CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The world is going through a rapid urbanization and industrialization process which has transformed the lives of crores of people and has led to the migration of people from villages to cities. The increased population has put an additional burden on the energy sector. Peak load demand for cooling is on the rise and there is an adverse impact on additional power generation capacity. The global energy demand keeps on increasing very rapidly from the last few decades as shown in Fig. 1.1. The increased population and fast economic growth are expected to increase energy demand in upcoming decades. It is estimated that world energy consumption will grow by nearly 50% between 2018 and 2050 (IEA, 2019). The other report states that global energy use is expected to increase by 30%, while EU energy use is expected to increase by 12.0% between 2006 and 2021 (Ahmad et al.,2020). However, 35 percent of the world's population lives in nations where the average daily temperature exceeds 25 degrees Celsius. Space cooling has more than tripled in energy demand since 1990, making it the fastest-growing building end-use. Over 2 billion air conditioners are currently in use around the world, making space cooling the primary driver of building electricity consumption and additional capacity to satisfy peak power demand (IEA, 2020). Buildings account for over 40% of worldwide energy usage and play a critical role in the energy market (Nejat et al., 2015). Between 2018 and 2050, energy consumption in the buildings sector, which includes both residential and commercial structures, will grow by 65 percent (IEA, 2019). In the coming decade, rising living standards, population expansion, and more frequent and intense heatwaves are projected to drive record cooling demand. The global energy emissions is shown in the Fig. 1.2. CO_2 levels in the atmosphere reached their highest ever average annual concentration of 412.5 parts per million in 2020, about 50 percent more than when the industrial revolution started (IEA, 2021). The space cooling carbon emission contributes significantly to this total emission. The energy demand from buildings (including residential and commercial structures) has increased at a rate of 1.8 percent per year for the past forty years (IEA, 2013), and it is expected to increase from 2790 Mtoe (116.8 EJ) in 2010 to over 4400 Mtoe (184.2 EJ) by 2050.

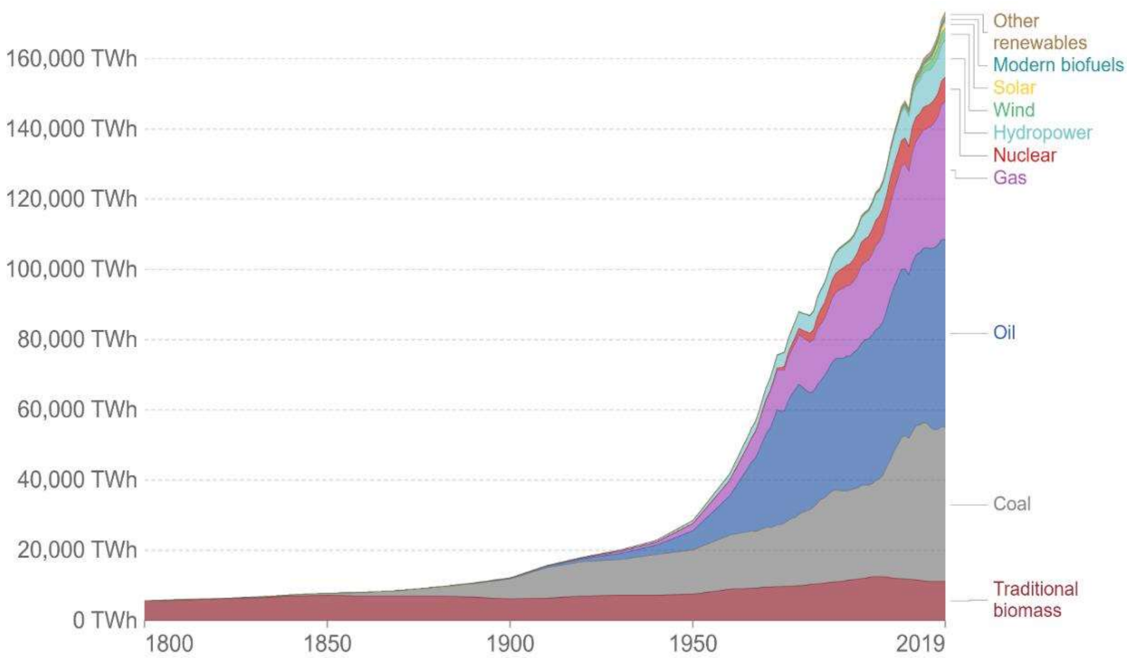

Fig. 1.1 Global primary energy consumption (source: Vaclav Smil (2017) & BP Statistical Review of World Energy.)

However, 35 percent of the world's population lives in nations where the average daily temperature exceeds 25 degrees Celsius. Space cooling has more than tripled in energy demand since 1990, making it the fastest-growing building end-use. Over 2 billion air conditioners are currently in use around the world, making space cooling the primary driver of building electricity consumption and additional capacity to satisfy peak power demand (IEA, 2020). Buildings account for over 40% of worldwide energy usage and play a critical role in the energy market (Nejat et al., 2015). Between 2018 and 2050, energy consumption in the buildings sector, which includes both residential and commercial structures, will grow by 65 percent (IEA, 2019). In the coming decade, rising living standards, population expansion, and more frequent and intense heatwaves are projected to drive record cooling demand. The global energy emissions is shown in the Fig. 1.2. CO_2 levels in the atmosphere reached their highest ever average annual concentration of 412.5 parts per million in 2020, about 50 percent more than when the industrial revolution started (IEA, 2021). The space cooling carbon emission contributes significantly to this total emission. The energy demand from buildings (including residential and commercial structures) has increased at a rate of 1.8 percent per year for the past forty years (IEA, 2013), and it is expected to increase from 2790 Mtoe (116.8 EJ) in 2010 to over 4400 Mtoe (184.2 EJ) by 2050.

Today's cooling technology is dominated by a vapor-compression air-conditioning system, which contributes to the significant sharing of building energy consumption as well as negative environmental effects. The refrigerants (such as R-12, R-22) used in these cooling systems contribute to global warming and ozone depletion. These devices are more complex, more expensive, and require more maintenance. The energy inefficiency and non-eco-friendly nature of these cooling technologies are a serious concern to the world. Hence, eco-friendly, as well as low energy consumption substitute, needs to be incorporated, such as evaporative cooling. Evaporative cooling technology can become an obvious alternative to vapor-compression air conditioning systems since this technology has the capacity to reduce global energy demand and global warming. Evaporative coolers depend on the fact that water will absorb a relatively large amount of heat in order to evaporate. Cooling of air is done by utilizing the very little amount of electricity since the pump and fan are the only components requiring electricity in evaporative coolers.

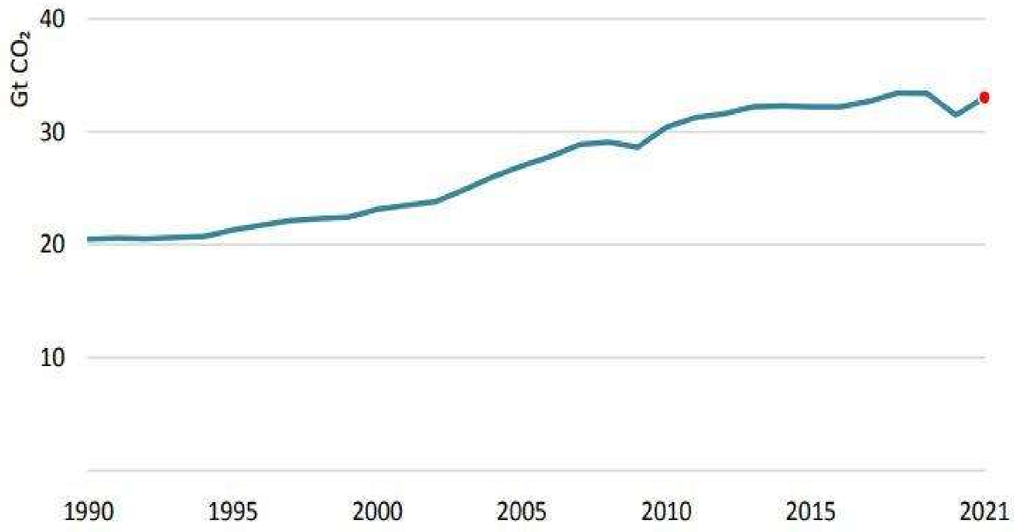

Fig. 1.2 Global energy-related emissions (source: IEA (2021), *Global Energy Review 2021*, IEA, Paris

Evaporative cooling, also known as adiabatic cooling, is based on the idea of water evaporation, which cools the air to a comfortable temperature. Evaporative cooling has been utilized to cool living spaces since the dawn of human civilization. Evaporative cooling is based on the notion that water must be heated in order to transform from a liquid to a vapor. When water evaporates, the latent heat of evaporation is transferred from the liquid water to change its phase. The evaporative coolers can be classified as direct evaporative coolers and indirect evaporative coolers. The direct evaporative cooler adds moisture directly to the supply air. The indirect evaporative cooler lowers air temperature by exchanging heat with adjacent channels and moisture is not added to the supply air. The hybrid system of the combined direct and indirect evaporative cooler also exists which utilizes both principles of air temperature reduction. A regenerative evaporative cooler is the modified version of an indirect evaporative cooler, where the fraction of cooled air in the dry channel is utilized in the wet channel to cool the air up to dew point temperature.

Direct evaporative cooling (DEC) is the earliest and most basic kind of evaporative cooling, in which the external air is brought into direct contact with water, converting sensible heat to latent heat and so chilling the air. The working of the direct evaporative cooling is shown in Fig. 1.3. The psychrometric chart representation of the moisture addition in the air is shown in Fig. 1.4. Direct evaporative cooling follows the approximate isenthalpic process. The minimum achievable temperature of the direct evaporative cooler is the wet-bulb temperature. The direct evaporative cooler is suited best for hot and dry climatic conditions. The High humidity is not ideal for direct delivery into conditioning space because it can cause warping, corrosion, and mildew in materials that are vulnerable to it. The basic goal of indirect evaporative coolers is to chill the air by reducing its sensible heat while maintaining its humidity. The indirect evaporative coolers are made up of channels similar to the plate heat exchanger. The alternate dry and wet channels are separated by non-permeable sheets. The ambient dry air exchange heat with the adjacent wet channels and get cooled. The working of the indirect evaporative cooling process is shown in Fig 1.5. The psychrometric chart representation of the cooling process is shown in Fig. 1.6. The wet-bulb effectiveness of this system is in the range of 40–80%.

The regenerative evaporative coolers are the modifications in the indirect evaporative coolers. Maisotsenko proposed an M-cycle-based evaporative cooler that can cool below the wet-bulb temperature. These evaporative cooler utilizes regenerated air in the cooling. The working of the regenerative evaporative cooler is shown in Fig 1.7. The dry channel air gets cooled by exchanging heat with adjacent wet channels. The air flowing in the wet channel is a fraction of the already cooled dry air. The regenerative cooling process of the cooler is shown in Fig. 1.8. DEC is a mature technology and is used worldwide. However, it has a limitation of wet bulb temperature and becomes ineffective in high humidity conditions (Al-Juwayhel et al., 2004). DEC adds moisture to the air, which makes occupants uncomfortable. IEC is developed to cool air at a constant humidity condition. IEC has been further modified as a regenerative evaporative cooler (REC), which is effective in wet conditions (Yan et al., 2019). This modification has been done by extracting a fraction of dry air and utilizing it as wet channel air. REC consists of a heat and mass exchanger in which alternate dry and wet channels are separated by non-permeable sheets. The dry channel air gets cooled at a constant specific humidity by exchanging heat with wet channels, and a portion of this cooled air is redirected in the wet channels. However, it has a disadvantage of low cooling energy produced as compared to DEC. The regenerative evaporative cooler may be configured in a variety of ways depending on the primary air, secondary air, and water flow directions. The performance of the regenerative cooler is also get affected by the different combinations of these flow directions. The best thermodynamically efficient configuration must be explored in the regenerative evaporative coolers.

The performance of the theses coolers is also affected by surfaces (used between the channels) and circulating fluid. The improved performance of the device for the same operating conditions reduces the energy consumption and Exergetic losses. The device's utility is also increased as a result of the improved performance. Nanofluids are generally employed as coolants in heat transfer equipment because of their improved thermal characteristics. In this domain, hybrid nano fluids are a recent development that is yielding promising outcomes

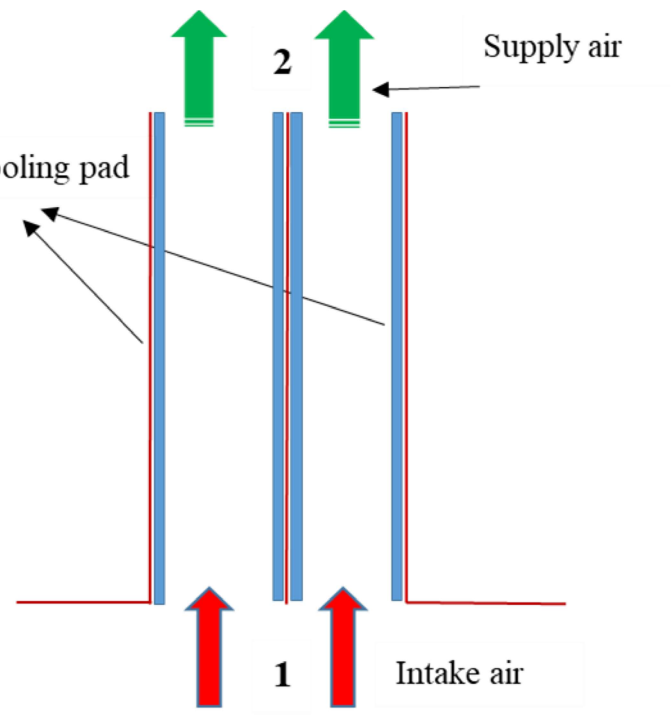

Fig. 1.3. Direct Evaporative Cooling (DEC)

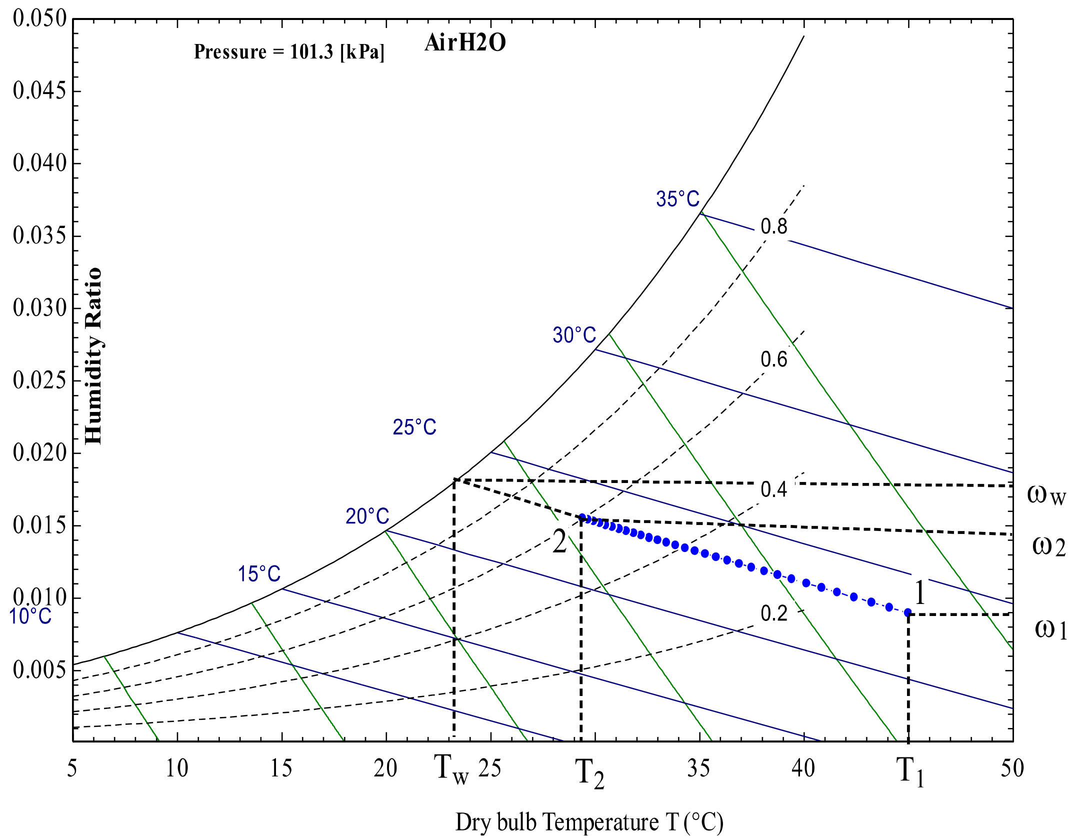

Fig. 1.4. Psychrometric representation of direct Evaporative Cooling

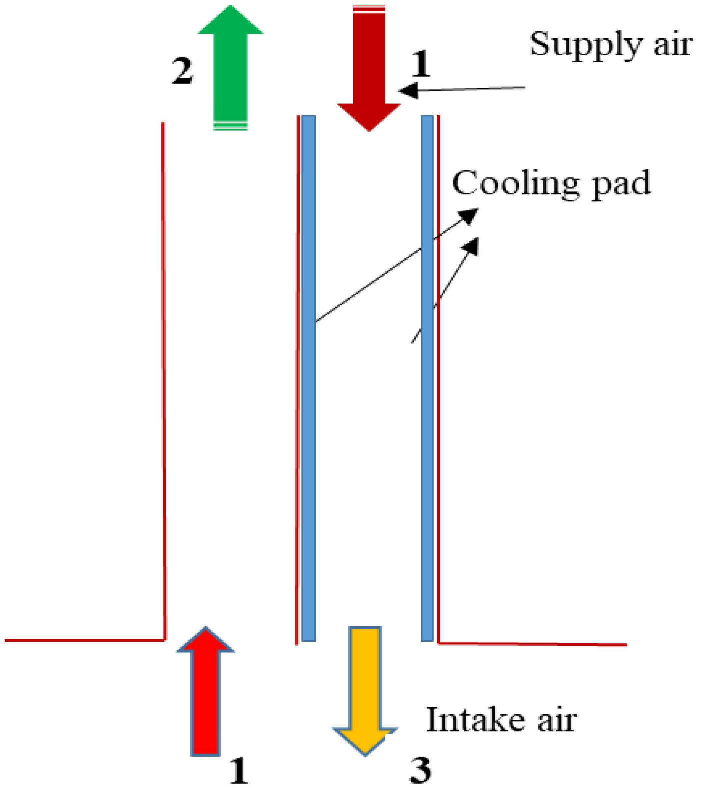

Fig. 1.5. Indirect Evaporative Cooling (IEC)

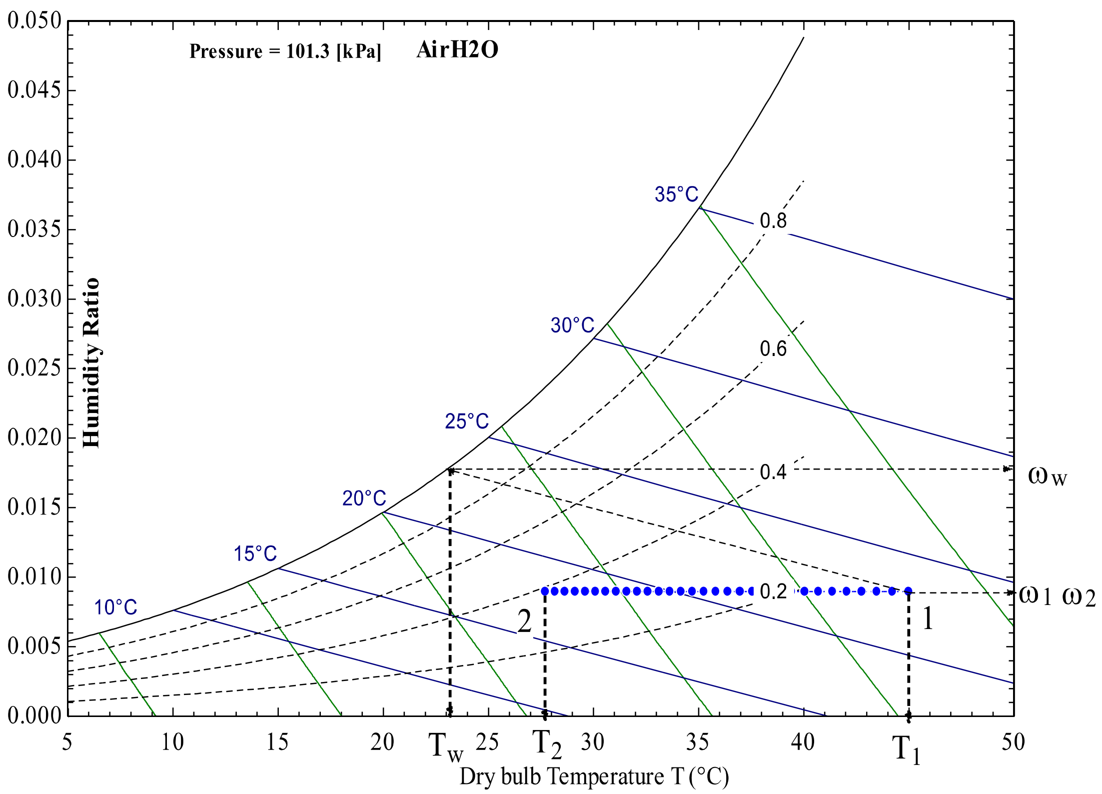

Fig. 1.6. Psychrometric representation of Indirect Evaporative Cooling (IEC)

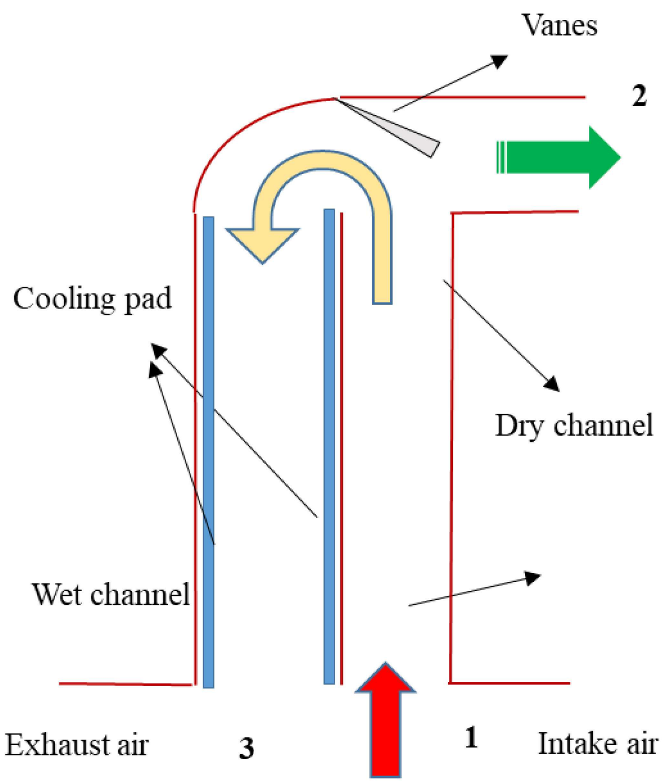

Fig. 1.7. Regenerative Evaporative Cooling (REC)

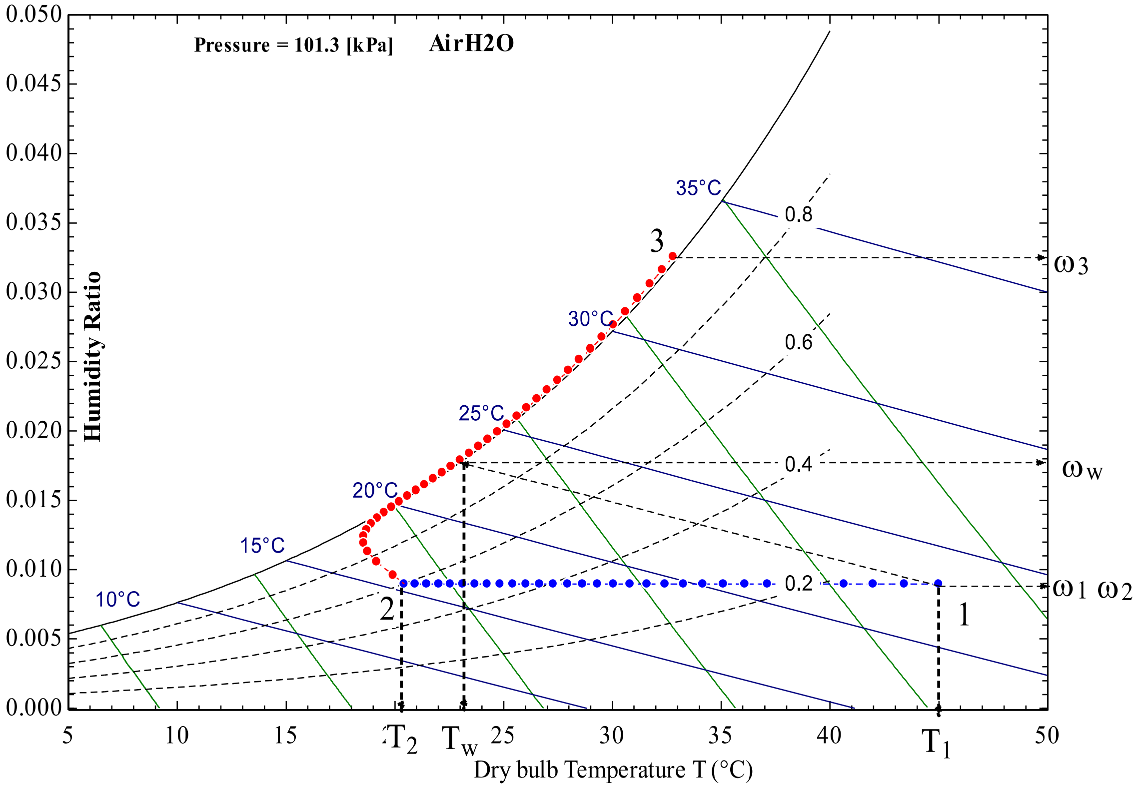

Fig. 1.8. Psychrometric representation of Regenerative Evaporative Cooling (REC)

. ASHRAE divides the world into eight different international climatic zones: four are hot and four are cold zones (ASHRAE, 2009). The outdoor conditions have a considerable impact on the evaporative cooling device's performance. For hot zones, DEC is the proven technology for dry seasons and REC is a better option for humid seasons. The climatic conditions varied drastically from April (hot and dry) to August (hot and humid) even at one place such as in composite climates. The direct evaporative coolers which are very effective in dry months is non-performing in humid outdoor conditions. The device change is needed to achieve effective space cooling in different climatic conditions at the same location.

The appropriateness of direct and indirect coolers changes as the temperature and humidity change. Climate change is a scientific fact, as evidenced by temperature data. The temperature rise is prevalent over the world. The applicability and suitability of the coolers may vary in the future depending upon the climatic data. To get a thorough view of the cooling device in different climate zones, energy, exergy, and economic study is required. Hence above fact has motivated me to extend research in evaporative cooling.

1.2 Thesis Objectives

The main objective of the thesis is to explore the regenerative evaporative cooler based on performance comparison and passive methods. The research focused on the investigation of the dual-mode (direct and regenerative) cooling device for the space cooling purpose of different climatic zones. The specific objective of the thesis is following:

- Performance Comparison of all possible configurations of the regenerative evaporative cooling. The energetic, exegetic, economic, environmental, and sustainability comparison of regenerative evaporative cooling topologies.

- ➢ The use of passive approaches to improve the performance of a regenerative evaporative cooler. To look at the impact of using Nano fluid in circulating water and how it affects surface modification.
- ➢ Fabrication and experimentation of the dual-mode evaporative cooling unit under the controlled intake operating conditions. The techno-economic analysis of this cooler and performance forecasting.
- ➢ Performance analysis of dual-mode evaporative cooler under different climatic situations based on forecasted data (by utilizing last 20 year data) for the futuristic scenario.

1.3 Novelties and contribution

The research work carried out in this thesis contributes significantly to the field of eco-friendly space cooling. The study enhanced the knowledge of sustainable and energy-efficient evaporative cooling technologies. The specific novelties and contribution of the research are as follows:

- To determine the best possible configurations, all conceivable configurations of the regenerative evaporative cooler are explored simultaneously for the first time using the same set of energy and mass conservation equations.
- A unique comparison of two passive performance enhancement strategies is undertaken for the regenerative evaporative cooler (using hybrid Nano fluid and surface modifications of the cooling plate).

- Instead of employing various coolers (DEC and REC) in different seasons, the need of dual-mode evaporative coolers is recognized for the first time for composite climatic zones. For the first time in the lab, a novel dual mode evaporative cooler testing device is created. This device has the ability to work in both direct and indirect modes, increasing comfort cooling adaptability.
- To bring the entire technical aspect together, research is being conducted on the economic, environmental, sustainability, comfort, and techno-economic analysis of the dual mode evaporative cooler.
- Contributing in the advancement of knowledge regarding the suitability of the modes of the dual mode cooler for the present and future scenarios for various climatic zones.

1.4 Thesis structure

The thesis is organized into seven chapters.

Chapter 1 includes a brief introduction about the topic, its significance, and motivation. It also covers thesis objectives, novelties, and contributions to the existing knowledge.

Chapter 2 discusses existing evaporative cooling technologies. This chapter includes a detailed literature review related to evaporative cooling technologies. The recent numerical and experimental work related to the regenerative evaporative cooler, direct evaporative cooler, and indirect evaporative coolers are summarized in table form. The important findings for the specific configurations of the cooling device are listed in the table. The important conclusions related to the performance parameter are listed in the table.

Chapter 3 discuss the all possible configurations of the regenerative evaporative coolers. The numerical modelling of the counter/parallel and cross-flow flow regenerative evaporative cooler are presented with some assumptions. The important energetic parameters such as coefficient of performance, cooling capacity, and dew point effectiveness are used to compare all eight configurations. The economic and environmental parameters are also used to compare all possible configurations. The important input parameters are varied to obtain its effect on the performance of the evaporative heat and mass exchanger.

Chapter 4 includes the study of the performance enhancement of the regenerative evaporative coolers by passive methods. The applications of the hybrid Nano particles in the circulating water are investigated in this chapter. The performance enhancement by the plate surface (between the dry and wet channels) modifications are investigated in the cooling device along with the Nano fluid. The parametric analysis was also performed in this chapter.

Chapter 5 discuss the experimentation methodology of the novel dual mode evaporative cooler. The fabrication of dual mode heat exchanger along with the figure is discussed in this section. The complete test unit along with the measuring instrument is described in this section. The experimental results are obtained by the testing unit by varying the inlet conditions of the dual mode heat exchanger. The water temperature and water flow rate effect on the performance is also studied in this section. The exergy and economic analysis is also performed on the obtained results.

Chapter 6 investigates the performance of dual mode evaporative cooler for different climatic conditions of India. The direct as well as regenerative mode performance is investigated with the variation of outdoor temperature and humidity. The suitability of modes is concluded in this section. The temperature and relative humidity are forecasted for futuristic climatic conditions. The forecasted data is used to predict the performance of the device and ensure the suitability of the modes. The performance of the dual mode evaporative cooler is also investigated for different global climatic zones (very hot-humid, hot-humid, warm-humid, mixed humid).

Chapter 7 concludes the key points obtained in the numerical and experimental analysis of the regenerative and dual mode evaporative cooling device. The direction for future work for full utilization of the device is recommended in this chapter.