Next generation air conditioner for sustainable cooling solutions

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Abstract. Generally in summer, air conditioning systems are essential for improving the human comfort and productivity. The mechanical vapor compression system (VCS) is probably the most used system. However, the refrigerant used in VCS is harmful to the environment and the initial cost is high. So, the aim of this study is to introduce a sustainable, energy-efficient and climate-friendly air conditioning system in which there is no refrigerant. The proposed system is the integration of two modules i.e., Direct evaporative cooling (DEC) module and vacuum-assisted isothermal membrane-based air dehumidification (VIMAD) module, where the DEC module will cool and humidify the entering air stream and then this cool and humidified air will enter into the VIMAD module and the air will get dehumidified. Finally, the output will be cool and dehumidified air at the exit of the system. In this paper, the proposed system is explained. Moreover, the basic principle of the DEC, the background of DEC and the basic principle of the VIMAD system, background on the types of membrane materials that can be used in VIMAD are explained. Also, the effects of various parameters on the performance of the DEC and VIMAD are presented.

Keywords: Air Conditioning, Direct evaporative cooling, vacuum membrane dehumidification, Isothermal dehumidification.

1. Introduction

Because of greenhouse gases and global warming, the ambient temperature of air is rising day after day. Staying in such a place where there is no proper air conditioning system is not easy. In order to convert the indoor situation to the human comfort zone, air conditioners play a major role worldwide. The inside relative humidity and air temperature play a crucial role in determining the human comfort conditions. Room air DBT of 25 °C and relative humidity of 55 % are declared to be in a human comfort zone [15]. The ASHRAE Standard 62.1-2016 also suggests that the HVAC (Heating, ventilation and air-conditioning) system must have the ability to keep the relative humidity between 30% and 60% for the indoor climate [10].

In several tropical and humid regions, where the relative humidity of outside air remains continuously above 80-90 % for many days, high humidity will cause the high latent heat load which consumes the 20 to 40% of the total energy consumed by the HVAC system. Certainly, the dehumidification of highly humid air can reduce the energy consumption significantly [3]. It has been shown that the energy
consumed by air conditioning system can be reduced by 20-64 % by incorporating appropriate dehumidification systems [5].

In addition, people are spending most of their lives in confined houses, so the indoor environment quality (IEQ) has a major influence on the health, efficiency and productivity of the people. So, it becomes necessary to control the relative humidity and temperature within the human comfort conditions of the environment. Otherwise, high temperatures and high level of humidity will restrict sweat evaporation, leading to irritation, discomfort and a decrease in productivity. The higher moisture content also provides an important breeding environment for the production of bacteria and fungi in residences that directly impact the people's health [7,8]. ASHRAE guidelines suggest humidity ratios below 0.012 and relative humidity in inhabited areas between 30% and 60% to maintain the indoor human comfort conditions and lessens the risk of bacterial evolution [9,10].

HVAC sector research has reinforced the techniques for these air conditioning systems, but it is still being done in the similar way like years earlier, i.e., dehumidification and cooling of air with the air conditioners having VCS. In hot environments, dehumidification and cooling of air with the help of VCS require a considerable portion of the highest electricity usage. Moreover, the control of relative humidity is very hard with the VCS because the improvement in energy also minimizes the sensible heat load of the building (e.g., from improved insulation), but the latent heat load is not influenced [11]. Therefore, a green alternative air conditioning system is strictly needed due to the energy crisis and its bad environmental impact.

The DEC system is reinforced again at the present stage as, due to its zero-emission features, energy efficiency, simplicity, energy conservation and environmental protection are two topics in all engineering areas. Compared to traditional A/C units, the reporting of electricity usage by the evaporative cooling systems (ECS) in a smaller residential building showed significant energy savings and improved comfort conditions for human beings [12].

The air is cooled but extremely moist from the outlet of the direct evaporative. Excessive humidity not only contributes to irritation, discomfort and affects the skin temperature of the body, but also promotes the growth of germs, which ultimately causes some health issues such as SARS [2]. Therefore, dehumidification is necessary. The conventional dehumidification technology, such as heat wheel powered desiccant dehumidification and condensing-based air dehumidification, consumes a lot of energy. Therefore, the alternative introduced in the proposed system is vacuum assisted isothermal membrane-based air dehumidification. Moreover, hollow fiber module is preferred because it can sustain a larger pressure drop as compared to the flat plate type module and also this module does not require any kind of additional support because the tubes are made up of membranes having higher strength. Moreover, the hollow fiber membrane system exhibits the better packing density characteristic that contributes to smaller equipment size.

So, in the present work, the system which is the integration of DEC module and the VIMAD module have been presented. Moreover, the basic principle of DEC and its background, basic principle of background of the membrane materials have been presented. Also, lastly the possible outcomes have been discussed.

2. Basic principle of the direct evaporative cooling (DEC) and the background of DEC
The basic concept behind the DEC is nothing but the transformation of the sensible heat into the latent heat. In this system, with the help of air blower, the flow of air is forced into an enlarged liquid water surface area for the evaporation of water. So, the heat and mass transfer between the air and the water occurs and a large amount of heat is absorbed by the water from the air stream for its evaporation (i.e., enthalpy of vaporization) and the non-saturated air will become cooled. So, the dry bulb temperature (DBT) of the air will decrease. In short, the water will take some amount of the sensible heat from the air which will evaporate the water and becomes latent heat and the evaporated water is diffuses through the air [13] which will increase the humidity of the air. A schematic principle of DEC is indicated in Figure 1.
This process is ideally considered as isenthalpic. Theoretically, the wet bulb temperature (WBT) of the supplied air stream is the lowest temperature that can be achieved. In practice, wetted porous surfaces or evaporative cooling pads have a huge water surface area where contact with air moisture is achieved and the pad is moistened via spraying the water over the top portion of the evaporative cooling pads which has been kept vertically. The key types of active DEC systems used by various researchers are shown in table 1.

**Table 1.** Main types of direct evaporative cooling (DEC) systems.

| System type | Evaporative Media | Cooling-effectiveness | Findings of study | Investigators |
|-------------|-------------------|-----------------------|-------------------|--------------|
| Random media | Plastic fiber/foam or Excelsior which is supported by the frame made up of plastic. | >80% | - Shorter life.  
- Tough to clean | Banik and Ganguly [17]  
Tewari and Priyam [16]  
Tewari and Priyam [18]  
Reddy and Prasanna [19] |
| Rigid media | corrugated materials block: plastic, cellulose, fiberglass. | 75-95% | - Higher initial cost.  
- Long life.  
Clean air.  
- High energy consumption  
- Bacterial growth | |
| Remote pads | Rigid and random pads positioned on the structure's roof and walls | 75-95% | |

Deepak et al. [15] experimentally compared honeycomb & Aspen cooling pads and it has been found that the Honeycomb cooling pads have greater performance in terms of energy efficiency ratio and cooling power compared to Aspen cooling pads. Jain et al. [14] compared the cooling pad materials (coconut and palash fiber with the Aspen and khus fibers) in laboratory and concluded that the saturation effectiveness of pad with palash fibers is 26.31% and 13.2% higher than the saturation effectiveness of khus and aspen pads respectively. While saturation effectiveness of coconut fibers is 8.15% more than the saturation effectiveness of the khus pads and roughly equivalent to the saturation effectiveness of the aspen pads.

Based on available literature, it is found that DEC is an attractive option in India. But the cool air available from DEC system is very humid. So, it is not satisfying the air quality standard for human comforts. So, the alternative is to be explored for controlling the humidity of cool air. Therefore, as stated before, VIMAD is used for the air-dehumidification purpose in present work.

### 3. Basic principle of the VIMAD and background on the types of membranes materials

The schematic principle and the psychometric representation of the dehumidification process is shown in figure 2.
The VIMAD membrane is a selective interface that enables only some molecules to penetrate through but restricts others because of its selectivity characteristic, which will result in isolation of the components from the gaseous mixture. Water vapor is extracted from the moist air by the membranes used in VIMAD. The gradient in the chemical potential between the two sides (i.e., feed and the permeate side) of the selective membrane is the driving force for vapor transfer. Because of chemical potential gradient, the permeate (here water particles) is passed through the membrane, which may be in the form of pressure gradient, concentration gradient, temperature gradient, or electric potential gradient. For the dehumidification processes, the first two gradients are most important. So, in present system the pressure gradient is used for the vapor transfer which can be created with the help of vacuum pump. As shown in figure 2, the water vapor particles from the feed side air is passed selectively on to the other side of the membrane and then the water vapor particles are pumped out by the vacuum pump. The remaining air is coming out for space cooling as the retentate stream. In short, the vapor is extracted from the air with the help of chemical potential gradient created in the form of pressure gradient with the help of vacuum pump. This process is isothermal dehumidification process which is shown in figure 3.

Control of the humidity in the cool air received from evaporative cooler is a key challenge. Various researchers over the worldwide have tried to solve this issue by various techniques. Isothermal membrane air dehumidification is studied critically. The review is tabulated in table 2.

**Table 2.** Main types of membrane materials.

| Sr. no | Types of Membrane Materials | Investigators | Findings |
|--------|-----------------------------|---------------|----------|
| 1      | Polymeric                   | Metz and Sybrand [27] Bolto [20] | Investigated 19 types of polymer membranes for vapor permeation. Concluded that Particles of the water diffuse more rapidly than the molecules of the other gases. Concluded that the hydrophilic organic polymers improve the water solubility in the membrane. |
| 2      | Zeolitic                    | Xing and Rong [21] Zhang, Jian and Liu. [22] | Hydrothermal membrane growth technique was used to manufacture a thinner NaA zeolite membrane on the porous and flexible Ni substrate. |
| 3      | mixed matrix                | Sanchez and Clément [23] | The mixed matric membrane has been shown to have improved reproducibility, cheaper and easier manufacturing process, efficient transportation characteristics and chemically and thermally stable. |
4. Proposed system schematic diagram and explanation

Figure 4 displays the schematic of sustainable air conditioning system. The diagram has been prepared using ‘draw.io’ online software. The system consists of following components.

- **Coconut fiber based evaporative cooling pad**
- **Water spray arrangement**
- **Direct Evaporative Cooling (DEC) Module**
- **Air intake**
- **Air blower**
- **Water collector**
- **Water circulation pump**
- **Permeate (Humid air)**
- **Permeate vacuum-pump**
- **Membrane Tubes**
- **Vacuum assisted Isothermal Membrane based air-dehumidification (VIMAD) module**
- **Tube plate**
- **Water vapor particles**
- **Cool & dry air into the space**

**Figure 4.** Schematic diagram of sustainable air conditioning system.
Both efficiency of dehumidification and coefficient of performance (COP) of dehumidification are considered for evaluating the performance of a membrane device. The efficiency of dehumidification is considered in terms of moisture removed percentage can be determined by the equation (2) [1],

\[
\text{Percentage of Moisture removed} = \frac{\omega_{\text{in}} - \omega_{\text{out}}}{\omega_{\text{in}}} 
\]
Where, ‘ω_in’ is the inlet humidity ratio and ω_out is the outlet humidity ratio of the dehumidification module.

The dehumidification COP (COP_{Latent}) is defined as the latent heat related to the vapor extracted (Q_{latent}) per vacuum pump work or the compressor work (W_{V, Pump}) and it is denoted by the equation (3) [1],

\[
\text{COP}_{\text{Latent}} = \frac{Q_{\text{Latent}}}{W_{\text{V, Pump}}} \tag{3}
\]

Where, the air pressure is raised with the help of vacuum pump to an ambient pressure of 101 kPa from the pressure on the permeate side, so that the work needed by the vacuum pump ‘W_{V, Pump}’. It is possible to express the pump work by the equation (4) [26],

\[
W_{\text{V, Pump}} = \frac{nRT}{\varepsilon} \ln \left( \frac{P_{\text{atm}}}{P_{\text{Permeate}}} \right) \tag{4}
\]

Where, ‘R’ is the specific gas constant, ‘n’ is the cumulative moles in the mixture collected with the help of vacuum pump, ‘T’ represents the absolute temperature, ‘P_{atm}’ represents the ambient pressure, the permeate side pressure is represented by ‘P_{Permeate}’ and ‘ε’ is the vacuum pump efficiency.

6. Possible outcomes

The effects of different parameters on the performance indicators of the DEC module and VIMAD module can be understood with the help of following literature presented in this work. For the DEC, the effect of thickness of pad ‘δ’ and feed air velocity ‘v’ on the cooling effectiveness have been shown.

For the VIMAD, the effect of the transmembrane pressure, feed velocity of air, water vapor permeance, membrane selectivity (also known as water/air permeance ratio) and the relative humidity (RH) on the percentage of moisture removed and the dehumidification COP have been explained.

6.1 Effects of frontal air velocity on the saturation effectiveness (ƞ) of DEC

From Figure 6, it is clear that the higher frontal air speed ‘v’ reduces the interaction time between the air and the water layer, thus the transfer of heat from the air to the water decreases, ultimately reducing the effectiveness of saturation ‘ƞ’.

6.2 Effects of Pad thickness on the saturation effectiveness (ƞ) of DEC

Figure 7 shows that the saturation effectiveness ‘ƞ’ is decreasing with the increase in frontal air speed ‘v’ at a given pad thickness ‘δ’. This behavior is only because of reduction in the time of interaction among the water and the air stream. At a given frontal air speed ‘v’, the saturation effectiveness ‘ƞ’ will rise with the rise in pad thickness ‘δ’, but it reaches to one, when pad thickness ‘δ’ attains some fixed value.
6.3 Effect of transmembrane pressure and permeate pressure on the percentage of moisture removed

Figure 8. Effect of transmembrane pressure and permeate pressure on the % of moisture removed [26]

However, lower air speeds and thick evaporative cooling pads demand bigger fans, pumps and wetting systems. Moreover, supply of nearly saturated air can cause warping and corrosion of susceptible materials. The suitable evaporative cooling pad thickness should be selected depending upon the required cooling efficiency. From figure 7, the optimum air speed should be around 2.5 m/s for the required volume of air. The frontal area of a direct evaporative cooler can be determined using this suggested value.

6.4 Effect of feed velocity and water vapor permeance on the moisture removed percentage

Figure 9. Effect of feed velocity and water vapor permeance on the % of moisture removed [26]

Figure 10. Effect of transmembrane pressure and water/air permeance ratio (membrane’s selectivity) on the % of moisture removed [26]

From figure 8, with the rise in the transmembrane pressure, the amount of moisture removed increases. But the behavior is non-linear. It can be observed that the moisture removed percentage is low at lower transmembrane pressure and rises progressively as the pressure on the permeate side drop to 100 mbar from the ambient pressure. As the pressure on the permeate side varies from 100 mbar to 5 mbar, the percentage of moisture removal increases sharply.

6.4 Effect of feed velocity and water vapor permeance on the moisture removed percentage

Figure 9 indicates that the moisture removed % raises with the rise in permeance of the water vapor for each feed velocity tested. Also, at certain water vapor permeability, the moisture removed % rises with lower feed velocity of air.
6.5 Effect of transmembrane pressure and water/air permeance ratio (membrane’s selectivity) on the percentage of moisture removed

It can be seen from the figure 10 that the COP of the dehumidification system does not change with the selectivity of the membrane for the transmembrane pressure below 500 mbar. At smaller transmembrane pressure, the COP rises. The COP rises sharply for the transmembrane pressure value below 200 mbar. It is evident from figure 10 that for a lower transmembrane pressure value, a maximum COP value of 11 is attainable. The COPs for transmembrane pressure levels above 500 mbar have substantial variations. Membranes with high selectivity achieve higher COPs for dehumidification.

6.6 Effect of transmembrane pressure and relative humidity (RH) on the percentage of moisture removed

As depicted in figure 11, at some certain transmembrane pressure, the COP of dehumidification increases with the rise in relative humidity. That means the system works more efficiently at the higher humidity condition. The primary parameters affecting the membrane efficiency and COP are shown in the table 3.

Table 3. Important aspects that affect the Efficiency of dehumidification and COP of dehumidification
[26]

| Factors                                      | Efficiency of dehumidification | COP of dehumidification |
|----------------------------------------------|--------------------------------|--------------------------|
| Rise in the supply air speed                 | Decreasing                     | Change is Negligible     |
| Rise in water vapor permeability             | Increasing                     | Change is Negligible     |
| Rise in the membrane selectivity to the water vapor | Decreasing                     | Increasing              |
| Rise in transmembrane pressure               | Increasing                     | Decreasing              |
| Rise in supply RH                            | Change is Negligible           | Increasing              |

7. Conclusion

The simple air conditioning system which integrates the direct evaporative cooling module and VIMAD module have been presented in this study in which natural and sustainable materials like coconut fiber-based cooling pad material has been suggested. Moreover, refrigerant have not been used unlike in case of conventional vapor compression, so it is totally climate friendly and so this technology holds a strong place in upcoming future. The study shows that the feed velocity of air and the pad thickness are the two major affecting parameters to the DEC cooling effectiveness. The transmembrane pressure drops, feed velocity of air, water vapor permeance, the membrane selectivity and feed air humidity are the major influencing parameters on the dehumidification performance and the dehumidification COP.

8. References

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