An Improved Indirect Evaporative Cooler Experimental Investigation

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Abstract

Air conditioning has enhanced the work efficiency and improved life style by maintaining comfortable environment. The growing demand of air conditioning has negative impact on energy and environment. In 2015, air conditioning consumed 6% of total global electricity produced and it is expected to increase to 20% by 2050. The leveling-off conventional chiller's efficiency at 0.85 ± 0.03 kW/Rton due to pairing of dehumidification and cooling processes in one machine is not only the major reason of high energy consumption but also the key limitation in efficiency improvement. The de-coupling of dehumidification and cooling processes can be one of the solution to achieve the quantum jump in the performance, 0.6 ± 0.03 kW/Rton, by improving individual processes. We proposed an improved indirect evaporative cooler system for sensible cooling that can be combined with dehumidification processes to achieve sustainable cooling goals. The experimentation on 800mm long and 280mm wide generic cell showed that it can produce temperature differential up to 10°C with small area of heat transfer. It was showed that the proposed vertical heat exchanger configuration with multi point injection of working air is the best configuration of the indirect evaporative cooler, achieving coefficient of performance level of 78 for cooling alone. We expect that overall coefficient of performance level of 7-8 is achievable by incorporating efficient dehumidification processes. We also presented detailed design parameters that can be used as a reference for commercial system design.

Keywords: Indirect evaporative cooler, chiller efficiency, coefficient of performance, air-conditioning

1. Introduction

Space cooling demand is increasing steadily at a cumulative average growth rate of 3.3% annually since 2010 [1]. It is estimated that room air conditioner (RAC) units alone will be over 4500 by 2050 and they will contribute approximately 170 gigatons of carbon emission to the environment. The contribution of different part of the world in RAC and emission is shown in Figure 1[2]. Since 2000 to 2015, it has been reported that energy consumption of air conditioning (AC) has increased two folds from 3.6 EJ to 7 EJ [3]. On average, AC represents 14-15% of peak electricity demand worldwide [4].

Figure 1: Room air conditioner units and corresponding carbon emission in the different part of the world by 2050 [2].

In the Gulf Cooperation Council (GCC) countries, the energy needed for cooling is even higher, over 3 times as compared to moderate climate regions, due to the severe weather conditions. In these countries, the space cooling systems such as; (a) windows unit, (b) split units, (c) air or water cooled central AC systems and (d) district cooling systems consume 50-70% of peak electricity [4, 5]. By 2030, the cooling demand is expected to be triple in GCC countries as compared to 2010 level. The Kingdom of Saudi Arabia (KSA) and the United Arab Emirates (UAE) will maintain their highest share in GCC member countries at 20–53 million Rton (MRT) (2010–2030) and 10–22 MRT (2010–2030) respectively [4]. Such a high energy demand for space cooling in the GCC countries is attributed to two key factors. Firstly, there is a rapid growth in the population from 22 millions in 1990s to 50 millions presently. Secondly, the rising GDP of GCC countries has transformed the cooling demand to an unprecedented rate. The demand for cooling energy consumption is further compounded by the low energy efficiency of AC units available hitherto, which is hovering around 0.85 ± 0.03 kW/Rton. The average efficiency of air conditioners sold today is less than half of what is typically available on the shelves and one third of best available technology as shown in the Figure 2 [6-8]. As per business as usual trend in GCC countries, by 2030, approximately \$100 billion will be required for cooling hardware to provided projected cooling demand. It will cost an additional over \$120 billion for power generation facilities to provide associated electricity [3].

Figure 2: The average efficiency distribution of air conditioners in the different part of the world [6-8].

Although there were lots of improvements in the efficacy of chillers since 2000, since three decades, the energy efficiency have levelled asymptotically [8-10]. The inability for kW/Rton of chillers to improve hitherto is attributed the embedded thermal lift caused by temperature requirements (i) imposed by dew point in the air handling units (AHUs) and (ii) the finite heat rejection from the condensation process of refrigerant vapor. Thus, to have a quantum jump in efficacy for chillers, an out-of-box solution is essential to achieve the goals of sustainable cooling. An innovative approach for outdoor air (OA) treatment is proposed where moisture removal and sensible cooling can be de-coupled with separate but efficient processes, unlocking new paradigms to achieve lower specific energy consumption in AC processes. The proposed system called dehumidification cum an indirect evaporative cooler (DH-IEC). A quantum jump in cooling efficiency of 0.6 ± 0.05 kW/Rton is tenable by DH-IEC processes. Dehumidification processes are well known and many developed technologies are available in the market with best efficiencies [11-15]. However, indirect evaporative cooler still at development stage and need urgent attention to improve their efficiency. In this paper, we demonstrated the improved IEC generic cell design and experimentation at assorted weather conditions. We also developed detailed operational parameters for industrial system design reference. **The proposed improved IEC unit will help to achieve sustainable cooling goals, energy efficiency and low CO₂ emission. In addition, it will also help to save capital as it only need 30-40% of conventional chiller's initial cost.**

2. Indirect Evaporative Cooling (IEC) System

An indirect evaporative cooling system works on the concept of decoupling of moisture (latent) removal from sensible cooling [16]. It avoids the use of mechanical vapor compressors, chemical-based (chlorofluorocarbons) refrigerants, cooling towers, chilled and cooling water

pipes that eliminates more than 75% of conventional infrastructure of mechanical or thermally driven chillers. In IEC processes, only clean water is employed for heat removal that utilizes the evaporative potential of the air. Such a phenomenon is observed in the daily processes of nature as it employs the properties of air and water with energy input from the sun. The key heat extractions are the latent and sensible heat flow (orthogonal direction) across the thin sheets of hydrophobic materials from dry channel to wet channel. On the other side of hydrophobic material sheets, also called wet channel, a layer of hydrophilic membrane keep interface moist and provide evaporative potential to the purged air. Ideally, the supply air temperature can reach to the wet-bulb temperature of the incoming OA but it need infinite area of heat transfer. Hence, conventional IEC units were not able to commercialize for many years because of supply air temperature limitations and it doesn't justify the high manufacturing cost for large heat transfer area [17]. In 2002, Maisotsenko presented an improved IEC cycle to overcome the conventional unit's limitations [18]. The Maisotsenko cycle (M-cycle) is based on pre-cooling of wet channel purged in dry channel and this can be done in different ways. The M-cycle design was able to achieve wet-bulb temperature without adding moisture contents into supply air. The counter flow arrangement was considered as most efficient but it was not able to commercialize due to fabrication issues of pure counter flow heat exchanger. Hence, the cross flow arrangement was commercialized successfully due to easy manufacturing but compromising on efficiency [19]. Unlike the conventional chillers, there is no proper standard available for IEC system's evaluation. There are some regional standards to investigate the performance at national level [20]. For example, in USA there two standards for IEC unit evaluation ANSI/ASHRAE Standards (133-2008/ 143-2007) and California Appliance Efficiency Regulations [21-23]. Similarly in Australia AS/NZS 2913-2000 [24], in Saudi Arabia SASO35/36 [25, 26], in Iran Labeling Program [27], in India IS 3315-1974 [28], in China GB/T 25860-2010 [29] and in Canada C22.2 No 104 [30]. Due to lack of international standard, scientist and researchers developed their own definitions to evaluate the performance of their systems as shown in Table 1 & 2. Some researchers showed effectiveness even over 100% that might not be accurate as it depends on individual performance parameter definition and calculation parameters.

Table 1: IEC heat exchanger arrangements and achievable outlet temperatures.

Ref#	Heat exchanger arrangement	Flow arrangement	Air velocity (m/s)	Outdoor temperature (°C)	Outlet temperature (°C)
31	Horizontal	Cross	0.5-1.1	25-45	18-24
32	Horizontal	Cross	-	30-36	23-24
33	Horizontal	Cross	-	29-35	21-23
16	Horizontal	Cross	-	30	20-28
34	Horizontal	Cross	-	25-45	17-25
35	Horizontal	Counter	1.5-6	25-45	15-32

Table 2: Measured effectiveness of IEC systems based on simulation and experimentations.

Ref#	Study type	Heat exchanger arrangement	Wet bulb effectiveness (%)	Dew point effectiveness (%)
36	Experiments	Cross	81-91	50-63
37	Simulation	Counter	54-130	36-82
38	Simulation	Counter	136	91
39, 40	Experiments & Simulation	Counter	92-114	58-84
41	Simulation	-	109-131	-
42	Experiments & Simulation	-	141	-
43	Experiments & Simulation	-	118-122	75-90

It was noticed from the literature that most of available data on IEC is based on almost similar configurations; (i) horizontal heat exchanger design, (ii) single working air injection to wet channel and (iii) poor heat transfer hydrophobic separation membranes. These conventional design and operational parameters have some limitations those are major hindrance in the performance improvements of IEC. Firstly, the horizontal heat exchanger design have water distribution and collection problems in wet channel that effects the system performance. It also cause sagging of membrane sometimes and block the air flow passage [44]. Secondly, the injection of working air at single point lose the effective utilization of purge air potential. Portion of working air is just purged out without interacting with hydrophilic surfaces. Lastly, the orthogonal heat transfer is based on conductivity of hydrophobic separation surfaces between dry and wet channels and in conventional systems they are poor conductors. The IEC cycle performance can be enhanced greatly if these design and operational parameters can be improved. The proposed improved IEC design will help to overcome all mentioned limitations. The detail of improved design is discussed in the following sections.

3. Proposed Improved IEC Schematic

A generic cell of indirect evaporative cooler was designed based on proposed improvements to investigate the performance at assorted weather conditions. A typical generic cell is a pair of one dry channel surrounded by wet channels. The purpose of a generic cell test was to investigate the wattage capacity for designed length and width. These cells can be stacked for higher capacity domestic and industrial applications. The simple schematic of a generic cell is shown in Figure 3 (a) and improved cell is shown in Figure 3(b).

Figure 3(a). Indirect evaporative cooler generic cell process schematic.

Figure 3(b). Improved indirect evaporative cooler generic cell process schematic [45].

During operation, outside air is forced through the dry channels via electric blower. While flowing through the dry channel, its temperature drop due to orthogonal heat transfer to the wet channel. This heat is taken away by the purged air that is extracted from the dry channel at the end of section. The dry purged air pick-up the moisture from the hydrophilic membrane of wet

channels and help to removes the heat emanated from the air flowing in the dry channels in the longitudinal direction. Even though aluminum is good heat conductor but due to high velocity, the longitudinal heat transfer is not effective that maintain the potential between the inlet and outlet of the section of generic cell. The cooling capacity that varies during the diurnal and nocturnal hours can be readily controlled with the proportion of the purged air needed for the application. In case of multi point injection, the purged air is injected at different points into wet channel. It help to utilize the purged air potential more effectively as compared to single point injection. In addition, the cells are arranged in vertical manners to improve overall performance.

4. Experimental Generic Cell

A test cell is designed based on Figure 3(b) schematic and fabricated at King Abdullah University of Science and Technology. The experimental system is shown in Figure 4 (a) and internal structure of dry and wet channels is presented in Figure 4(b). In new generic cell design, three modifications are incorporated. Firstly, it was arranged in vertical manner (width side) for better wettability of hydrophilic membrane in wet channels and also for easy flow of additional water to the lower section for recirculation.

Figure 4 (a). Improved indirect evaporative cooler generic cell test pilot at KAUST.

Figure 4 (b). IEC test cell dry and wet channels structure.

Table 3. Design and operational parameters of improved indirect evaporative cooler.

Description	Dimensions	units	comments
Length of effective cell area	800	mm	Air contact length
Width of effective cell area	280	mm	Air contact area width
Hydrophilic membrane	0.3	mm	Special woven with high capillary action
Aluminum foil	0.02	mm	Thin and strong foil for high heat transfer
Dry channel height	4	mm	Special spacer are utilized to create turbulence in flow
Wet Channel height	4	mm	Special spacer are utilized to create turbulence in flow
Dry channel air flow rate	73.5	m ³ /hr	
Purge ratio	30	%	

In conventional horizontal design, dry patches are observed that leads to poor performance. In addition, there is also excess water flow problem that sometimes block the narrow wet channels. Secondly, the hydrophobic materials in dry channel is replaced by thin aluminum foil. In wet channel, to provide moist surfaces, hydrophilic membrane is laminated onto aluminum foil using special high conductivity glue. This arrangement of highly conductive as well as water repellent dry channel surfaces will help to improve the performance as compared to poor heat transfer hydrophobic film surfaces utilized in the conventional systems. Lastly, multi point injection of the purged air is introduced as compared to single injection in conventional systems. This proposed multi injection points help to utilize the purge air potential effectively. The detail

specifications of generic cell are given in Table 3. The summary of instrumentation is presented in Table 4.

Table 4. Instrumentation provided on IEC experimental system.

Parameter	Instrument
Temperature	OMEGA thermistors Measuring range: 0 to 80°C Accuracy: $\pm 0.15^\circ\text{C}$
Air velocity	Testo 425 - Air Velocity Meter with thermal flow probe Measuring range: 0 to 20 m/s Accuracy: ± 0.03 m/s
Humidity	Fisher Scientific Traceable Humidity Temperature Dew Point Meter Humidity range: 20 to 95% Accuracy: $\pm 1\%$

5. Results and Discussion

The generic cell shown in Figure 4 is fabricated using acrylic spacers and end covers. The cell is tested at assorted outdoor air temperatures to investigate the performance of proposed improved design. Initially, it was tested at 40°C outdoor air temperature without insulation and found over 40% heat leak due to lower room temperature. To investigate the real performance of generic cell, one inch thick insulation was provided to prevent the heat leak. After insulation, the system was tested to ensure minimal heat leak as shown in Figure 5. It can be seen that less than 1% heat leak was observed when system was operated as dry before wetting the hydrophilic membranes. After successful heat leak test, water was supplied to the one side of wet channel and purge air valve was opened to circulate 30% of supply air. The supply air temperature was dropped to 32°C due to good orthogonal heat transfer from dry channel to wet channel. This higher temperature difference as compared to conventional 5-6°C is due to improved design of cell as explained in earlier sections. To test full operation, water was supplied to the both side of wet channel that helped to lower down the supply air temperature to 30°C. The lower potential after both wet channel operation shows that the cell was already operating at optimum conditions with one wet channel. In other words, for same capacity with two wet channels, the size of the generic cell can be smaller. It can also be observed that system operation was very stable that shows the robustness and workability of proposed improved IEC system.

Figure 5. Temperature profiles at 40°C outdoor air temperature.

The measuring stations are provided at different locations to track all important parameters. The wet bulb temperatures and relative humidity (RH) values of inlet and supply air are presented in Figure 6. It can be noticed that the supply air RH remains same as there is no water mixing in the dry channels. On the other hand, the RH of wet channel air was increased to 90% due to excellent wettability of hydrophilic membranes. The water supplied was optimized after many tests and it was found that 2-3% additional water supply is important to make sure 100% wettability of hydrophilic membranes all the time. This additional water supply will also help to accommodate temperatures and air flow fluctuations. The vertical arrangement of heat exchanger have two major effects in water management. Firstly, it help to spread water by gravity on top hydrophilic action of membranes. Secondly, any additional water supply will flow to the bottom of the cell by gravity and it can be easily collected without partial blockage or sagging chances that can be happened in case of horizontal arrangements. The similar conclusion was also found in latest literature [44]. They tested horizontal and vertical arrangements of IEC for five different cities of China and found that vertical arrangement is almost two times more efficient as compared to horizontal systems.

Figure 6. Wet bulb temperature and RH profiles at 40°C outdoor air temperature.

Figure 7. Summary of supply air temperatures at different operating conditions.

After successful testing at 40°C outdoor air temperature, the generic cell was tested at assorted inlet conditions to investigate the performance at different weather conditions. Also, cell performance was investigated at different injection points. The summary of results is presented in Figure 7. It can be seen that around 2°C temperature improvement can be achieved with both sides of wet channel operation. Although it may be insignificant but it shows that cell can be designed with shorter length for same capacity. This parameter is important for large capacity design for residential and commercial applications. The significant improvement was observed by efficient utilization of purged air at multi point injections. It can be noticed that 3-4°C temperature improvement can be achieved by three point's injection of same amount of air flow as compared to conventional single point injection. It shows that the commercial units can be designed even compact size by multi point injection for same capacity.

The cooling capacity of tested generic cell is calculated based on temperature difference of inlet and supply air at designed air flow rate. The summary of cooling capacity of improved cell at different operating conditions is presented in Table 5. It can be noticed that the cooling capacity varies from 73.8 watt to 197 watt when outdoor temperature changes from 32°C to 40°C during one wet channel in operation. These capacities figure changes to 135 watt and 246 watt respectively when both side of wet channels are operated. This set of data can be used as a reference for design of commercial scale units.

Table 5. Cooling capacity of generic cell at assorted operating conditions.

Cooling Capacity (watt)			
Inlet air temperature	One side of wet channel in operation		
	1 injection	2 injections	3 injections
40	115.7	155.1	197.0
37	98.5	142.8	172.3
32	37.0	49.2	73.8
	Both sides of wet channel in operation		
	1 injection	2 injection	3 injection
40	160.0	197.0	246.2
37	147.7	184.7	202.0
32	73.9	103.4	135.4

The static pressure across fan was calculated to investigate the coefficient of performance (COP) of generic cell. The fan head was calculated 260 pascal to deliver the required air flow rate. Based on measured fan power (3.17 watt), the COP was calculated for all conditions and presented in Figure 8. It can be noticed that with one side of wet channel and 3 points injection, COP varies for 23 to 62 at outdoor air temperature 32°C to 40°C respectively. These values can be as high as 42 and 78 with both side of wet channel in operation. The COP presented is just an IEC cell performance but in reality it will be an overall COP of dehumidifier (DH) and indirect

evaporative cooler. It means that if DH has also good COP (around 4-5) then overall COP can achieve the sustainability goal of 0.6 ± 0.03 kW/Rton.

Figure 8: Coefficient of performance of improved IEC generic cell at assorted operating conditions.

Conclusion

An improved indirect evaporative cooler is proposed with three major modifications in conventional systems to overcome their limitations. A generic cell was designed and tested at assorted weather conditions to investigate the performance. The generic cell test showed the following outcomes:

1. The vertical heat exchanger configuration is the best for water spreading and collection. In addition, it also help to overcome the issues of membranes sagging in horizontal heat exchangers designs.
2. The multi injection of working air into wet channels improve its utilization factor as compared to single injection in conventional systems. It can be observed that 3-4°C can be improved by injecting the same amount of working air at different points into the wet channels.
3. The use of aluminum foil instead of conventional poor heat transfer hydrophilic membranes enhance the heat transfer. In addition, it also prevent any biological organism growth that may occur on conventional membranes.
4. The proposed improved design summary chart can be used as a reference for commercial system design.

5. The COP of just IEC system varies from 37 to 78 depending on operating conditions.
6. The improved IEC with best DH system can achieve sustainable cooling goals.

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Abbreviations

RAC	Room air conditioner
AC	Air conditioning
IEC	Indirect evaporative cooler
COP	Coefficient of performance
GCC	Gulf cooperation council
EJ	Exajoule
KSA	Kingdom of Saudi Arabia
TWh	Terawatt hour
KWh	Kilowatt hour
AHU	Air handling unit
DH	Dehumidification
OA	Outdoor air
RH	Relative humidity

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