

Development and Evaluation of Multistage Evaporative Cooling System

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Abstract

Air conditioning has become a vital part of our day to day lives, but with the current cooling solutions there are concerns regarding to high energy consumption and emission of dangerous gases depleting the ozone layer. An evaporative cooling system (ECS) is considered as one of the oldest and low-cost cooling systems. However, the temperature drop in ECS is low and hence in this work, a multistage cooling system was developed and tested for its performance. This system consists of indirect and direct evaporative cooling system. The combination of indirect and direct ECS reduces the dry bulb temperature significantly. The experimental results show that the temperature drop in two stage is higher than the single stage. It is also observed that the energy consumed by this system is low as compared to conventionally used HVAC system. From this work, we conclude that the multistage evaporative cooling system can be used as an alternative to the HVAC system for commercial and industrial applications.

Keywords

Cooling, evaporative cooling, multistage, performance, HVAC

1. Introduction

Energy demand worldwide for buildings cooling has increased sharply in the last few decades, which has raised concerns over depletion of energy resources and contributing to global warming. It is suggested that the climate change mitigation policies could increase demand for resources perceived as critical, because these are used in many renewable energy technologies. The phasing out fossil fuels has the potential to reduce both the supply potential (i.e. primary flow) and recoverable resources (i.e. stock) of materials (Månberge et al. 2021, Endang et al. 2019, Kumar and Majid 2020). The ASEAN region as a whole is relatively well endowed with various energy resources however the energy resources are not evenly distributed. As the population and energy demand continues to increase and existing fuel supplies begin to run out, most ASEAN countries will have to find ways to tackle their country energy security (Kongre et al. 2015, Hussain et al. 2016). The primary objective for deploying renewable energy in India is to advance economic development, improve energy security, improve access to energy, and mitigate climate change. Sustainable development is possible by use of sustainable energy and by ensuring access to affordable, reliable, sustainable, and modern energy for citizens (Model Project Report on Fruit and Vegetable Processing Unit National Bank for Agriculture and Rural Development 2014, Liberty et al. 2013).

It is suggested that India is the second largest producer of fruits and vegetables in the world and the wastage of fresh horticultural produce is about 18 % (Deoraj et al. 2015). The ECS can be used as a short term preservation of fruits and vegetables, because it reduces the storage temperature and increases the relative humidity of the air which keeps the fruits and vegetables fresh (Amit 2016). The integration of ECS with good sanitation will help to attain high quality level of freshness for some period (Cayli et al, 2021, Kowalski et al. 2020).

Most of the traditional refrigeration systems depend on non-renewable energy sources like coal and natural gases which have heat utilization of only 70% which leads to excessive smoke, smog, and other natural disasters. Even the refrigerant used in mechanical refrigeration systems are harmful and produce greenhouse effect. For this reason, we have used indirect direct ECS, however there are some limitations in the cooling effect produced by it. Hence in this work, we have developed a multistage ECS consisting of Indirect Direct Evaporative Cooling (IDEC). Figure 1 and Figure 2 depicts the working of the different stages involved.

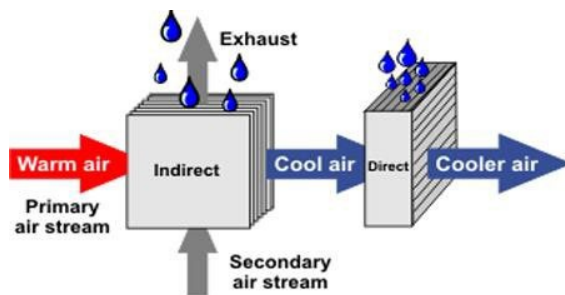


Figure 1. IDEC Process

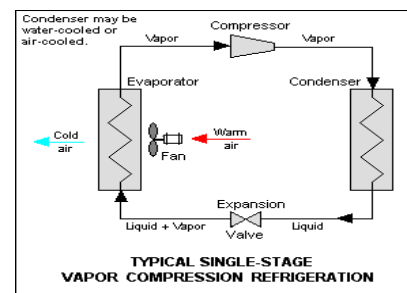


Figure 2: Vapour compression refrigeration

1.1 Objectives

The objectives of this work are as follows

1. Fabrication and testing of multistage ECS consisting of IDEC system
2. Optimizing process variables of ECS
3. Comparing the performance of single stage and multistage ECS

2. Literature Review

Kongre et al. (2015), carried out study showing that ECS is a very efficient and eco-friendly cooling option. By using direct ECS it was seen that it led to Legionella disease in few people due to increase in humidity of the air. On the other hand, indirect ECS proved less effective and less efficient also. Due to this reason the combination of both indirect and direct ECS used in series. This forms the Indirect Direct ECS which was very feasible providing exceptional cooling with zero pollution and exceptional energy efficiency. Various analysis was carried out based on the optimization of heat and mass transfer and it was also found that this system is applicable at both domestic and industrial application.

Hussain et al. (2016), collected data which shows that a large amount of condensate water produced from AC gets wasted. In this model there are three stages where first the condensate water from traditional refrigeration system collected through pipes and stored in thermally insulated tank. Later this water is only used for the indirect evaporative cooling where sensible cooling occurs. Now this cool air passes through final stage of direct evaporative cooling where the air temperature is decreased even more with little addition of humidity.

Lv et al. (2021), experimented many options to increase the cooling efficiency of an indirect ECS. Various optimization to the structure of indirect evaporative cooling (IEC) was carried out like making the heat exchanger as fins or baffles which proved to be very useful because of the increased area for heat exchange to occur. But it was later found that using of porous material is more feasible option than making changes to the structure of IEC. Various analysis was carried out considering materials like fibers and ceramic. Materials with food hydrophilicity proved to be excellent choice in providing good cooling effect. It was also studied that best results in IEC were obtained by using medium spray of water in the system.

Muhsen et al. (2021), study has been conducted using two heat exchangers in a typical summer climatic condition. This consists of a dual stage cooling system i.e., direct-indirect ECS. In the first stage, water is passed through the first stage to reduce the air temperature and then it is passed to the next stage (second stage) where it is a working fluid. The results show that temperature can be reduced by 13% compared to the standard regular design and also in

an economical and ecofriendly way. The overall effectiveness also increases by roughly 25% and this design is apt for regions where the climate is hot and dry and where the cost of a new HVAC system based on refrigerants is high.

Jain et al. (2021), modification been done to the conventional existing evaporative cooler by introducing water to air and a heat exchanger at the outlet of the air stream. This heat exchanger further cools down the air with the help of cooled water. The results of this experiment has shown that there is an increase of 25%-30% in the COP and efficiency of the system. This system having more efficiency can be advantageous as it consumes less energy and proves useful in both commercial and residential units. Hence maximum utilisation can be seen by the public.

Mahdi et al. (2021) discusses about PV panels that utilizes underground water to study the performance of Indirect-Direct Evaporative Cooling system. For the Indirect evaporative cooler, two cooling coils are used which is followed by three cellulose pads for the direct evaporative cooling stage. With this combination of three cellulose pads and two cooling coils, temperature difference of about 18.6°C achieved. An efficiency of 82.73% noticed for the IEC stage, while overall efficiency of 125% is seen. Due to the use of underground water, it decreases the PV panel temperature by 20°C and power production improved by 24%. This type of IDEC system is best suited to provide comfort in dry and torrid regions with reduced energy consumption.

Sadgir et al. (2016), two-stage indirect-direct ECS consists of two methods one is indirect evaporative cooling and second is direct evaporative cooling. A promising way to increase the thermal performance of evaporative cooling system is to decrease the DBT of the air at constant absolute humidity. Such process is achieved by combining indirect type and direct type of evaporative cooler. In indirect and direct evaporative cooling system ultimately reduce the temp of the incoming air near about its WBT.

Hassan (2016), special type of curtain known as khus curtain where water is spread over this curtain through which cooling takes place. Here the effectiveness and accuracy of the wet bulb temperature is dependent on the flow rate of air through the wet curtain. In the two-stage ECS there is direct contact between the air and water hence lower temperature is attained. At the second stage there is a increase in COP upto 15% and there is a decrease in the effective temperature which are higher than the HVAC systems' and coolers. In this stage the noise of the cooler's cover has also reduced significantly by increasing the damping effect of the covers, also the increase in the humidity is lower as well. Makeup water recharge time also increase compared to the conventional coolers where the time is 23 hours and 15 hours respectively.

Çaylı et al. (2021), broiler houses which are used in evaporative cooling system to reduce the uncomfortable effects of temperature being high. In order to predict the production expenditure and capital costs of the design of these systems it is very much important to have the idea of cooling efficiency and it plays a vital role in developing these systems. Here, two similar kinds of broiler houses are used to whose features are alike. Out of the two broiler houses one was used to test the traditional fan pad and another for a water spray evaporative cooling system. The broiler houses dimensions are as follows - Length being 21 metres, width 7.2 metres, and floor area being 151.2 m². Fans of ventilation capacity 48,000 m³ h⁻¹ were used for checking ventilation. The efficiency of cooling drastically reduced under high relative humidity conditions.

Piotr and Dariusz (2021), discuss about the popularity gained by evaporative cooling system for its application in industrial buildings. There is a lack of detailed study and literature survey for the effectiveness of evaporative cooling system in industrial buildings especially for the climatic conditions of Europe. Using TRNSYS software, evaporative cooling system is evaluated for an industrial building located in Poland. Evaporative cooling system consisting of both indirect and direct cooling stages used and analysis carried out for six such devices located in four Polish cities namely Suwałki, Wrocław, Lublin and Koszalin. The results were observed and for Koszalin the TTF ranged from 178h to 611h, while for Lublin it ranged from 429h to 1194h. The results show that Koszalin has the highest TTF hours, while Lublin had the least for the system analyzed. Therefore, from the study, with the use of evaporative cooling system there is a great potential to save energy for the climatic conditions of Europe.

3. Methods

The structure of equipment is made of aluminum hollow profile of 23 mm thickness having the skin made of GI24S and the insulation material is made of CFC Free Puff. The air from the surrounding is passed through air intake passage where its properties are varied with the help of heater and humidifiers in order to study the working of equipment at

different environment conditions. The conditioned air then passes through an air filter of 10 microns (ATEEPL) to remove dust and foreign particles, this air then passes through a belt run Kruger make air blower having 500 CFM capacity for air to be sucked, this increases the velocity of air which eventually increases the temperature too. The first stage is Indirect evaporative cooling, in this stage sensible heat transfer occurs. The concept of DAMA (Dry air Moist air) comes to play. The heat exchanger used is a hi-tech polymer designed by HMX. The second stage is Direct evaporative cooling. Here adiabatic heat transfer occurs due to which there is a slight increase in humidity. In this stage cellulose pads (Munters make) having 7mm flute are kept wet from a water spray jet and the water is recirculated with the help of a pump of 0.05kW capacity through UPVC pipes. In the final stage a 2-ton vapor compression refrigeration system is placed, with this we can achieve desired room temperature. In this case the vapour compression refrigeration system receives cool air after the first two stages hence this reduces the work of the compressor, making this system cost efficient and eco-friendly.

Figure 3 depicts the evaporative cooling system setup consisting of two stages. The air from the surrounding is passed through air intake passage where its properties are varied with the help of heater and humidifiers in order to study the working of equipment at different environment conditions. This conditioned air then passes through an air filter to remove dust and foreign particles, this air then passes through a belt run air blower for more air to be sucked, this increases the velocity of air which eventually increases the temperature too. Figure 4 shows the air blower and pumps equipped to spray water over the heat exchangers.

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Figure 3. Experimental setup

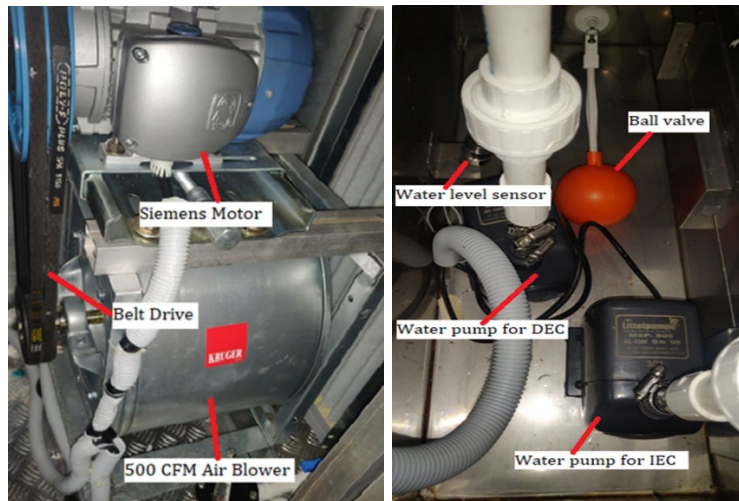


Figure 4. Air blower, motor and water pumps



Figure 5. Heat exchangers for IDEC system

4. Results and Discussion

4.1 Graphical Results

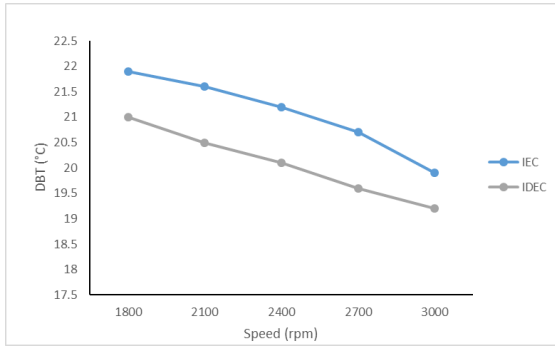


Figure 6. Speed vs DBT for high humidity

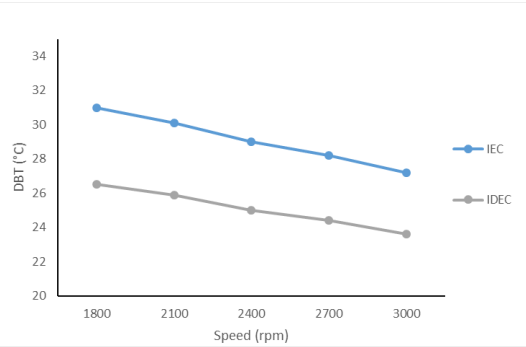


Figure 7. Speed vs DBT for high temperature

Figure 6 depicts the Dry Bulb Temperature (DBT) in °C at various speed. The speed of the air blower varied from 1800 to 3000 rpm. In IEC curve, with the increase in speed the DBT reduces from 21.9 to 19.9 °C, while in the IDEC curve we can see a further drop in temperature from 21 to 19.2°C due to the cooling from both the evaporative cooling stages. The DBT drop in IEC is higher than the IDEC.

Figure 7 depicts the DBT in °C at various speed at higher temperature condition. The speed of the air blower varies from 1800 to 3000. In IEC curve with the increase in speed the dry bulb temperature reduces from 32 to 26°C, while in the IDEC curve we can see temperature drop from 28 to 22°C. It is observed that the DBT drop in IEC is higher than the IDEC.

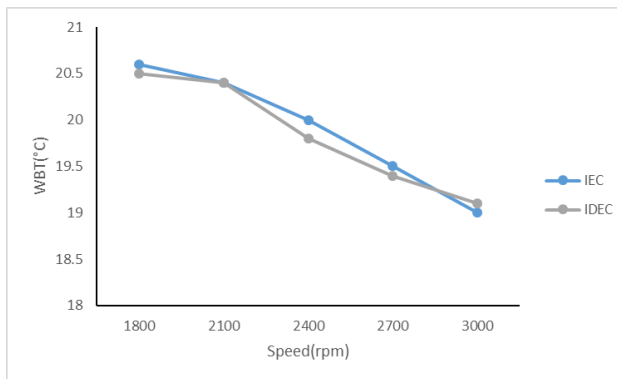


Figure 8. Speed vs WBT for high humidity

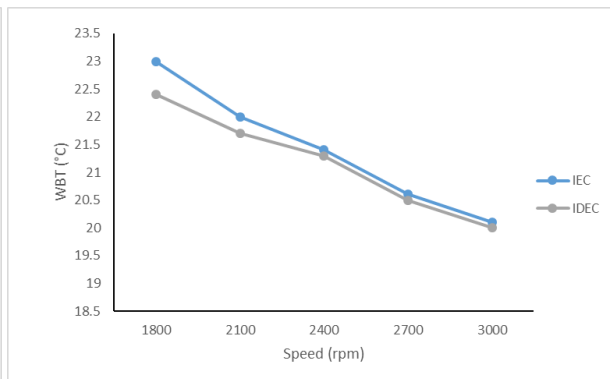


Figure 9. Speed vs WBT for high temperature

Figure 8 depicts the Wet Bulb Temperature (WBT) in °C at various speeds at higher humidity. In IEC curve with the increase in speed, the temperature reduces from 20.6 to 19 °C, while in the IDEC curve we can see no much change in WBT with comparison to IEC stage curve, this is due to the increase in humidity caused by direct evaporative cooling. From the Figure 8, it is observed that the WBT drop in IDEC is higher than the IEC due to direct contact between air and water mixture and also extended duration of evaporation in the indirect stage.

Figure 9 depicts the WBT in °C at different speeds at higher temperature. The speed of the air blower varies from 1800 to 3000 rpm. In IEC curve with the increase in speed the wet bulb temperature reduces from 23 to 21°C, while in the IDEC curve we can temperature drop from 22.5 to 20°C, while in multistage curve we can temperature drop from 5 to 3°C. The better evaporation in IDEC results in higher WBT drop as compared to IEC.

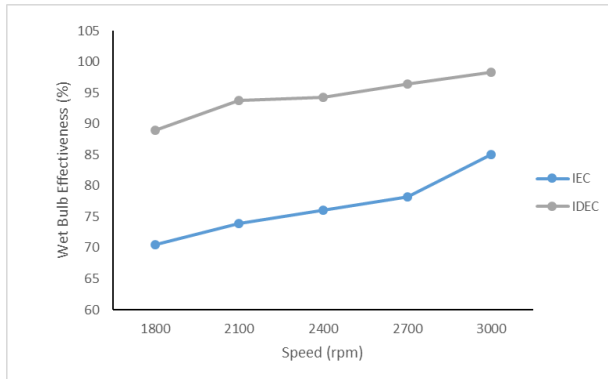


Figure 10. Speed vs WBE for high humidity

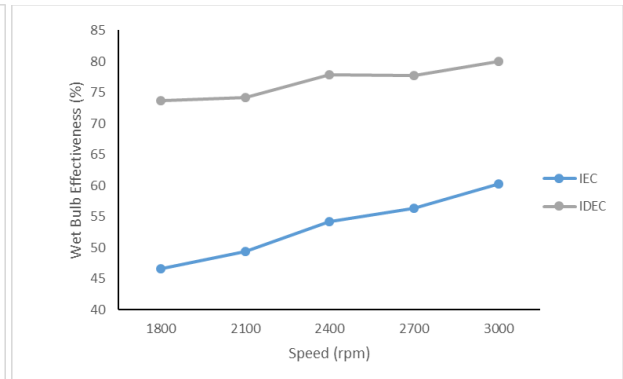


Figure 11. Speed vs WBE for high temperature

Figure 10 depicts the graph for speed in rpm versus Wet Bulb Effectiveness (WBE) for high humidity condition. Here in IEC curve there is an increase in wet bulb efficiency from 70% to 85% with the increase in speed. In case of IDEC the wet bulb efficiency achieved is higher in comparison to IEC, ranging from 88% to 98%.

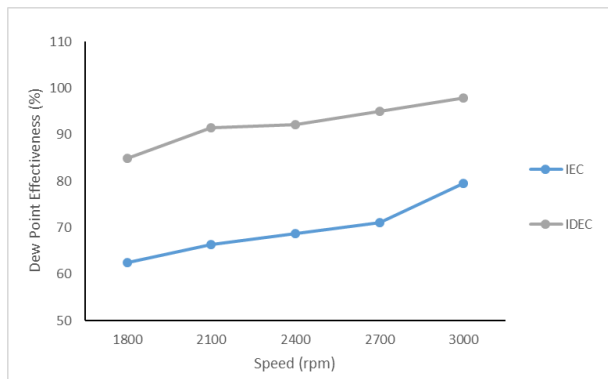


Figure 12. Speed vs DPE for high humidity

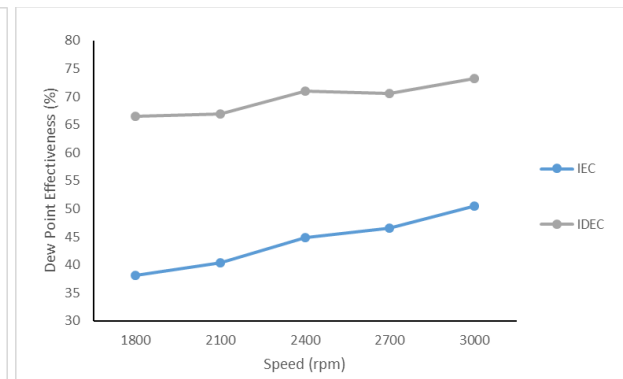


Figure 13. Speed vs DPE for high temperature

Figure 11 depicts the graph between speed in rpm and Wet Bulb Effectiveness (%) for high ambient temperature condition. The speed of the air blower varies from 1800 to 3000 rpm. In IEC curve with the increase in speed, the wet bulb effectiveness increases from 42% to 59%, while in IDEC curve we can see increase in effectiveness from 72% to 79%. The IDEC results in higher DPE due to better evaporation and higher temperature drop. The multistage ECS is better than the single stage ECS.

Figure 12 depicts the graph between speed in rpm and Dew Point Efficiency (DPE) for high humidity. Here, in IEC stage the dew point effectiveness is seemed to gradually increase from 62% to 80% with the increase in speed. Whereas, in IDEC with the cooling from two stages the dew point effectiveness is further seen to increase ranging from 85% to 98%. The IDEC results in higher DPE due to better evaporation and multistage system.

Figure 13 depicts the graph between speed in rpm and Dew Point Effectiveness (%) for high temperature. In IEC curve with the increase in speed, the dew point effectiveness increases from 38% - 50, while in IDEC curve the effectiveness increases from 66% to 73%.

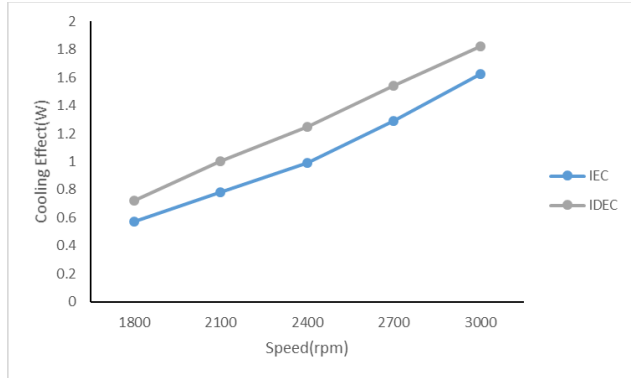


Figure 14. Speed vs Cooling effect for high humidity

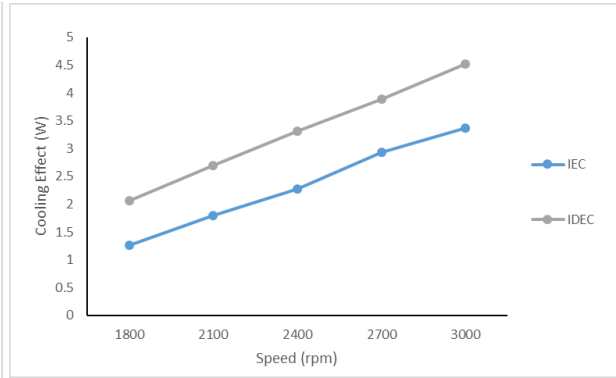


Figure 15. Speed vs Cooling effect for high humidity

Figure 14 depicts the graph between Speed and Cooling Effect measured in watt. In the IEC stage the cooling varies from 0.5W to 1.6W as the speed increases and increase of the IDEC stage the cooling effect produced is further increased due to the addition of a second heat exchanger. In this stage the cooling effect varies from 0.7 to 1.8W. The IDEC results in higher cooling effect as compared to single stage IEC. The multistage increases the cooling effect.

Figure 15 depicts the graph between speed in rpm and Cooling Effect (W) for high temperature condition. In IEC curve with the increase in speed the cooling rate also increases, ranging from 1.3W to 3.4W, while in IDEC curve the cooling rate increases from 2W to 4.5W.

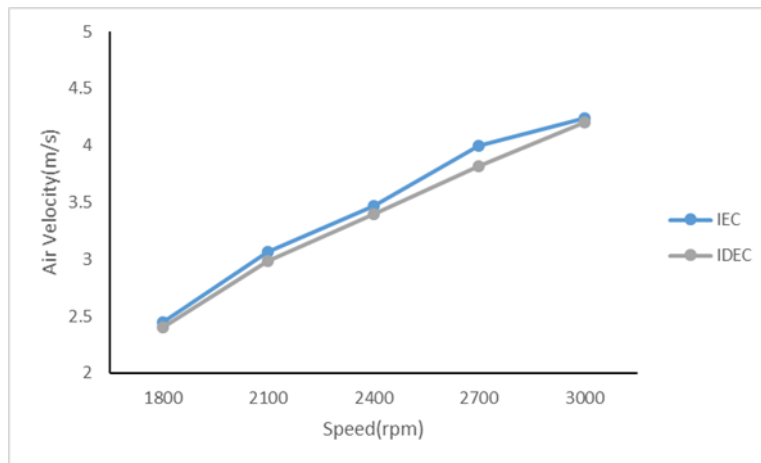


Figure 16. Speed vs Air velocity

Figure 16 depicts the graph between speed in rpm and air velocity in m/s that is measured at the outlet of the evaporative cooler. The trend of IEC curve is increasing in nature with respect to speed and air velocity. Whereas, in IDEC curve there is a decrease in velocity due to the inclusion of second heat exchanger.

Figure 17 depicts the graph between speed in rpm and Energy Consumption in kWhr/day. The air blower's speed increases from 1800 to 3000. In IEC curve, as the speed increases, there is a raise in the energy that is being consumed which changes from 6kWhr/day to 12kWhr/day, in the IDEC curve, it shows follows similar nature as that of IEC curve with a marginal increase in the energy consumption.

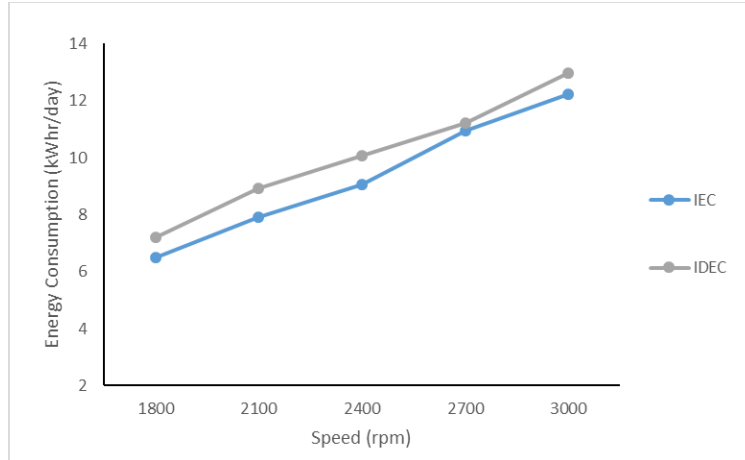


Figure 17. Speed vs Energy consumption

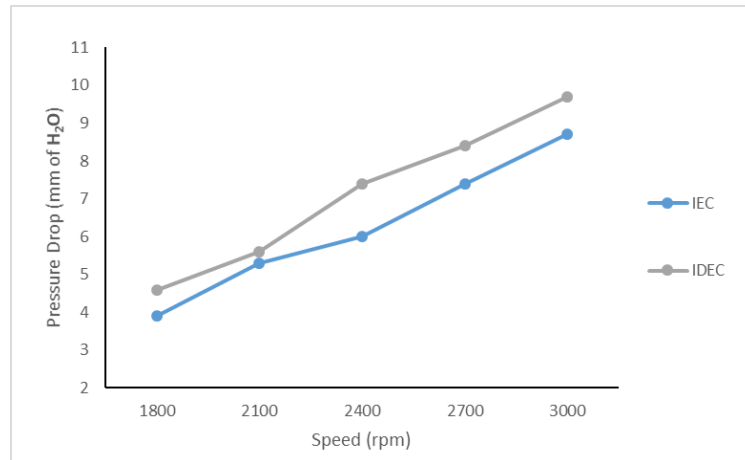


Figure 18. Speed vs Pressure Drop

Figure 18 depicts the graph between speed in rpm and pressure drop in mm of H₂O. As the blower speed varies from 1800 to 3000 rpm. In IEC curve, as the speed changes, the pressure drop varies ranging from 3.9mm to 8.7mm, while in the IDEC curve, in comparison with IEC it raises further up to 10mm due to the addition of another stage. The ECS with multistage results in higher pressure drop as compared to the single stage ECS.

6. Conclusion

There is a need to develop environmentally friendly low cost ECS. The multistage ECS is an efficient and eco-friendly cooling solution. It has high application in dry and torrid regions and can be used in a variety of fields. The first stage is an indirect ECS where heat exchanger designed in such a way that there is no contact between air and water, hence there is no increase in humidity and sensible heat transfer occurs, due to which this stage is preferable in regions where humidity is high. The second stage is direct ECS where the heat exchanger has direct contact with water and the air passing through this is cooler and contains little more moisture as compared to the first stage. Therefore, IDEC system has a huge scope of application in industrial and commercial buildings as it reduces temperatures to a level that provides thermal comfort while the humidity also is maintained. The multistage ECS consumes 25% less energy compared to vapour compression refrigeration system thus making it a preferable and feasible option.

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Biographies

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