RESEARCH ARTICLE

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Energy Performance of Window Air Conditioner in the Hot Climate using Evaporative Cooling Pads

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Abstract

The high demand for power, industrialisation, transportation and global warming are all significant contributors to the rise in average earth temperature. Because of the greater ambient temperature, the total performance of the air conditioning system with an air-cooled condenser reduces dramatically. These limits pushed the researcher to look for other ways to improve the performance of air conditioners, such as increasing the heat transfer rate in the condenser using evaporative cooling pads. The influence of combining the condenser of a 1.5-tonne window air conditioner with evaporative cooling pads of varied thicknesses on air conditioner performance has been investigated in this study. The present work determines the optimal cooling pad thickness for the maximum Coefficient of Performance (COP) of air conditioner based on the experimental investigation. Experimental results have shown that a honeycomb cellulose cooling pad with a thickness of 2 inches would lower power usage of air conditioner by 15% and increase the COP by 45 %.

Keyword: - Coefficient of Performance; Compressor work; Cooling pad; Evaporative cooling; Window air conditioner; honeycomb cellulose cooling pad.

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Introduction

Domestic power consumption accounts for 40 to 50 % of total primary power consumption worldwide. An appreciable amount of this electric power is consumed in air conditioning. The air conditioning industry is growing very fast, with 15-20 % annually, reflecting the vast demand for such equipment [1]. Domestic air conditioners make use of a heat rejection system through the condenser. The system is capable of performing efficiently in moderate ambient conditions. At higher temperatures, such as that above 50^{0}C, the efficiency of the air-cooled condenser reduces. Correspondingly, higher work is consumed by the compressor due to increased pressure ratio [2]. According to reports, every 1°C increase in condenser temperature reduces air conditioner COP by 2-4 % [3]. In the summer, energy demand is already at its height, and any additional load puts additional pressure on the power sector, which is undesired. In the summer, the outside air temperature is relatively high. Suppose this air is utilised to absorb the heat from the refrigerant vapour in the AC condenser, compressor work will be more significant to provide a higher pressure ratio to meet the condensing temperature. The best solution to enhance the functioning of air conditioners under such a situation is to reduce the condenser temperature by some means. It will drop the pressure ratio across the compressor resulting in power saving to a considerable extent, as there are

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millions of AC users in the world. Lowering the incoming air temperature with the help of evaporative cooling can substantially help in reducing the condenser temperature.

The evaporative cooling system reduces the temperature of the surrounding environment by the process of evaporation. Any liquid, when evaporates, utilises/extracts heat from the surrounding system for the change in its state, thereby making the system cooler. It should be noted that direct evaporative cooling, indirect evaporative cooling, and different cooling pad substances may all increase the effectiveness of the evaporative cooling system.

Indirect / Direct Evaporative Cooling System

Figure 1 depicts the operation of a direct evaporative cooling (DEC) system. The heated inlet air at state 1as shown in figure 1, passes through a pad material sprayed with a water stream maintained at the inlet air WBT. The direct evaporative cooling technique uses the latent heat of evaporation to reduce the temperature of the air, resulting in cold and moist air. Here water evaporates straight into the stream of supply air, reducing the DBT of the air with a slight increase in its humidity as the supply air is in direct touch with water through an evaporative medium or wetted pad or a chain of spray misters. Still, the enthalpy of air at the inlet and outlet remains the same. Therefore in direct evaporative cooling, cool and wet air should be exhausted from the conditioned space and no longer reused or reconditioned. The temperature of the conditioned room reduces without affecting the humidity of the conditioned area in indirect evaporative cooling [4]. There is now a lot of research going on in terms of novel heat exchanger shapes and materials, enhanced thermodynamic cycles, humidification systems, and calculating power savings against traditional devices.

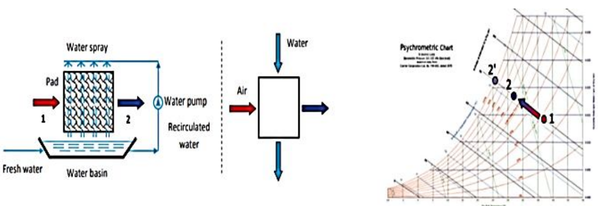

Figure 1: Working principle of DEC and its representation on the psychrometric chart [1]

Figure 2 depicts the operation of an indirect evaporative cooling (IEC) system. The hot primary airstream at state 1 is circulating through the dry channels and, in doing so, transfers heat via the heating surface to the wet channels through which secondary air stream passing. Here, in a heat exchanger, water, while evaporating in a secondary airstream, transfer sensible heat to the primary one. The primary air at state 2 in figure 2 will have less heat loss than at the inlet. At state 3, the secondary (working) air flows through the water's wet channels. The flow behaviour of the secondary air stream and water in the wet channel is identical to that of the DEC process in this case. Water absorbs latent heat; it is the heat transferred by the medium between the dry and wet channels, resulting in a rise in the moisture content of secondary air due to water evaporation. The significant advantages of the IEC are that the primary air is cooled at a constant moisture content. However, the main disadvantage of the system is that the WBT of secondary air stream's limits the primary air-cooling process.

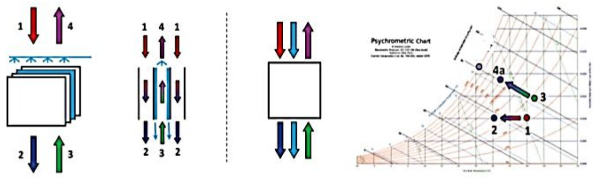

Figure 2: Working principle of IEC and its representation on the psychrometric chart [1]

Evaporative Cooling Pads

The evaporative cooling pad is a cross-flow kind structure essentially used for the cooling process and is so designed that it facilitates smooth contact of air and water. Cooling pads are available in various shapes and sizes and material types. The primary purpose of the cooling pads is to cool and humidify the outside, warm air and then use it for cooling the various applications. This is an evaporative cooling phenomenon wherein fans or blowers suck hot and humid air with less moisture content through these cooling pads and is made to come in contact with the water at the pad's interface. As air and water interact, it loses its sensible heat and gains an identical quantity of latent heat of vapour. More and more water is evaporated with increased air velocity with the corresponding drop in air temperature. More is the inlet and the outlet air temperature difference; more is the cooling effect. The main factors that affect the evaporative pad performance are the surface area of the pad, pad thickness, pad material, pad perforation size, flow rate and volume of water used [5].

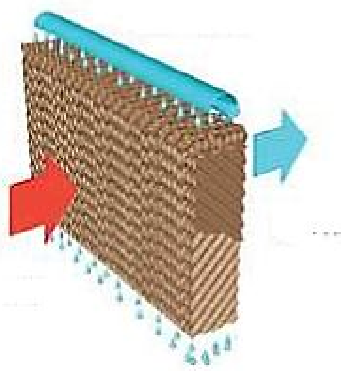

Figure 3: The air passing through the cooling pad

Literature Review

A lot of researchers have researched improving the performance of evaporative cooling systems. Dutta et al., [6] explain the feasibility of direct and indirect type evaporative cooling systems for many areas of India and Australia. El-Dessouky et al., [7] developed a combined (indirect evaporative and direct evaporative cooling) experimental test rig for the test in the Kuwait environment. Bajwa et al., [8] conducted the same investigation on several evaporative cooling systems to determine their practicality in a multi-climate nation. The effects of air velocity, static pressure drop over the pad, water flow rate, and pad thickness have been tested. Gunhan et al., [9] investigated the viability of using natural materials as evaporative cooling pads. Rawangkul et al., [10] used coconut coir as evaporative cooling pad material in the Thailand region. They stated that the efûciency of evaporative cooling of this pad material is around 50% proximity to the commercial paper pad. Camargo et al., [11] determined convective heat transfer coefûcients by performing experimental analysis on the direct evaporative cooler. Sawant et al., [12] tested the window air conditioner experimentally with an evaporative cooling system using the condensate from the air conditioner. The experimental results have shown an energy saving of 13%, whereas COP increased by 18%. Ali et al., [13] provide a performance study of several configurations of combined direct and indirect evaporative cooling in five climatic zones of Pakistan from April to September for the parameters cooling capacity and outlet temperatures. The mathematical model of these configurations is developed for operating conditions like air temperature and humidity for the performance analysis. Goswami et al., [14] employed four media pads surrounding the condenser coil to provide evaporative cooling while injecting water with a tiny water pump on a 2.5-tonne air conditioner. At 34°C ambient air temperature, they recorded a power savings of roughly 20% for the retrofitted system.

Motivation behind the study

Many doubts about evaporative cooling methods and the expected rise in COP, mainly a sizzling area. Even though many manufacturers of air conditioners have air-cooled condensers on the market and the advantages of employing evaporative cooling in terms of power savings potential, there is still relatively little work being done in this field. So, substantial efforts are necessary to deal with the many benefits; and achieve the best possible design with the optimum possible arrangement of evaporative cooling in the air conditioner.

Specific objectives of the study

In light of the preceding, an experimental investigation is carried out in this research work to analyse the impact of the evaporative cooling system with different pad thicknesses on the overall performance of a window air conditioner at different ambient temperatures to determine the amount of savings in COP and power consumption with the changed system. The novelty of this research work is, it provides optimum thickness for condenser cooling pads; that would be used by designers in the industry and promising researchers for sustainable product development.

DESIGN OF EXPERIMENTAL SET-UP

To perform experimentation work, an existing conventional window air-conditioner of 1.5-tonne capacity has been used. An evaporative cooling facility is provided to the air conditioner incorporates media pads between the evaporator and condenser coils from both sides across the air passage that caused air cooling, passing through the condenser coil due to the water evaporation figure 4. Media pads used for evaporative cooling is honeycomb structured cellulose pad. A water tank is placed below the pads to collect the water from the pads. Condensate formed through dehumidifying room air while passing over the cooling coil is contained in a water tank instead of letting it drip from the unit at dew point temperature.

For recirculating and spraying water over the media pads, a tiny pump is employed. For all testing, the water flow rate is maintained constant. While passing over the media pad, hot ambient air cools owing to evaporation before entering the condenser and eventually exiting from the backside of the condenser. An energy metre is used to calculate the total energy usage of the system. Pressure gauges are installed for recording the pressure in the condenser and evaporator. T-type thermocouples are installed at strategic locations to record the temperatures of all parameters as specified in the observation tables. The condenser and the evaporator pressure drop were presumed to be 7% and 5%, respectively. Based on earlier research in the literature, it was discovered that assuming these pressure drops had no significant influence on the final findings. K-type thermocouples measure refrigerant temperatures and airflow at different places.

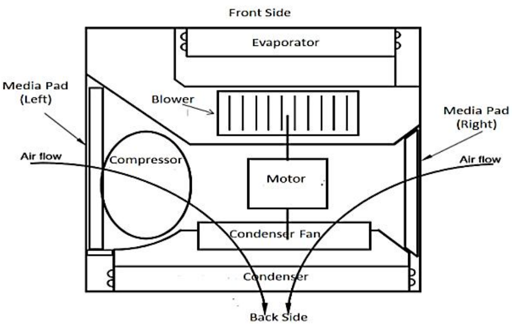

Figure 4: Aerial image of an air conditioner equipped with an evaporative cooling system [5]

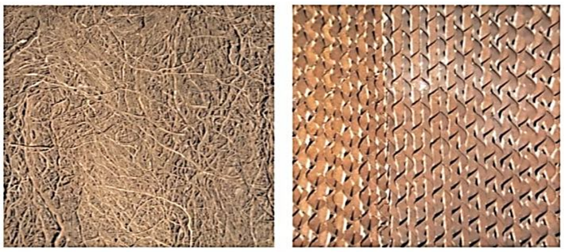

Figure 5: (a) Media Pad - khus, (b) Media Pad -Honey-comb cellulose [5]

Experimental Results and Discussion

Many preliminary tests were carried out to get accurate results. Each test was completed in two steps to evaluate the influence of the evaporative cooler on the system and compare performance with and without the evaporative cooling system. In the first experiment, a typical air conditioner with an air-cooled condenser was employed without a media pad, and performance metrics were recorded. Then in the second stage, the air conditioners' condenser was retroûtted with an evaporative cooling system very fast by using honeycomb structured cellulose media pads of different thicknesses 1, 2 and 3 inch and performance parameters were recorded. The time gaps between the two stages were made as little as possible to guarantee similar weather conditions (about 15 min.). All data in all experiments were recorded only after the steady state. To estimate the impact of an evaporative cooling system on the performance of an air conditioner, several experimental tests were conducted at various ambient temperatures. The results of the tests at three different ambient temperatures (30, 37, and 43 degrees Celsius) demonstrated the maximum possible impact of an evaporative cooling system on the performance of an air conditioner. Tables 1 and 2 provide the experimental results that were recorded.

Table-1: Experimental results of the conventional air conditioner & air conditioner retrofitted with an evaporative cooling system coupled with different pad thicknesses at different ambient temperatures.

Parameters	**Ambient temperature 30°C**				**Ambient temperature 37°C**			
	CVA	**EC1**	**EC2**	**EC3**	**CVA**	**EC1**	**EC2**	**EC3**
Evaporator Pressure (P_1) in PSI	56	51	49	50	59	54	51	53
Condenser Pressure (P_2) in PSI	227	203	201	202	239	214	212	214
Compressor exit temperature (T_1) in °C	89	79	75	77	95	89	86	88
Condenser exit temperature, T_2) in °C	41	32	29	30	46	35	30	33
Compressor inlet temperature, (T_3) in °C	23	21	19	21	22	21	21	21
Temperature inside the room, (Td_4) in °C	22	22	22	20	22	23	22	21
Air temperature before pad, (Td_5) in °C	30	30	30	30	37	37	37	37
Air temperature after pad (Td_6) in °C	--	27	24	27	--	34	29	31
Air temperature at condenser exit, (Td_7) °C	34	33	32	31	43	43	39	41
Wet bulb temperature of the air inside the room, (Tw_1) in °C	18	22	20	20	18	22	18	20
Relative humidity of air after pad ($?_1$) %	21	21	22	20	21	22	21	22
Evaporator inlet relative humidity ($?_2$) %	58	61	60	63	58	59	59	59
Outside atmospheric, $?_2$	48	52	53	55	32	42	37	40
Current in amp, I	7.7	6.7	6.4	6.5	7.9	7.1	6.8	7

CVA- Conventional A.C. without an evaporative cooling system.
EC1- AC retrofitted with an evaporative cooling system having a pad thickness of 1 inch.
EC2- AC retrofitted with an evaporative cooling system having a pad thickness of 2 inches.
EC3- AC retrofitted with an evaporative cooling system having a pad thickness of 3 inches.

Table-2: Experimental results of the conventional air conditioner & air conditioner retrofitted with an evaporative cooling system coupled with different pad thicknesses at ambient temperatures of 43ºC.

Parameters	Ambient temperature 43°C			
	CVA	EC1	EC2	EC3
Evaporator Pressure (P_1) in psi	64	61	56	59
Condenser Pressure (P_2) in psi	251	228	226	226
Compressor exit temperature (T_{c2}) in °C	99	92	91	93
Condenser exit temperature, T_{cn2}) in °C	52	39	33	39
Compressor inlet temperature, (T_{c1}) in °C	23	21	21	22
Temperature inside the room, (Td_4) in °C	23	24	23	22
Air temperature before pad, (Td_5) in °C	45	45	45	45
Air temperature after pad (Td_6) in °C	--	35	32	33
Air temperature at condenser exit, (Td_7) in °C	49	46	45	46
The wet-bulb temperature of the air inside the room, (Tw_1) in °C	19	23	19	21
The wet-bulb temperature of the air Outside atmospheric, Tw_2	23	21	22	22
R.H. Inside the room, $?_1$	60	61	57	59
R.H. Outside atmospheric, $?_2$	20	29	24	27
Current in amp, I	8.4	7.3	7.1	7.4

In the evaporative cooling system, due to air precooling before feeding it to the condenser, there is a significant drop in the inlet air temperature to the condenser. As seen from Tables 1 to 2, it is observed that electric current, pressure in the condenser, compressor exit temperature increase substantially high with the rise in ambient temperature in conventional air conditioner but with the evaporatively cooled condenser, better performance is recorded. When precooling pads are linked with the condenser, the incoming air stream temperature of the condenser is reduced below the ambient temperature, lowering the condensing pressure and temperature in the cycle and, consequently, reducing compressor effort.

Calculation of Performance Parameters

The following equations (1) to (4) were used to calculate the mentioned parameter using the thermodynamic properties of refrigerant R-22 from the P-h chart. Enthalpy at the various points is noted from the P-h chart and tabulated in Tables 3 to 8. Eq. (1) gives compressor work consumption. Eq. (2) is for mass flow rate. Refrigerating effect and COP can be calculated by Eq. 3 and 4, respectively.

Compressor work, in Kw, $W_c = V \times I \times \cos\varnothing$ —(1)

Where, V-voltage, I-current in amp & $\varnothing$-power factor

Mass of refrigerant, in Kg/sec, $m = \dfrac{W_c}{(h_2 - h_1)}$ — (2)

Refrigerating effect, in kJ/sec, $R_E = m \times (h_1 - h_4)$ — (3)

Coefficient of performance, $COP = \dfrac{R_E}{W_c}$ — (4)

Where

h_1: enthalpy at evaporator outlet in kJ/kg,

h_2: enthalpy at compressor in kJ/kg

h_3 ($=h_4$): enthalpy at the inlet to the evaporator in kJ/kg

To calculate the compressor work, the mass of refrigerant, refrigerant effect, COP and energy analysis of the evaporative cooling system, thermodynamic properties of refrigerant are needed to specify at various sections on the p-h chart the experimental results as depicted in table 3 to 8. P-h charts for the conventional and retrofitted system with pad thickness 1, 2 & 3 inches at T_{amb} 30ºC are shown in figure 6 to 8 to find the enthalpy value as a sample.

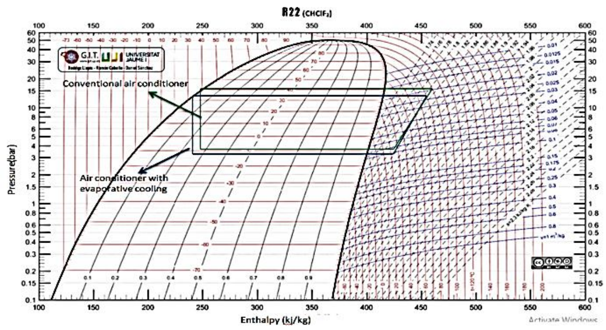

Figure 6: P-h chart of the conventional and retrofitted system with pad thickness 1 inch at Tamb. 30ºC.

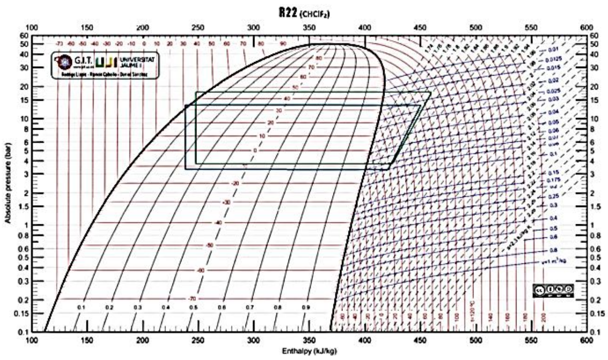

Figure 7: P-h chart of the conventional and retrofitted system with pad thickness 2 inches at Tamb. 30ºC

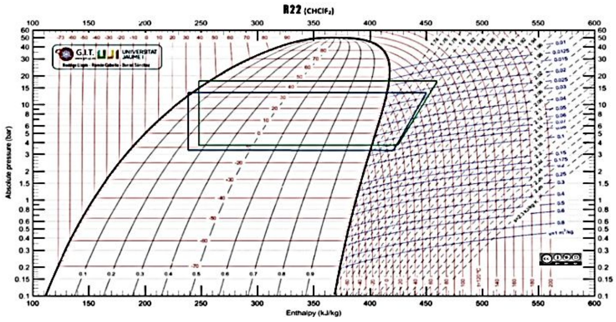

Figure 8: P-h chart of the conventional and retrofitted system with pad thickness 3 inches at Tamb. 30°C

Table-3: Results of the air conditioner's performance with and without evaporative cooling at (Tamb-30oC).

	h1	h2	h3	I	W_C	m	R_E	COP
CVA	418	463	253	7.7	1.54	0.03	5.65	3.67
E1	420	462	242	7.3	1.46	0.03	6.19	4.24
E2	416	452	233	6.7	1.34	0.04	6.82	5.08
E3	416	454	235	6.9	1.38	0.04	6.58	4.76

Table-4: Results of the air conditioner's performance with and without evaporative cooling at (Tamb-37oC).

	h1	h2	h3	I	W_C	m	R_E	COP
CVA	417	465	252	7.9	1.58	0.03	5.43	3.44
E1	418	460	241	7.1	1.42	0.03	5.99	4.21
E2	419	458	232	6.8	1.36	0.03	6.52	4.79
E3	421	461	237	7	1.40	0.04	6.44	4.60

Table-5: Results of the air conditioner's performance with and without evaporative cooling at (Tamb-43oC).

	h1	h2	h3	I	W_C	m	R_E	COP
CVA	417	457	265	8.4	1.68	0.04	6.39	3.80
E1	416	449	250	7.3	1.46	0.04	7.35	5.03
E2	417	448	246	7.1	1.42	0.05	7.84	5.52
E3	419	450	250	7.4	1.48	0.05	8.07	5.45

Tables 3 to 5 show the calculation results at various ambient temperatures. According to these data, the evaporative air cooling effect increases as the ambient temperature rises. Performance comparison of the conventional air conditioner with evaporative cooling assisted air conditioner as depicted in fig. 9 for all the combinations.

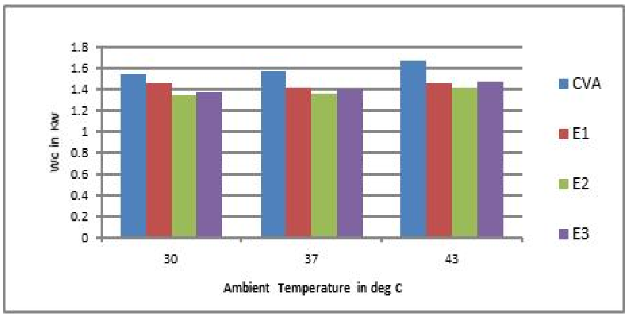

Figure 9(a): Comparison of compressor work with and without evaporative cooling

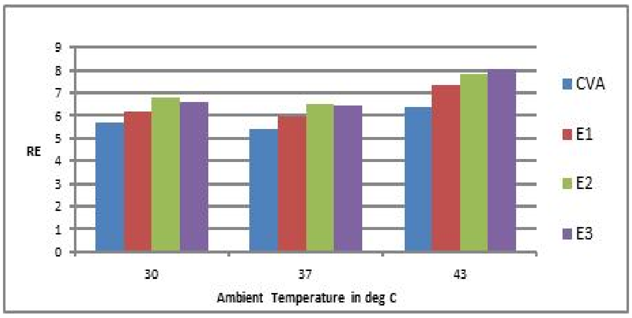

Figure 9(b): Comparison of refrigerating effect with and without evaporative cooling.

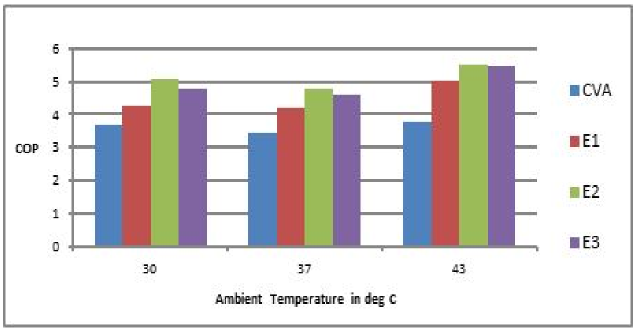

Figure 9(c): Comparison of COP with and without evaporative cooling.

This observation reveals that the maximum power reduction of 15% and maximum rise of 45% in COP are found with a media pad of thickness of 2 inches. Numerous tests were performed at different ambient temperatures ranging from 30°C to 43°C to better understand the system's functionality. Figures 10 to 12 show how the performance of two condensers varies with ambient air temperature. The evaporative cooled condenser's performance is significantly better than that of the air-cooled condenser, and it improves as the ambient temperature rises.

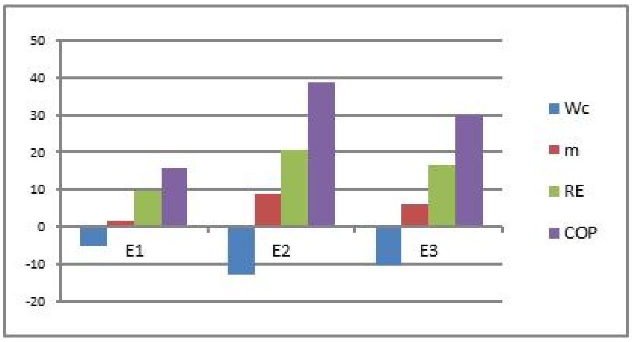

Figure 10: Performance variation of the retrofitted system at Tamb. 30°C

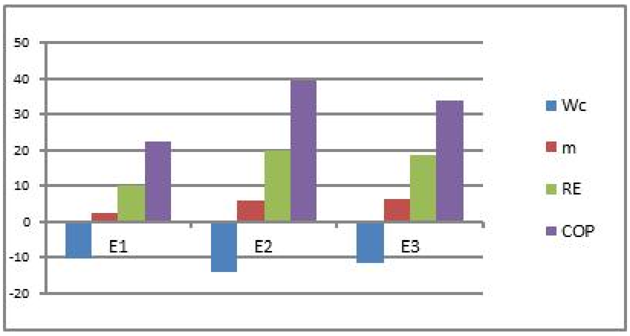

Figure 11: Performance variation of the retrofitted system at Tamb. 37°C

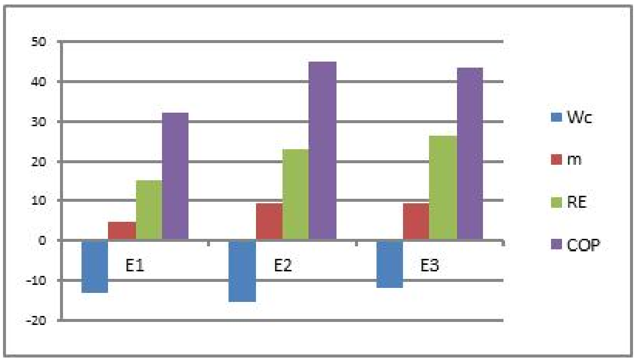

Figure 12: Performance variation of the retrofitted system at T_{amb} 43°C

Conclusions and Future Scope of Work

This study investigates the influence of evaporative cooling systems on conventional air conditioners in hot temperature zones. The performance and energy savings of a standard air conditioner retrofitted with an evaporative cooling system consisting of cooling pads of varying thicknesses that produce precooling of air at the condenser unit were investigated experimentally. From this experimental exploration, the following conclusions are drawn:

- The performance of an air conditioner retrofitted with an evaporative cooling system improved significantly compared to a standard air-cooled condenser. It improved as ambient temperature increased.
- The significant decline in input air temperature to the condenser, condenser pressure, and compressor power consumption even under high relative humidity circumstances are the preliminary results of the utilisation of an evaporative cooling system.
- The peak demand of the electricity grid will be reduced in hot weather regions with the aid of an evaporative cooling system since air conditioners operating on the VCR cycle are often responsible for the peak load.
- The use of an evaporative cooling system with precooling pads improves the performance of the air conditioning equipment.
- The best lower condensing pressure, refrigerating effect, compressor power consumption, and COP are observed with different pad thicknesses.
- The proposed system has a high commercialisation potential since it can be successfully linked to the existing system at a reasonable cost.

The experimental results may be validated in future using advanced computational fluid dynamics software or suitable machine learning programming to forecast optimal cooling pad thickness at any hot and dry location on the globe.

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Abbreviations

AC	Air conditioner
COP	Coefficient of performance
CVA	Conventional air conditioner
DEC	Direct evaporative cooling
E_1	Air conditioner with a 1-inch pad
E_2	Air conditioner with a 2-inch pad
E_3	Air conditioner with a 3-inch pad
IEC	In-direct evaporative cooling
Ph	Pressure Enthalpy Chart
VCR	Vapour Compression Refrigeration

Nomenclature

DB (°C)	Dry-bulb Temperature
H (kJ/kg)	Enthalpy
I (A)	Current
M (Kg/sec)	Mass flow rate of refrigerant
þ	Power factor
P_1 (Psi)	Evaporator pressure
P_2 (Psi)	Condenser pressure
R_E (kJ/sec)	Refrigerating effect
RH (f)	Relative humidity
T_{amb} (°C)	Atmospheric temperature
T_{c1} (°C)	Refrigerant temperature at compressor inlet
T_{c2} (°C)	Refrigerant temperature at compressor exit
T_{cn2} (°C)	Refrigerant temperature at condenser exit
T_d (°C)	Air temperature
V (volt)	Voltage
WBT (°C)	Wet-bulb temperature
W_c (kW)	Work of compression