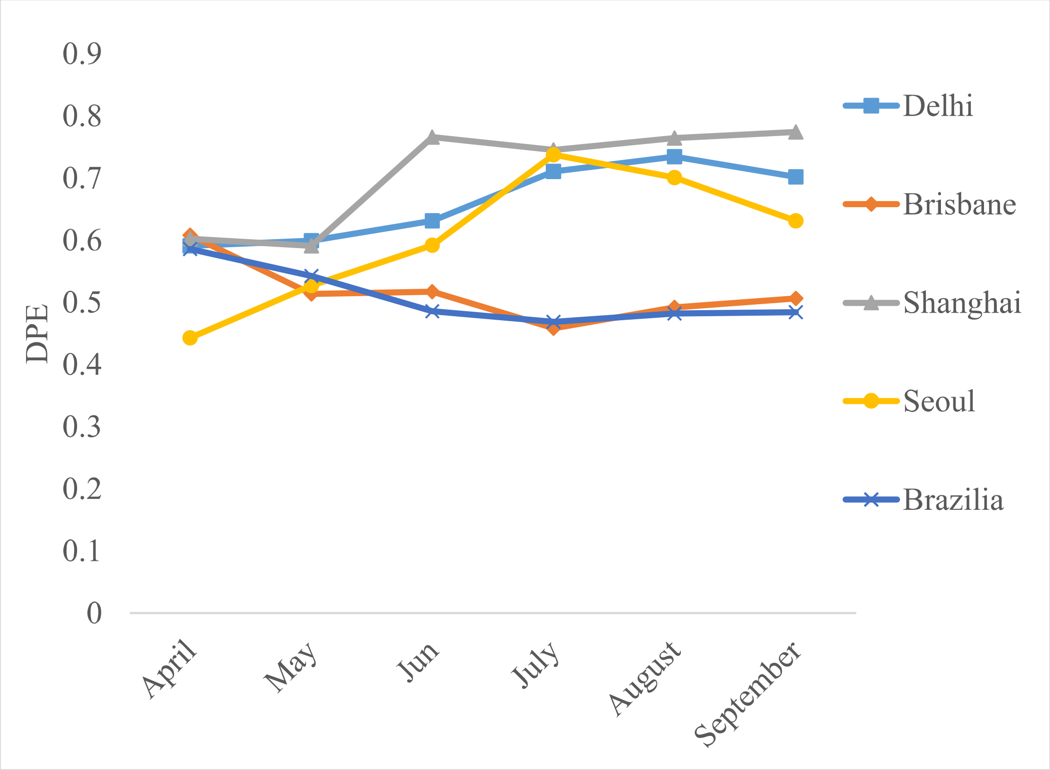

Fig. 6.19 Dew point effectiveness of REC modes of evaporative cooler

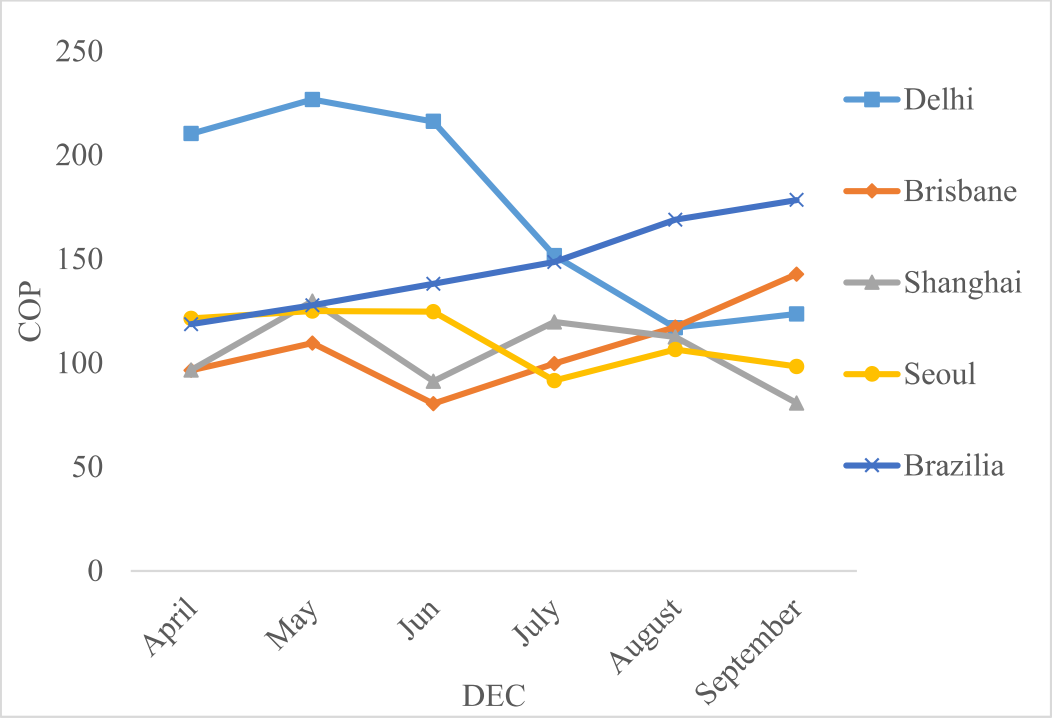

Fig. 6.20 Coefficient of performance of DEC modes of evaporative cooler

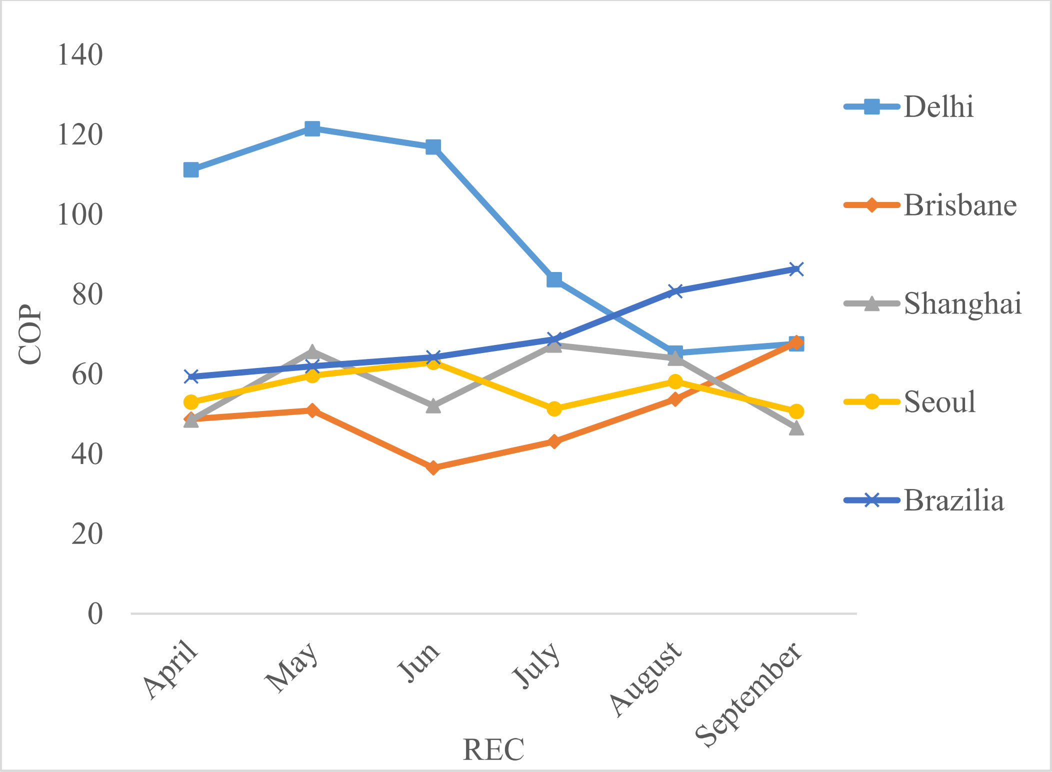

Fig. 6.21 Coefficient of performance of REC modes of evaporative cooler

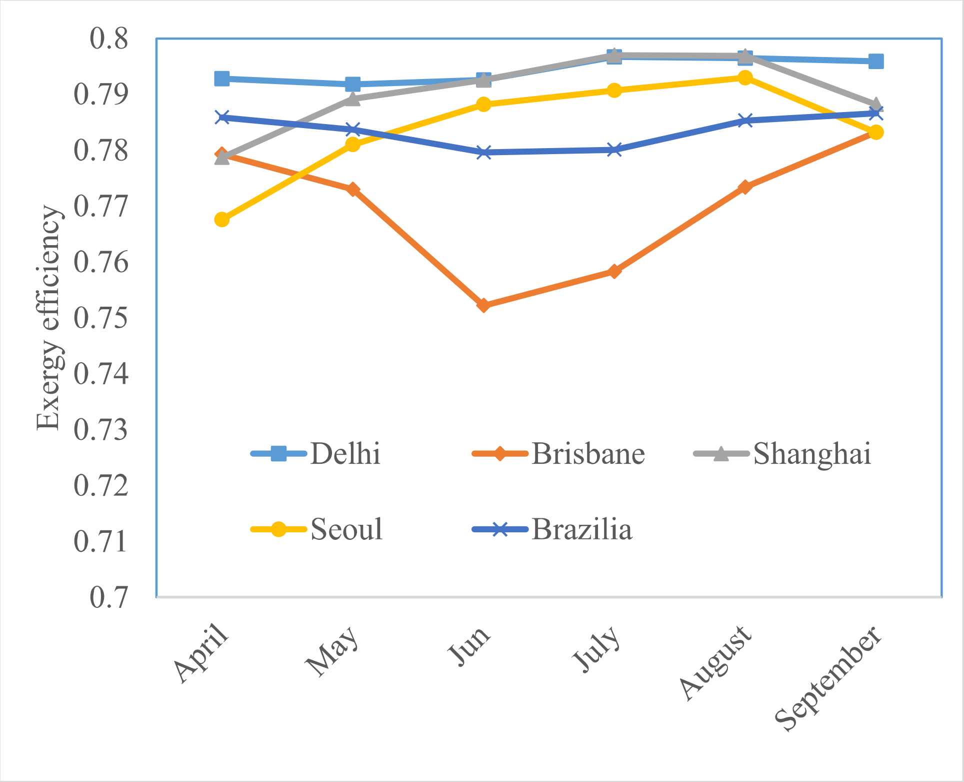

Fig. 6.22 Month-wise variation of exergy efficiency in REC mode

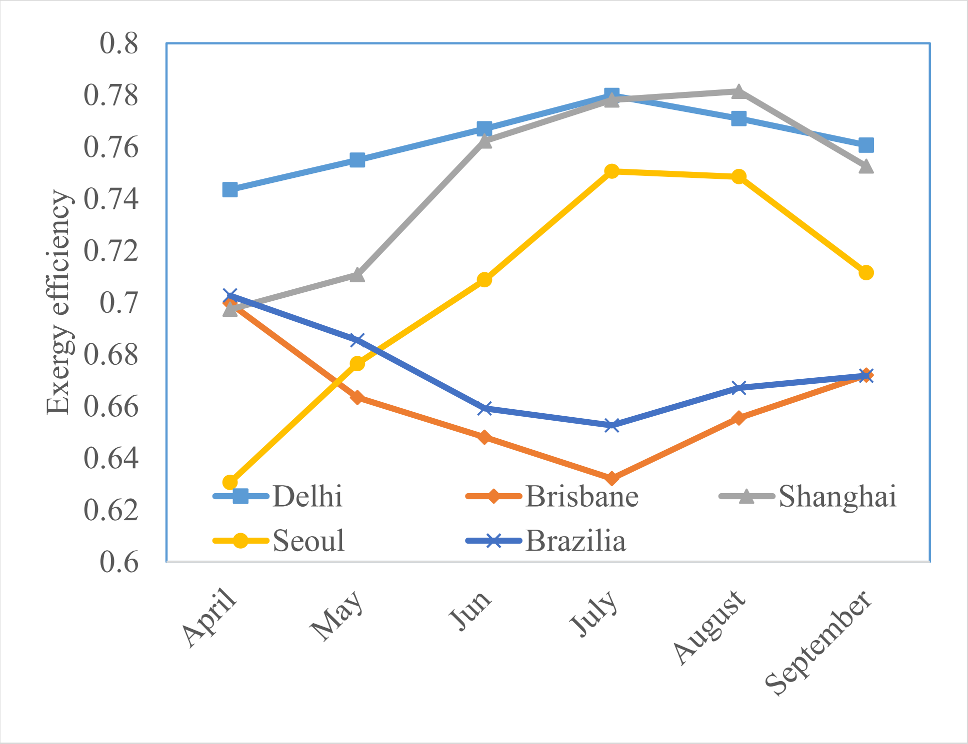

Fig. 6.23 Month-wise variation of exergy efficiency in DEC mode

The month-wise specific total cost for REC and DEC modes is presented in Figs. 6.24 and 6.25, respectively. The specific total cost of Brisbane is highest in both modes due to the high operating cost of the device. Delhi city shows a low specific total cost from April to July due to high cooling energy produced and low electricity charges. The specific total cost of DEC mode is less in all zones for all six months. The specific cost of Shanghai city keeps decreasing and increasing trend from April to August in both modes. The specific cost for zone-1 increases while for zone-2, it decreases from April to September. The specific cost for zones 2 and 3 do not show too many fluctuations from April to September. In climatic zone 2 (Brisbane city), REC gives lower temperature and cooling energy produced while DEC shows lower specific total cost. Brazilia city has the lowest total specific cost in the month of August and September.

The single-mode direct evaporative cooler is available in the market, and its wet-bulb effectiveness range is similar to that of the dual-mode cooler in DEC mode. REC mode performance of the dual-mode evaporative cooler is similar to the regenerative evaporative cooler presented in the literature, where effectiveness lies closer and above one. The cooling capacity of the dual-mode cooler can be improved by increasing the height (number of plates) of the heat and mass exchanger. The dual-mode evaporative cooler is best for composite climate (DEC is suitable for some months and REC for others), and about 40% annual cost saving is possible by using this device instead of two single-mode (DEC and REC) devices. The operating mode selection depends upon the climatic (inlet temperature and inlet humidity) conditions. The wet-bulb temperature includes both performances influencing properties (temperature and humidity). The analysis shows that the device should be operated in REC mode if the wet-bulb temperature of intake conditions is greater than 24 ºC. The dual-mode device should be switched to DEC mode below this wet bulb condition.

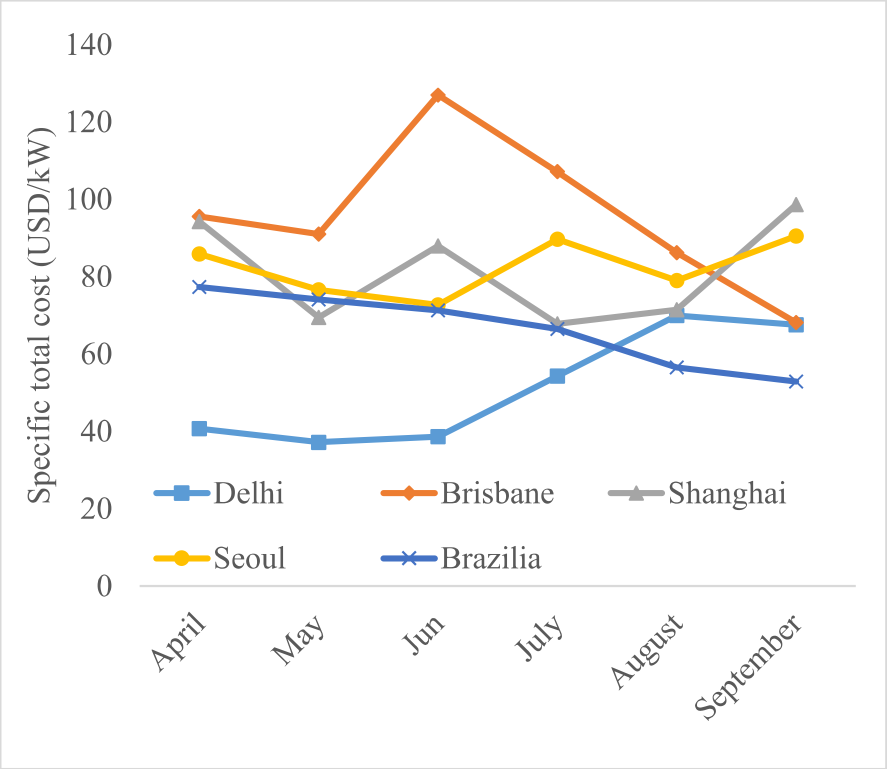

Fig. 6.24 Month-wise variation of specific total cost in REC mode

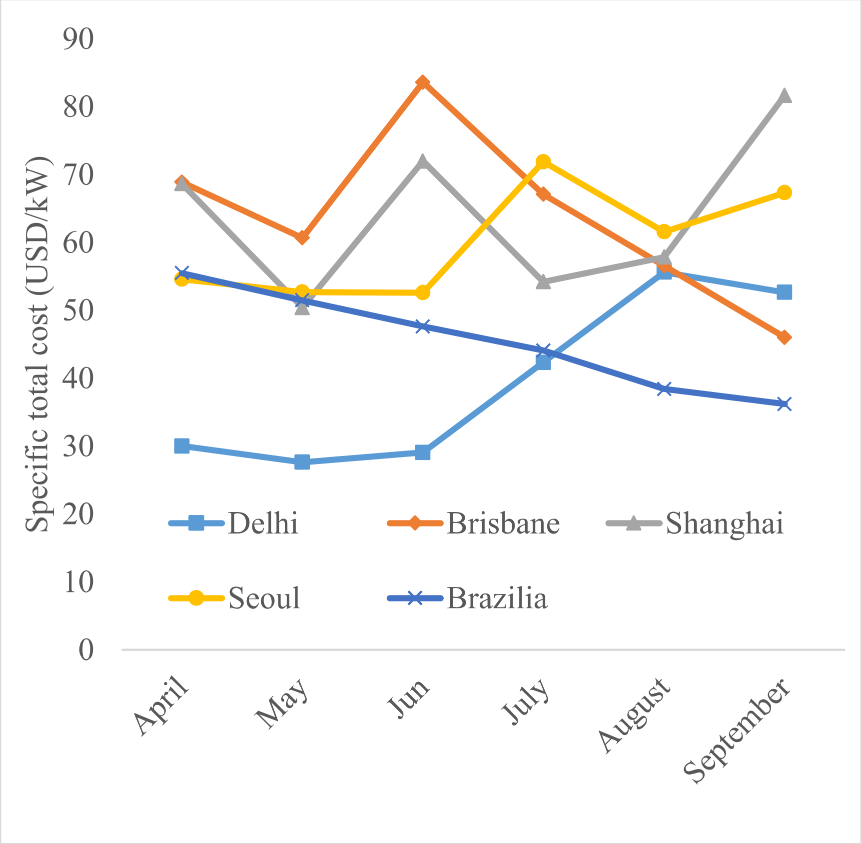

Fig. 6.25 Month-wise variation of specific total cost in DEC mode

6.5. Performance assessment for futuristic climatic scenarios

There is a scientific consensus that climate change is occurring, and its evidence can be seen through temperature data. The temperature increase is widespread across the globe and is greater at higher northern latitudes. The average global surface temperature (combined land and ocean), as calculated by a linear trend, shows warming of 0.85 [0.65 to 1.06] °C over the period 1880 to 2012 (I. P. C. C., 2014). Climate change also affects the performance of the device, which mainly depends on outdoor conditions (temperature and humidity). The suitability of the device may vary from one climate to another over a decade. To check the future suitability, of the device, it is needed to do city-specific weather forecasting and evaluate its performance on that predicted data. However, to the best of the authors' knowledge, no such study has been performed on an evaporative cooler to date.

Hence, in this study, the performance of the dual-mode evaporative cooler is evaluated for the varied climatic conditions of India. The specifications which have been used for the dual-mode evaporative cooler are listed in Table 6.5. The future weather forecast has been made using past data of temperature and humidity over the period 1999-2019. The historical data is taken from the National Centres for Environmental Prediction (NCEP) and Climate Forecast System Reanalysis (CFSR) (Globalweather.tamu.edu, 2020) data center. For this purpose, 4 Indian cities were chosen, and the performance of regenerative and direct evaporative was made for present (2019) and future weather (2030) conditions. For model validation, the experimental test rig of a dual-mode evaporative cooler has been developed and tested. The performance of the regenerative mode and direct mode of the cooler has been compared. The usefulness of the modes and devices for different months of the different climatic zones has been investigated. The novelty of this work is the performance forecasting of dual (regenerative and direct) mode cooling devices in future scenarios for diverse (composite, hot-dry, and hot-humid) climatic conditions.

6.5.1 Weather forecasting

Weather forecasting is still a complex and very challenging task for researchers. The changing weather conditions make it more complicated. However, ARIMA and the exponential smoothing method is a proven and very powerful technique to predict climatic data. The triple exponential smoothing is the most effective tool to predict the time series weather data. The forecasting of the temperature and relative humidity of the next ten years has been done with the help of the exponential smoothing method. The historical data used to do forecasting is based on additive trend, additive seasonality, and additive error. The forecasting is done with a 95% confidence interval. It indicates that 95% of the future forecasted data lies within the range. This forecasting method is known as the recursive time-series technique. This method reduces the weight of the past data exponentially. The most recent data gets the highest weight. The smoothing constant used in the triple exponential smoothing method is calculated by minimizing the error sum of square in the observed (In hand) data. Marera and Beichelt, (2016) used the 1950- 2014 data set to predict rainfall and 1956-2014 data to predict the temperature and compared the result with the four applied forecasting methods. They concluded that exponential smoothing gives better prediction than seasonal native forecasting methods. The excel advance forecasting tool is used to create a forecast sheet with the help of historical monthly averaged data.

The temperature of Varanasi city for the month of May, June, July, and September months increases from 2019 to 2030 (Fig. 6.26). The relative humidity increases for three months while it decreases for the remaining three months (Fig. 6.27). A similar analysis has been done for other chosen cities, and the results are presented in Figs. 6.28 and 6.29.

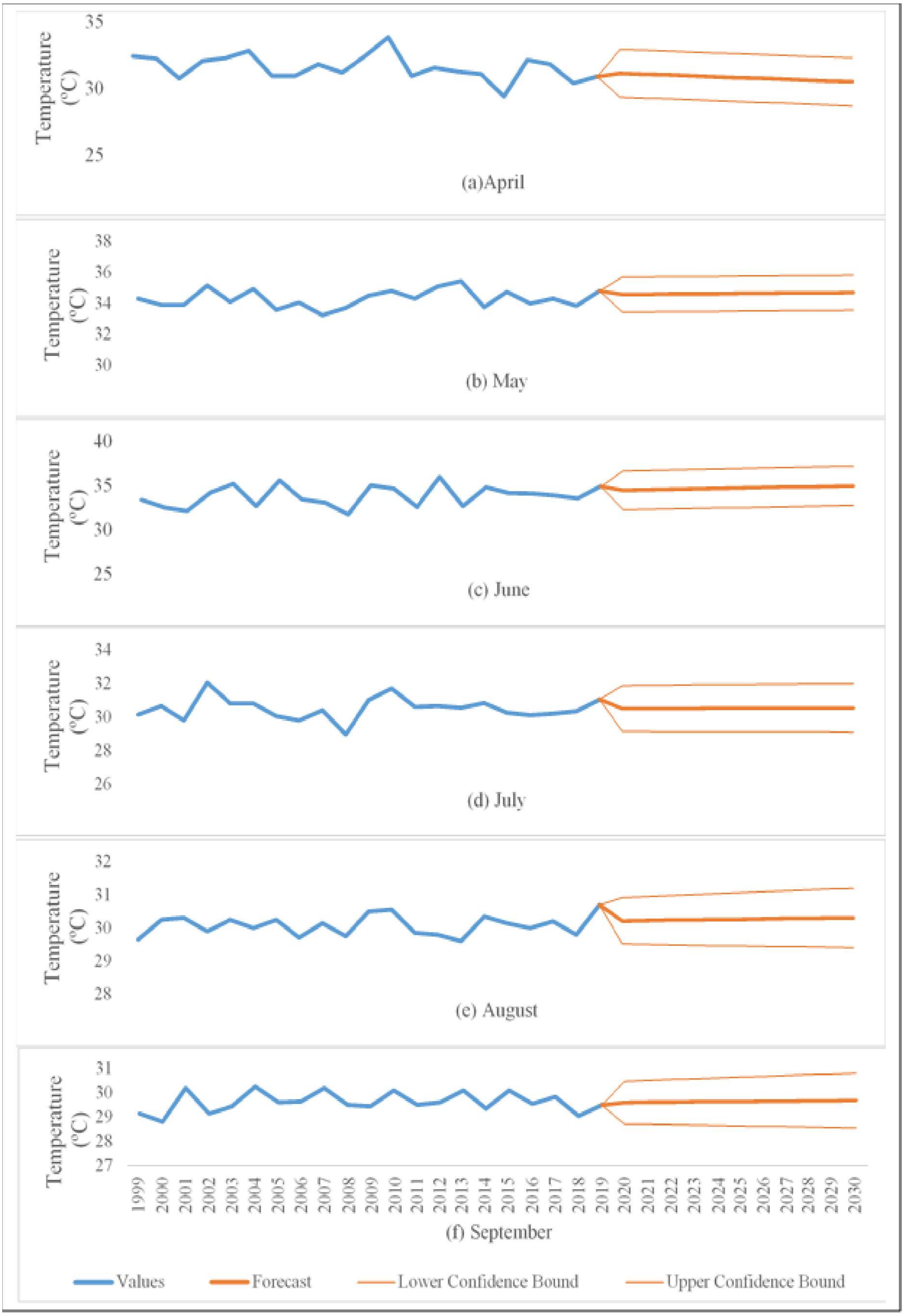

Fig. 6.26 The forecasting of temperature for the Varanasi City

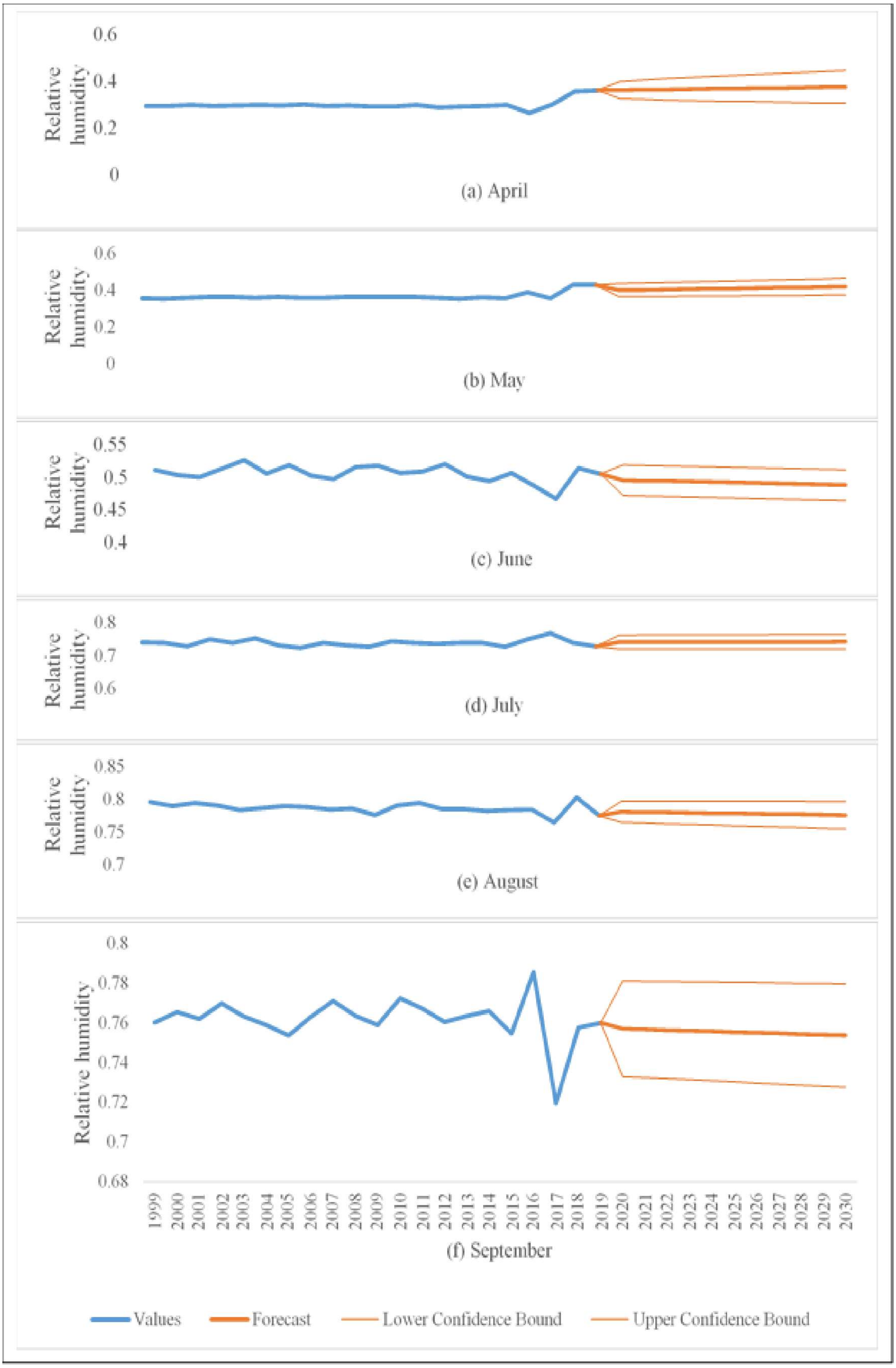

Fig. 6.27 The forecasting of relative humidity for the Varanasi City

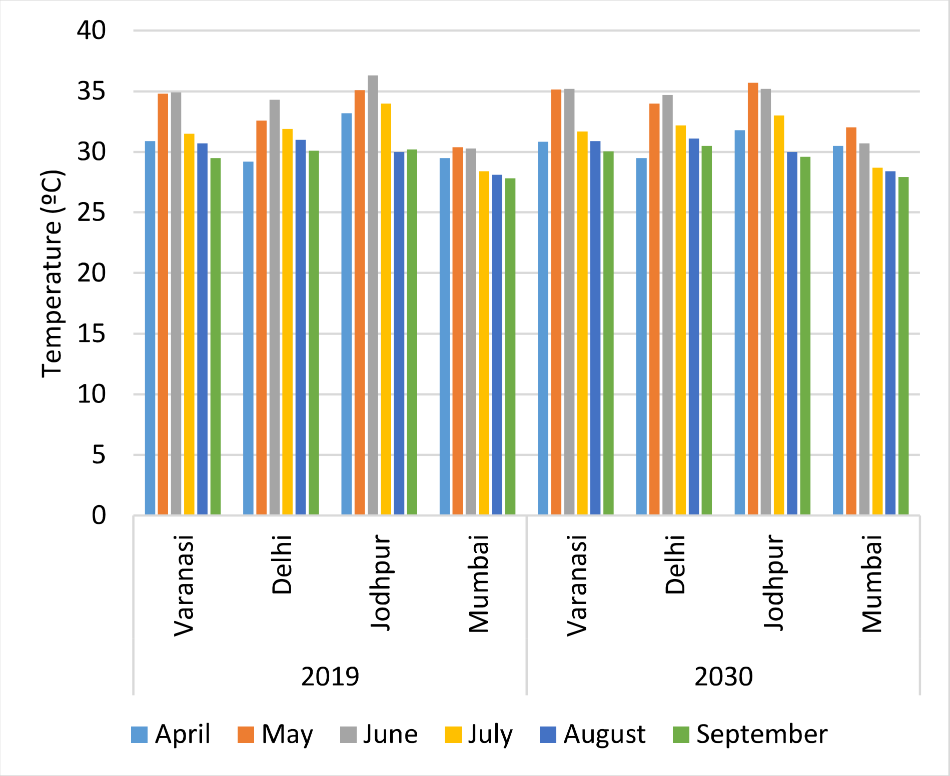

Fig. 6.28 Monthly present and forecasted temperatures of the different city

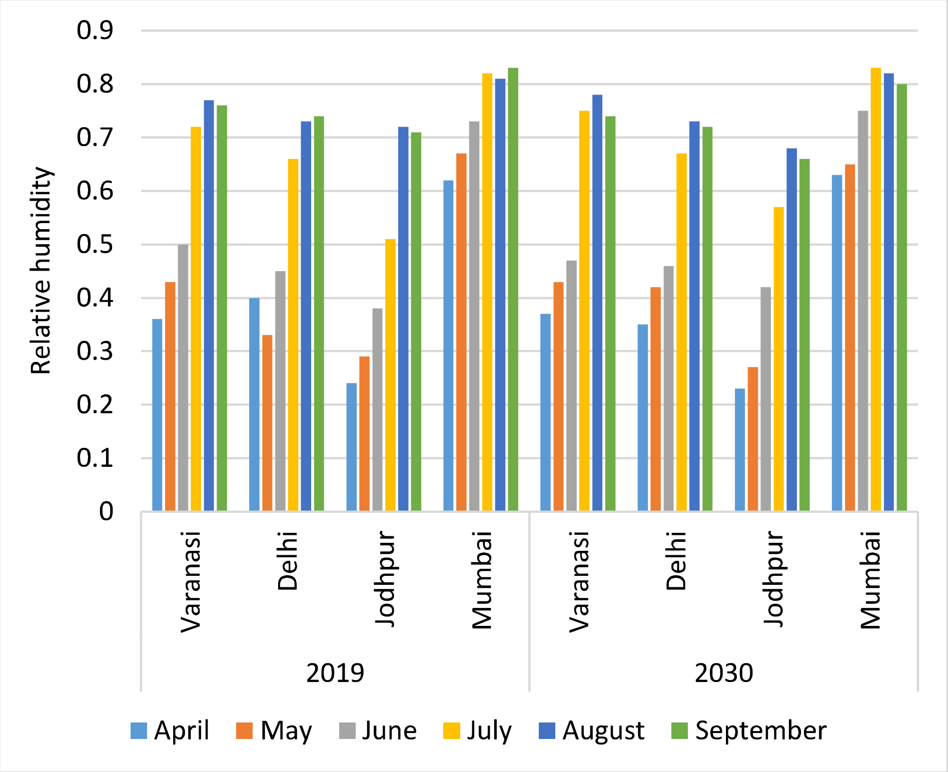

Fig. 6.29 Monthly present and forecasted humidity of the different city

The first city (Jodhpur) is chosen from the hot and dry climates of India, while the fourth city (Mumbai) is a coastal city that remains humid for most of the years. The temperature of all six months of Delhi city increases for the forecasted year of 2030. The relative humidity of the June and July months of Jodhpur city increases for the forecasted 2030 weather scenario. Mumbai city will be hotter in 2030 as compared to 2019 in all six investigated months. The relative humidity of Mumbai city decreases for May and September month while remaining close for the rest of the months in forecasted years.

Table 6.5: Geometric and operating parameters of evaporative HMX for forecasting

Length of the cooling device (regenerative and direct)	1.2 m
Width of the cooling device (regenerative and direct)	0.5m
The total height of the HMX	0.7 m
The gap between the channels	0.005 m
The thickness of the plate separating two channels	0.5 mm
The volumetric flow rate of water per channel	1 L/h
Inlet temperature of the water	17 ºC
Air extraction ratio	0.33
Inlet primary air velocity	2 m/s

6.5.2 Performance forecasting

The performance of the dual-mode evaporative cooler has been assessed for various future climatic conditions. The state points of the cooling device are plotted at the psychrometric chart with the thermal comfort zone. The thermal comfort for evaporative cooling lies between 20% and 80% relative humidity curves (Watt, 2012). The rusting and contamination of material started above 80% while below 20 % skin and respiratory problem was reported. However, this zone varies marginally with the indoor air velocity.

Forecasted results of the year 2030 are shown in Figs 6.30 and 6.31 for DEC and REC modes, respectively. The dry months (April and May) are only suitable for DEC mode. The rest of the months are out of the thermal comfort zone. Psychrometric chart shows the dry channel (Primary) air states while passing through the cooling device. The outlet condition of the April month lies on the left side of the comfort zone. This shows its potential to deliver it in the thermal comfort zone. This can be achieved by increasing air velocity or adjusting other parameters of the device. So the REC mode of the device shows its suitability for the month of April, May, and June. The conditions of July, August, and September months are out of the thermal comfort zone. Delhi is also a city of the composite climatic zone, which has a hot summer, followed by humid seasons. The results of Delhi city are also similar to Varanasi city, where April, May, and June months show the suitability of the regenerative mode of the cooling device.

Jodhpur City belongs to the hot and dry climate of India. The direct mode result is only suitable for dry months (April and May), while for the month of June, it just touches the comfort zone. The regenerative mode of the cooling device performs satisfactorily for all six months of the year. Primary air passes through the thermal comfort zone. It shows the complete usefulness of the REC device for Jodhpur city. The evaporative cooling technology is still going to be useful and relevant for the hot and dry climates of India. Evaporative cooling will be suitable for only one month (April) in both modes of the device. In the case of Mumbai city, high humidity conditions are reached at a lower temperature compared to other cities. The relative humidity of Varanasi, Delhi, and Jodhpur city lies in the range of 0.24 to 0.5 for the April, May, and June months in 2019. The relative humidity of July month is the lowest (0.51) for Jodhpur city in 2019. The July and August months remain unsuitable for all four cities in both modes of the evaporative cooler except Jodhpur. The supply air of the device in these months remains

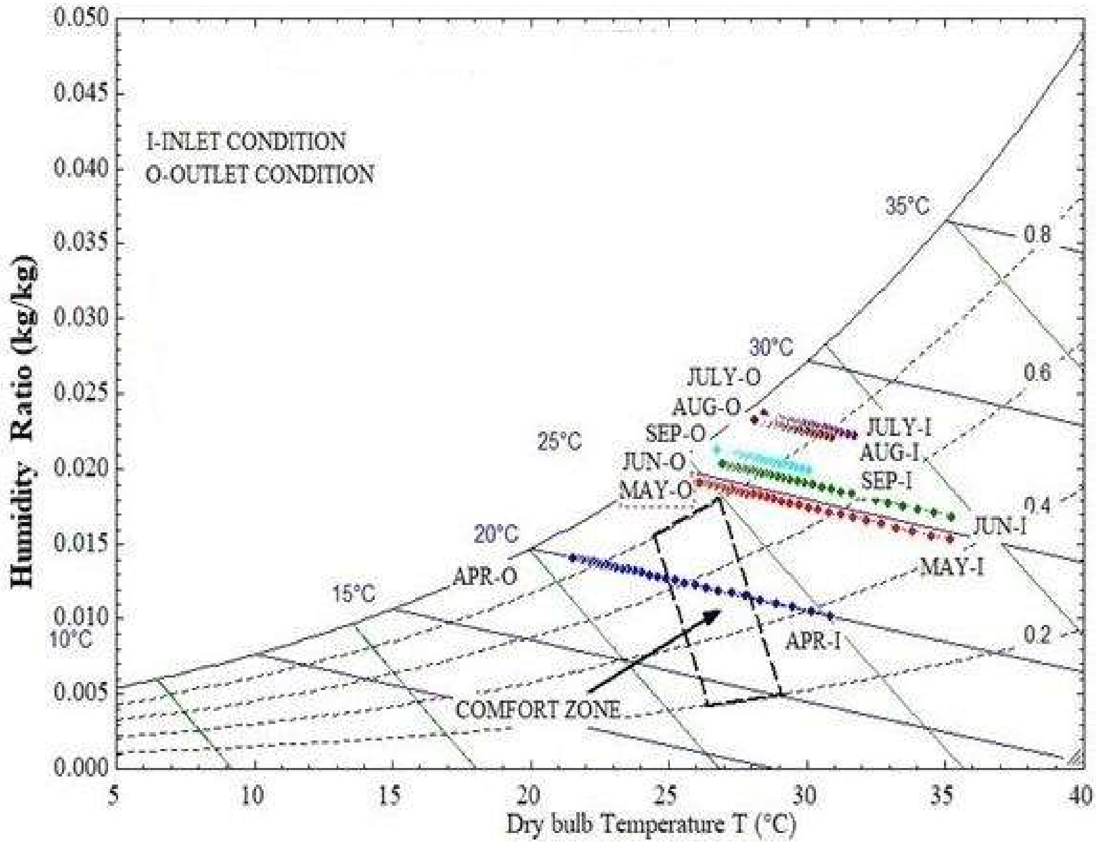

Fig. 6.30 Direct mode result of Varanasi city on the psychrometric chart

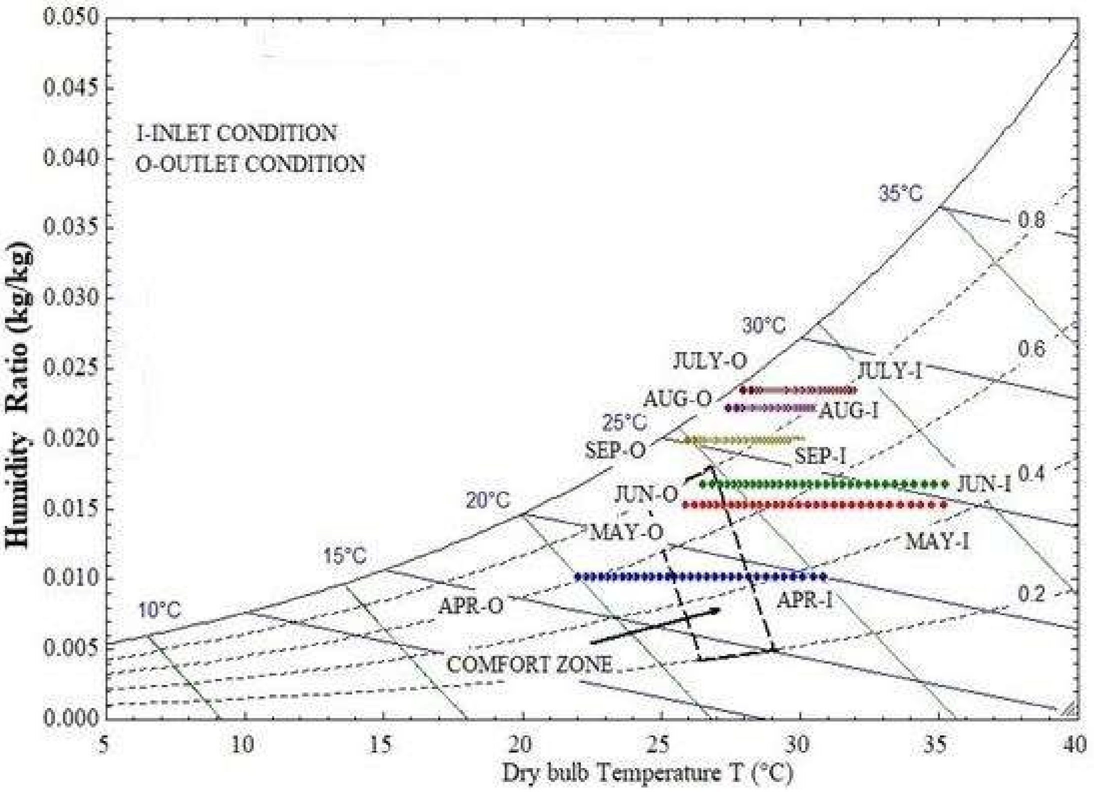

Fig. 6.31 Regenerative mode result of Varanasi city on the psychrometric chart

out of the thermal comfort zone due to high intake relative humidity at low temperature. The use of direct evaporative cooling will not be justified for Mumbai city. The humid climatic zones are usually not suited to evaporative cooling technology since inlet humidity is the key parameter that affects its performance. The above-presented performance of the device is for averaged monthly temperature and humidity. The actual outdoor conditions vary throughout the days. The Dual mode evaporative cooler can be automated to easily switch from direct mode (high cooling capacity and COP) to regenerative mode (cooling without moisture addition).

Table 6.6 and Table 6.7 summarise the result of both modes for the present (2019) and for future (for example, 2030) climatic scenarios. The table concludes the suited mode based on the state points of the cooler analyzed on the psychrometric chart. The state point passing through thermal comfort (even outlet state points at the left and top of the comfort zones) are recommended for evaporative cooling. Many cases occur where both modes provide comfort cooling; in such cases, DEC mode is preferred (selected as a suited mode) because of high cooling capacity and high COP. The direct mode performs effectively in dry months (April and May) for all cities except Mumbai. The REC mode shows lower supply air temperature and higher dew point effectiveness for most of the humid months. The only regenerative mode can provide comfortable cooling as the outdoor humidity increases. The REC mode is suited for two months in Mumbai city in the present scenario (2019), while it is going to be useful for just one month in a futuristic scenario (for example, 2030). None of the modes are suited for Jodhpur in the August and September months at present, while REC will be helpful in the futuristic scenario. Fig. 6.32 shows the hours of usability of the individual modes in a year based on the forecasted results. The device is assumed to be operated for 12 hours a day for particularly suitable modes. In Varanasi city, REC mode usability increases after 2026. The Jodhpur city predicts two times (2023 and 2028) increase in the REC mode usability hours. Mumbai city shows zero usability for DEC and decreased usability for REC after 2022. Overall, the usability of REC mode will increase, and that for DEC mode will increase in the future.

Table 6.6: Summary of results of both modes of the dual-mode cooler for the present (2019) scenario

	Outdoor condition		DEC mode result		REC mode result		Suited mode
	T_{in} (°C)	RH_{in}	T_{OUT} (°C)	RH_{out}	T_{OUT} (°C)	RH_{out}	
Varanasi							
April	30.9	0.36	21.45	0.8716	21.98	0.6091	DEC
May	34.8	0.43	25.88	0.8913	25.63	0.7274	DEC
June	34.9	0.5	27.29	0.9086	26.74	0.7964	REC
July	31.5	0.72	27.83	0.9534	26.93	0.9375	NONE
August	30.7	0.77	27.78	0.9623	26.83	0.9638	NONE
September	29.5	0.76	26.52	0.9604	25.7	0.9489	NONE
Delhi							
April	29.2	0.40	20.82	0.8825	21.36	0.6376	DEC
May	32.6	0.33	22.18	0.8631	22.67	0.5898	DEC
June	34.3	0.45	25.86	0.8963	25.57	0.7429	BOTH
July	31.9	0.66	27.31	0.9421	26.54	0.8993	NONE
August	31	0.73	27.51	0.9552	26.63	0.9404	NONE
September	30.1	0.74	26.81	0.9569	25.99	0.9403	NONE
Jodhpur							
April	33.2	0.24	20.73	0.8342	21.68	0.4711	DEC

May	35.1	0.29	23.21	0.851	23.62	0.5625	DEC
June	36.3	0.38	26.08	0.8783	25.88	0.688	DEC
July	34	0.51	26.7	0.9107	26.22	0.7971	REC
August	30	0.72	26.44	0.9532	25.68	0.9262	NONE
September	30.2	0.71	26.48	0.9514	25.74	0.9210	NONE
Mumbai							
April	29.5	0.62	24.55	0.9337	24.16	0.8485	REC
May	30.4	0.67	26.1	0.9438	25.45	0.8943	REC
June	30.3	0.73	26.85	0.9551	26.04	0.9352	NONE
July	28.4	0.82	26.26	0.9707	25.39	0.9786	NONE
August	28.1	0.81	25.84	0.969	25.03	0.9703	NONE
September	27.8	0.83	25.81	0.9724	24.98	0.9804	NONE

Table 6.7: Summary of results of both modes of the dual-mode cooler for the future (for example, 2030) scenario

	Outdoor condition		DEC mode result		REC mode result		Remark
	T_{in} (°C)	RH_{in}	T_{OUT}(°C)	RH_{out}	T_{OUT} (°C)	RH_{out}	
Varanasi							
April	30.83	0.37	21.58	0.87	22.07	0.62	DEC
May	35.15	0.43	26.17	0.89	25.88	0.73	REC
June	35.21	0.47	26.99	0.90	26.53	0.77	REC
July	31.70	0.75	28.44	0.95	27.45	0.95	NONE
August	30.90	0.78	28.11	0.96	27.11	0.97	NONE
September	30.06	0.74	26.77	0.95	25.95	0.94	NONE

Delhi							
April	29.50	0.35	20.19	0.86	20.94	0.58	DEC
May	33.99	0.42	25.03	0.88	24.91	0.70	DEC
June	34.70	0.46	26.38	0.89	26.01	0.75	REC
July	32.20	0.67	27.73	0.94	26.91	0.90	NONE
August	31.10	0.73	27.6	0.95	26.71	0.94	NONE
September	30.50	0.72	26.9	0.95	26.10	0.93	NONE
Jodhpur							
April	31.80	0.23	19.54	0.83	20.72	0.44	DEC
May	35.70	0.27	23.19	0.84	23.65	0.54	DEC
June	35.20	0.42	26.01	0.88	25.76	0.72	DEC
July	33.01	0.57	26.88	0.92	26.28	0.83	REC
August	30.01	0.68	25.88	0.94	25.25	0.89	REC
September	29.6	0.66	25.22	0.94	24.69	0.88	REC
Mumbai							
April	30.50	0.63	25.60	0.93	25.06	0.86	REC
May	32.04	0.65	27.29	0.94	26.53	0.89	NONE
June	30.70	0.75	27.51	0.95	26.60	0.95	NONE
July	28.70	0.83	26.67	0.97	25.75	0.98	NONE
August	28.40	0.82	26.26	0.97	25.39	0.97	NONE
September	27.90	0.80	25.53	0.96	24.77	0.96	NONE

Figs. 6.33 and 6.34 show the cooling capacity of the device in direct and regenerative modes, respectively. The direct mode of the evaporative cooler has a higher cooling capacity since no extraction of primary air occurs in the direct mode. Jodhpur city

shows the highest while Mumbai city shows the least cooling capacity. The April and May months show the highest cooling capacity as compared to other months of the year. The dry months are suited for both modes, but the direct mode has a higher cooling capacity. It is better to use direct mode in dry months till the temperature and humidity provided by it lie in the comfort zone. Suitability may also depend upon the volume of space to be cooled. The humid months (July, August, and September) already have much higher inlet humidity conditions, which make it unsuitable for the direct mode of operation. The highest regenerative mode cooling capacity of 3.2 kW is obtained for the May month in Jodhpur city (Fig 6.34). The REC mode six-month averaged cooling capacity of the Varanasi, Delhi, and Mumbai city increases from 2019 to 2030 forecasted conditions. The REC mode cooling capacity decreases sharply after June months in both present and futuristic climatic conditions. The composite climatic cities (Varanasi and Delhi) show a futuristic (for example, 2030) increase in cooling capacity for September month while a decrease for July.

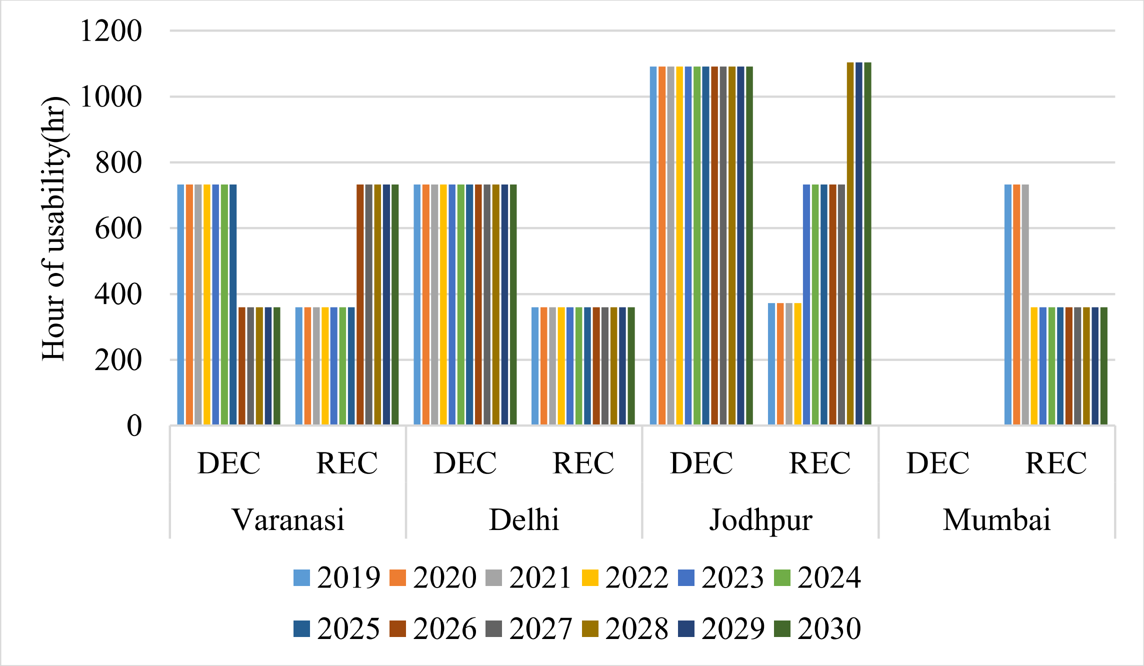

Fig. 6.32 Yearly hours of usability of the individual modes

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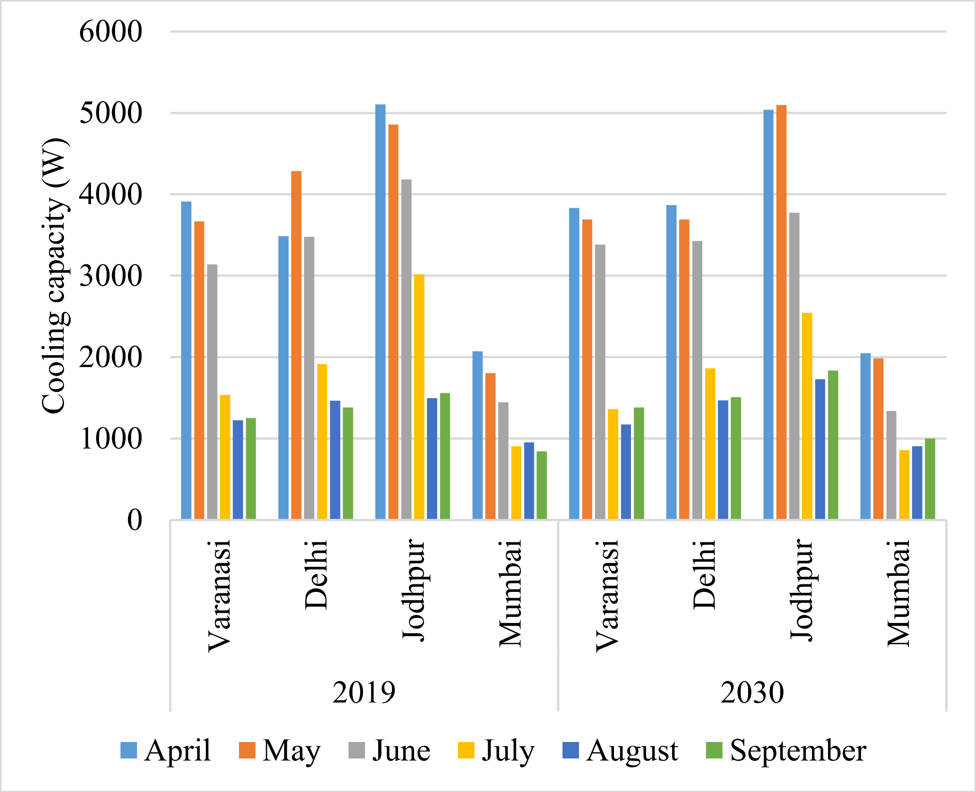

Fig. 6.33 Monthly present and forecasted cooling capacity of different city in DEC mode

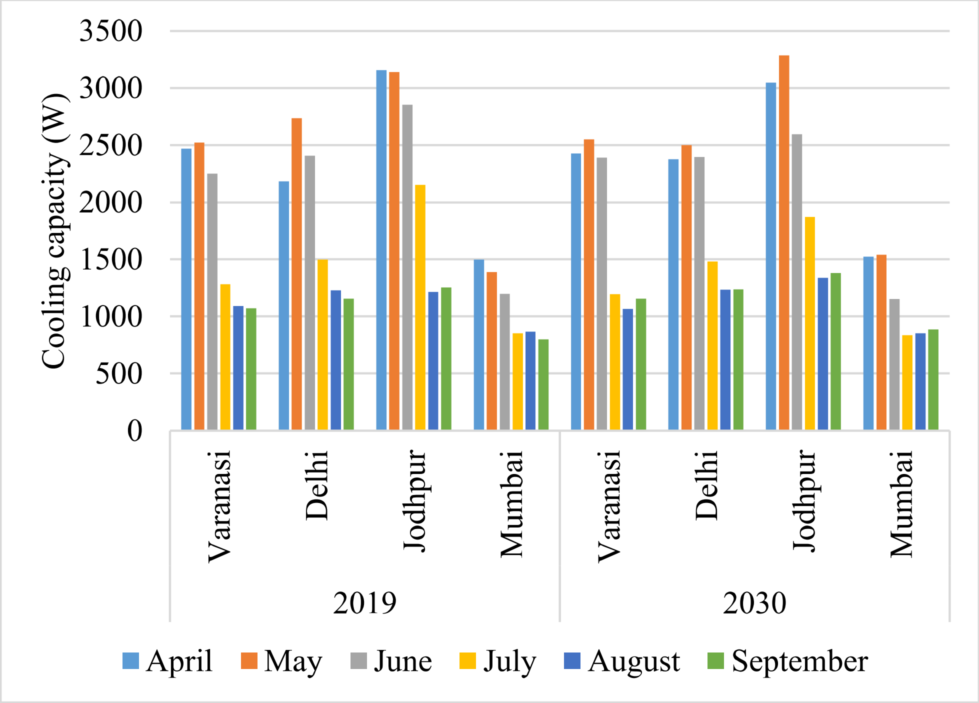

Fig. 6.34 Monthly present and forecasted cooling capacity of different cities in REC mode

The dew point effectiveness results of direct mode are presented in Fig. 6.35. The effectiveness of the direct mode lies in the range of 0.5 to 0.65. The humid months show the highest effectiveness, but the cooling produced is poor. The dew point effectiveness of the devices increases from April to June for all cities except Mumbai. The effectiveness of the device decreases for Delhi and Jodhpur city by 2.3 % and 3.2 %, respectively, in April months from 2019 to 2030. The effectiveness of the device for Mumbai city increases for all months except September when compared 2019 to futuristic conditions. The Varanasi and Delhi cities show similar trends since both cities belong to the composite climate zone. The effectiveness of Mumbai city is highest, but it is the least favorable city for evaporative cooling applications. The effectiveness results for regenerative mode are shown in Fig. 6.36. The regenerative mode is a preferred mode in terms of supply air temperature and thermal comfort but has the disadvantage of less supply of air volume flow rate. The dew point effectiveness of the regenerative mode of the cooling device is varied between 46 -92 %. The effectiveness of the device decreases in the 2030 year for September month in all four cities. The regenerative mode effectiveness of the April, May, July, and August months increases while it decreases for the rest months. Mumbai city shows increased effectiveness for the first five investigated months. The increased relative humidity for the August month decreases regenerative dew point effectiveness by 5.6%. The effectiveness in the July and August months is higher as compared to other analyzed months.

The COP of both modes is shown in Figs. 6.37 and 6.38. The direct model shows a higher COP due to higher cooling capacity and lower fan power consumption. The direct. mode does not require additional fans to operate to make regeneration which reduces power consumption drastically. The COP of April, May, and June months is higher in both modes for all cities. The April and May months have the lowest relative

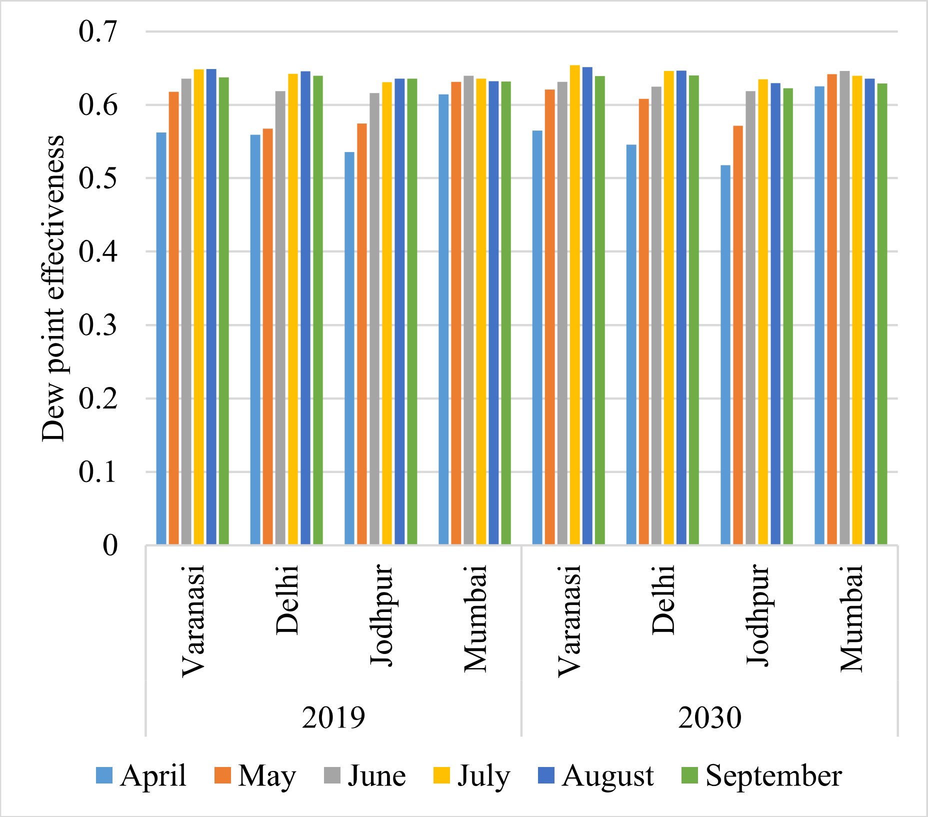

Fig. 6.35 Monthly present and forecasted effectiveness of different city in DEC mode

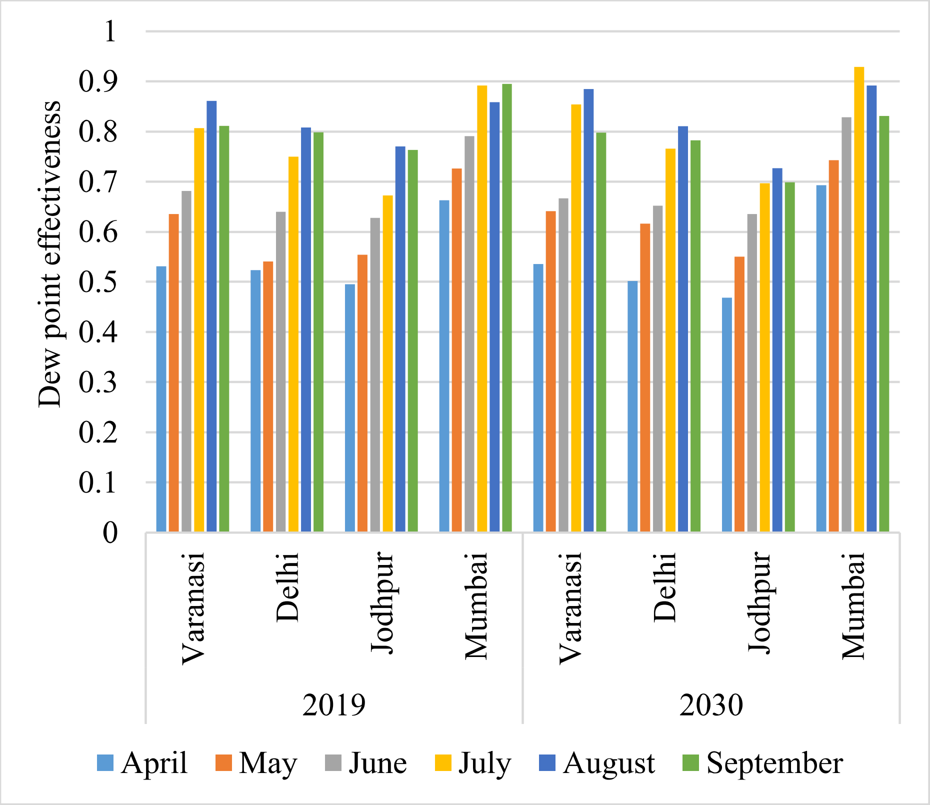

Fig. 6.36 Monthly present and forecasted effectiveness of different city in REC mode

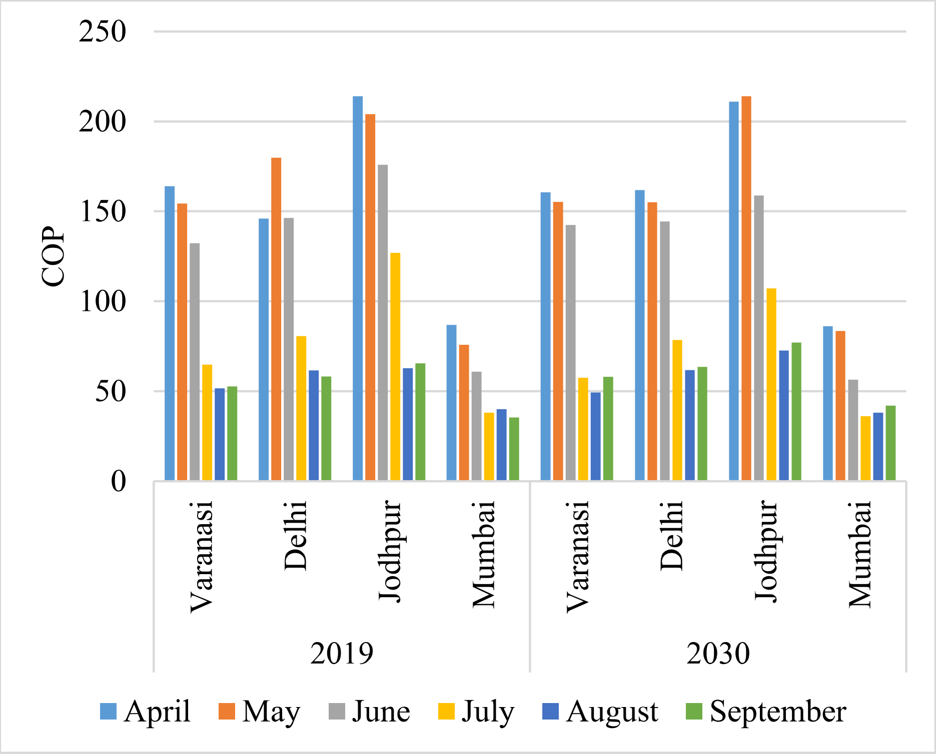

Fig. 6.37 Monthly present and forecasted COP of different city in DEC mode

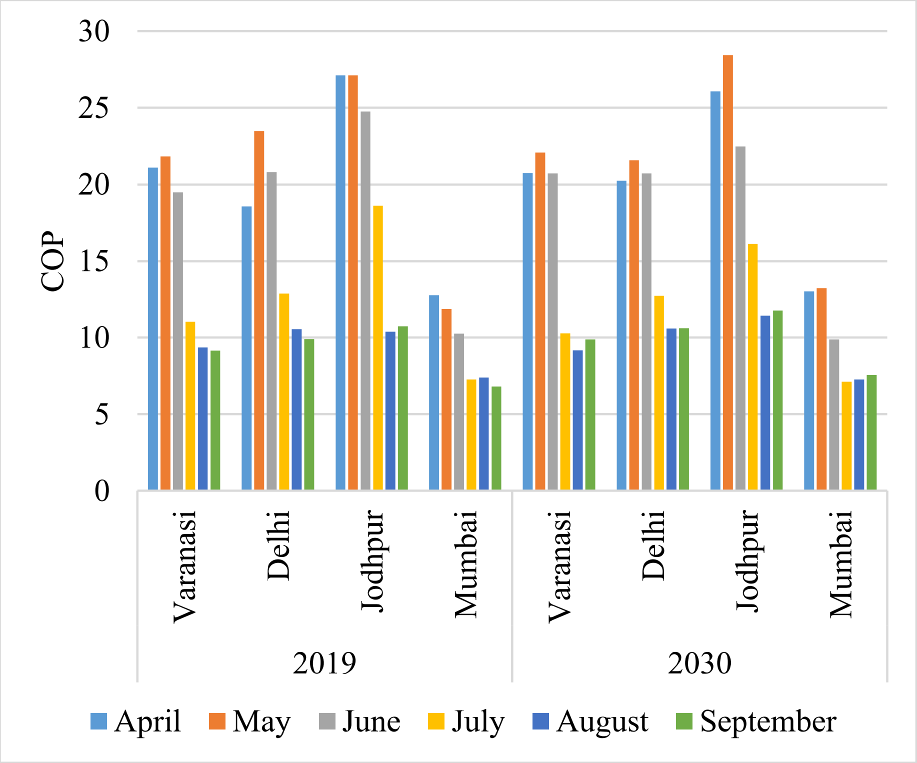

Fig. 6.38 Monthly present and forecasted COP of different city in REC mode

humidity among all six months, which is the key parameter for the high performance of the evaporative cooling device.COP decreases for humid months. The six-month average coefficient of performance of Jodhpur city is highest, while least for Mumbai city. The COP of regenerative mode varies in the range of 6-29. The highest COP (28.44) of the regenerative cooler is obtained for Jodhpur city for the month of May 2030. The COP of regenerative mode decreases drastically after June month in all three climatic zones. The COP of Varanasi and Jodhpur city decreases in April month for futuristic (2030) conditions. The COP of Mumbai city decreased by 46.71% and 42.08 %, respectively, in 2019 and 2030 from April to September. The regenerative model shows better performance in terms of effectiveness. But the suitability of the device varies from one zone to another and from month to month.

6.6. Important findings

In this chapter, the month-wise performance of the dual-mode evaporative cooler in both modes for five cities of India is evaluated. The energy, exergy, and economic analyses of the dual-mode evaporative cooler are presented for five different international climate zones. Annual as well as monthly performances are investigated based on ASHRAE climatic data for both DEC and REC modes. The last 20 years' data have been used to forecast the next ten years' temperature and humidity conditions. The numerical results of the dual-mode evaporative cooler have been used to predict its performance and suitability for different climatic zones and months. From results and discussion, the following conclusions can be drawn:

- REC mode of the dual-mode evaporative cooler performs satisfactorily for four months (April, May, June, and September) for all cities except Kolkata.

- DEC mode operation of the dual-mode evaporative cooler gives high humid supply air, but for dry months (April and May), its outlet condition passes through comfort zone, which gives a possibility to restrict it near comfort zone.
- For the months of July and August, both the modes of operation give supply air which is away from the comfort zone because its inlet condition is very humid.
- The monthly design results show that the cooling energy produced of DEC mode is higher than REC. So the direct mode is found to be more suitable for high sensible heat removal of the conditioning space for dry months.
- The very hot-humid zone has higher wet-bulb depression, which results in higher exergy destruction for DEC mode as compared to REC mode. The exergy efficiency for REC mode is higher than DEC mode, independent of the climatic zone.
- The running cost for the REC mode is always higher than DEC mode. The difference between the running cost of REC and DEC is significantly affected by electricity charges.
- The specific total cost is more for climate zone 4. The difference in specific total cost between REC and DEC modes is marginal for climatic zone 1 and climatic zone 4; whereas, significant (46 USD/kW) for climatic zone 3.
- REC mode is better in terms of wet-bulb effectiveness and exergy efficiency; whereas, DEC mode is better in terms of COP and specific total cost.
- In the futuristic (for example, 2030) composite climatic conditions, only two months (April and May) will remain suitable for the direct mode of evaporative cooler. Regenerative mode suits for the month of June in Delhi and Varanasi city.
- The hot and dry climatic zone shows the positive impact of the climatic change. The regenerative mode of the device is suited for all six months, while the direct mode can

also be used for higher cooling capacity in dry months (April and May) in 2030 scenario.

- Similar to 2019, in the future (for example, 2030) scenario also the hot and humid climates remain unsuitable for five out of six months investigated. Not any single evaporative cooling system shows usefulness in its application in this zone.
- The six-month average temperature of the Delhi and Mumbai cities increases from 2019 to 2030. The relative humidity of Delhi increases in 2030 and almost remains the same for Mumbai city when compared to 2019 data.
- The Direct mode has the advantage of higher cooling capacity and COP, but it is only suitable for dry months in both 2019 and 2030 climatic conditions. The practical usefulness of the dual-mode or only regenerative mode device depends upon cost and climatic conditions both.