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Approaches to Energy Efficiency in Air conditioning: Innovative processes and thermodynamics

Kim Choon Ng[a]*, Muhammad Wakil Shahzad[a], Muhammad Burhan[a], Seung Jin Oh[a]

[a] *Water Desalination and Reuse Center (WDRC), Biological and Environmental Science & Engineering (BESE), King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia*

Abstract

Air conditioning in buildings has transformed our human lives greatly with work efficiency in commercial buildings and improved lifestyle in all weather. However, these improvements are accompanied with the negative effects from the emissions of greenhouse gases (GHG), both directly via refrigerant emissions and indirectly through electricity generation by the burning of fossil fuels. Although there were significant improvements in the efficacy of chillers since 2000, the kW/Ron of chillers for cooling for electrically driven DCS have reached an asymptotic level of 0.85±0.03 kW/Rton for the tropics and a 20% higher for the hot and dry arid climate. The levelling-off phenomenon of chillers' energy efficiency is attributed the improvements limits exploited from the efficacy of compressor and refrigerant technologies. Thus, an out-of-box solution, such as the decoupling of latent to sensible cooling in the dehumidification cum the indirect evaporative coolers (DH-IEC) to improve energy efficiency, It is projected that a quantum jump of 0.5 kWh/m3 or less is urgently needed for future sustainable cooling. In this paper, we adopted a top-down approach in evaluating the upper-bound energy savings of an economy if one were to employ the innovative DH-IEC cycle is assumed to be applied to the Singapore city state is highlighted with respect to the savings in the primary energy, emission of CO2 and the water savings of up to 40 % can be potentially achieved.

Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.

Keywords: IEC, Air Conditioning, Chiller, Cooling, Efficiency

* Corresponding author.
E-mail address: kimchoon.ng@kaust.edu.sa

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1. Introduction

The global space cooling industry has been estimated to be about US$130 billion with nearly 100 million units of chillers/coolers being manufactured and sold annually. Air conditioning in buildings has transformed our human lives greatly with work efficiency in commercial buildings and improved lifestyle in all weather. However, these improvements are accompanied with the negative effects from the emissions of greenhouse gases (GHG) [1-4], directly via refrigerant emissions and indirectly through electricity generation by the burning of fossil fuels.

Over the past 3 three decades, a hot and dry climate country, Saudi Arabia (except coastal cities along Red Sea and Gulf) and the other is a tropic Singapore island state with a high urban population density (> 7400 people per km^2) [5], both countries have similar electricity annual growth rates of 5%. However, the KSA has recorded more than 50% of the annual electricity production (272TWh, 2014) is consumed for HVAC, amounting to 139 TWh per annum whilst the latter, the demand for electricity for air conditioning annually is 17 TWh, about 36% of the total electricity consumption (47TWh, 2015). Should these energy demand trends in cooling is not abated, the future energy and environmental sustainability in both developing countries may be untenable [6].

Although there were significant improvements in the efficacy of chillers since 2000, the kW/Ron of chillers, for electrically driven DCS, have reached an asymptotic level of 0.85±0.03 kW/Rton for the tropics and a 20% higher consumption for the hot and dry arid climate of the Kingdom of Saudi Arabia. The levelling-off phenomenon of chillers' energy efficiency is attributed the improvements limits exploited from the efficacy of compressor and refrigerant technologies. In a recent report from the Building Technologies Office (BTO, EERE) of DoE, there is an imperative need for engineers, scientists and industry professionals to innovative cooling technologies that substantially improve the efficacy of chillers, reducing both the energy consumption and greenhouse gas (GHG) emissions [7-9] in all buildings. For a quantum jump in efficacy for cooling, an out-of-box solution, such as the decoupling of latent to sensible cooling [10,11] in the dehumidification cum the indirect evaporative coolers (DH-IEC) to improve energy efficiency, and it is projected that a quantum jump of 0.5 kW/Rton or less is urgently needed. In this paper, we employ a top-down analysis by a DH-IEC cycle as well as the appropriate figure of merits embedded in these innovative cooling cycles. It is assumed that the analysis is based on the successful adoption of DH-IEC cycles being applied to the Singapore's and the KSA's cooling needs. The study highlights the savings in the primary energy, emission of CO_2 [12] and the water savings [13] of up to 40% can be potentially achieved in the tropical region. In addition, the author focuses on the electrical energy consumption for air conditioning in two economies; the discussion emphasizes on the shares of district cooling systems (DCS) to overall cooling is presently 30±5% and how DCS could be exploited for future sustainability in cooling.

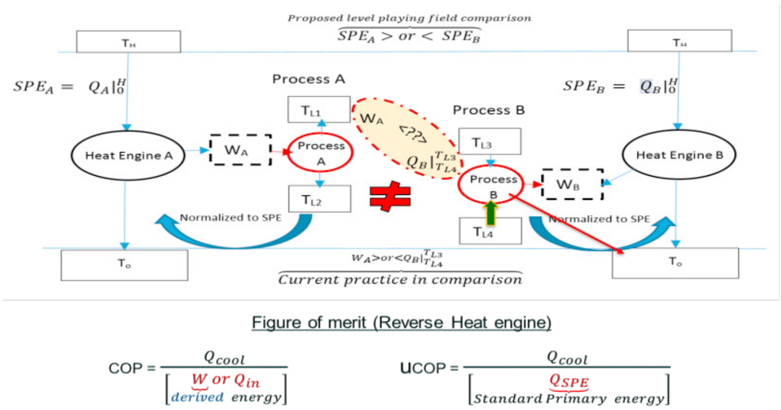


Fig. 1. Concept of a Level Platform for a Fair Efficacy Comparison of assorted types of Chiller.

2. The Chillers' Efficiency viewed from Thermodynamics

Laws of Thermodynamics permit one to be inefficient or non-innovative. It does not restrict one to be wasteful. Converting primary energy (fossil fuels) into derived or secondary energy (electricity, steam, thermal, etc.), is performed today for convenience. However, to compare energy efficiency of cooling devices that uses assorted forms of derived energy, it requires one to be concerned with both quantity and quality of the supplied energy. If derived energies are not thermodynamically equal, then there must be a common datum to compare the performances of the chiller systems, e.g., the primary energy which analyzes the available work of exergy destruction across the process [14] Therefore, a universal performance ratio (UCOP) is proposed for the cooling devices based upon primary energy, to conduct a fair energy efficiency comparison. The use of best available conversion technology Otherwise, it is futile exercise to base on methods of lower efficiency. Fig. 1 presents the comparison of conventional COP (conventional) and the proposed universal COP (UCOP). However, to compare the performances of electricity and thermal operated chillers, a detailed calculation of UCOP is given in table 1.

Table 1. Universal Coefficient of Performance (UCOP): A level platform for efficacy comparison.

Types of chiller	Mechanically driven chillers using electricity	Thermally driven chillers using thermal energy
COP_conv	COP_conv=Qcool /W_elec = 4.5	COP_conv = Qcool/Qin_thermal = 1.35
2nd law & equivalent work	A reversed engine using standard primary energy (T_{ADIA}=2100K) $\frac{\eta_{II,SPE}}{\eta_{II,chiller}} = \frac{W_{AC}{}^2}{Q_{SPE}\left(1-\frac{T_0}{T_{ADIA}}\right)} \frac{1}{Q_{Ai}\left(\frac{T_o}{T_{L1}}-1\right)}$ T_{ADIA}=2100K, T_{L1}=278K, T_o=300K	A heat engine $\frac{\eta_{II,SPE}}{\eta_{II,chiller}} = \frac{Q_{chiller}\left(1-\frac{T_0}{T_{H2}}\right)}{Q_{SPE}\left(1-\frac{T_0}{T_{ADIA}}\right)}$ T_{H2}= 423K.
Cooling capacity	1 kWh at T_{L1} (278 K)	1 kWh at TL2 = T_{L1}= 278K
Derived Energy	1/COP_conv = 0.2222 kWh_elec per kWh cooling (derived energy basis).	1/COP_conv =0.7407 kWh_thermal per kWh cooling (derived energy).
Standard Primary energy (kWh)	0.4728 kWh_spe	0.1645 kWh_spe
UCOP (Using SPE)	UCOP = Qcool / Q-_SPE = 1/ 0.4728 = 2.11	UCOP = Qcool/Q_SPE =1/0.1645 = 6.07

The conventional chillers based upon district cooling concept, require huge investment and face many operational problems, due to complex systems such as piping work, pumping cost, heat leak to ambient. On the other hand, the environmental impact is increasing day by day due to increased cooling demand, which require more fossil fuel burning, due to high electricity demand of such energy extensive system. On the other hand, a large amount of water is also required to be used in cooling towers of conventional cooling units. Therefore, there is a need of innovative technology with low energy requirement and capital cost. Indirect evaporative cooling based an innovative system is proposed in next section which will lower the energy and capital cost requirement for same cooling capacity, with avoided infrastructure and components.

3. Indirect Evaporative Cooling (IEC) with Dehumidifier (DH-IEC)

Fig. 2 shows a novel indirect evaporative cooling and dehumidification based all-weather cooling system which works on the concept of decoupling of moisture (latent) removal from sensible cooling. In case of sensible cooling, the water is evaporated by air flowing over moist surfaces, employing thin (high orthogonal heat transfer) & impervious membranes to demarcate wet and dry channels, causing decrease in its dry-bulb air temperature. The air flowing in the dry channel, exchanges heat with the cooled felt interface causing decrease in its temperature while keeping humidity level constant (due to the dry channel flow) [15-18]. As the performance of the system is depending upon the evaporating potential of the purged but dry air which is flowing over the moist felt, therefore, for better performance of the system, the air must have lower humidity content. The tropical regions like Singapore and coastal cities of KSA, the outdoor air is almost reaching its saturating limit in certain time of the day. In this scenario, the proposed system cannot perform well and therefore, desiccant based humidification system, utilizing novel microwave based regeneration with 1/3 desorption energy, is introduced before the IEC to remove the moisture content of the supply air, as shown in Fig. 3. Such system can perform in all-weather condition with lowest energy consumption as IEC only requires power to operate its circulating fan and dehumidifier utilized low energy microwave unit for regeneration of desiccant, as compared to the conventional chillers based combined cooling system. The decoupling of moisture removal lowers the energy requirement of the overall cooling system as major portion of energy of conventional chiller is consumed in removing moisture from the supplied air, which can go very high for tropical weathers.

The energy saving for such proposed system is investigated in the next section, for the case study of Singapore, if conventional chiller based cooling systems are replace with proposed DH-IEC system.

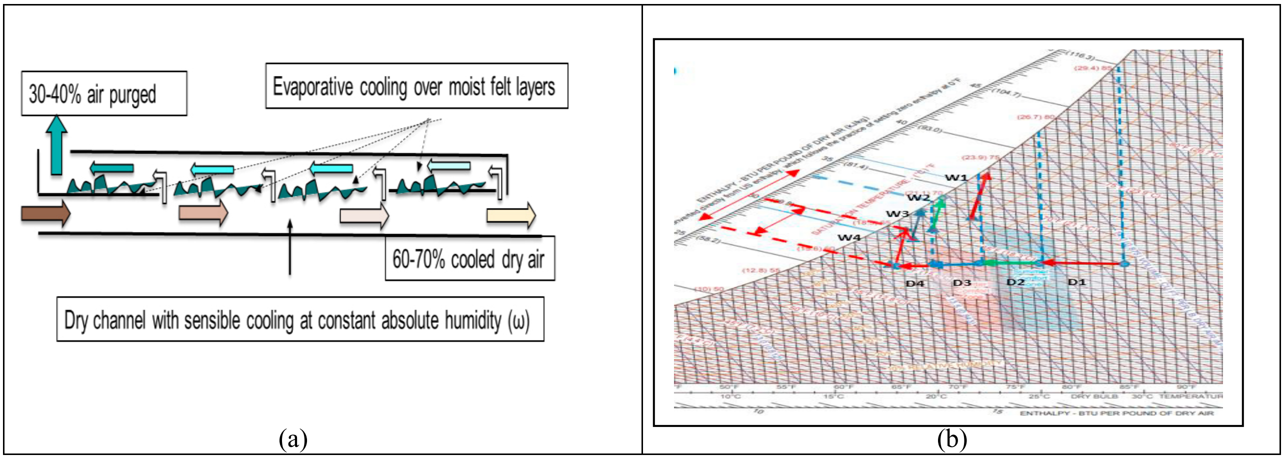


Fig. 2(a). Design of Indirect Evaporative Cooling (IEC) and Fig.2(b) depicts the psychrometric states of air flows in the dry (D) and wet (W) channels. The ratio of the enthalpy arrows gives the effectiveness of each counter flow segment.

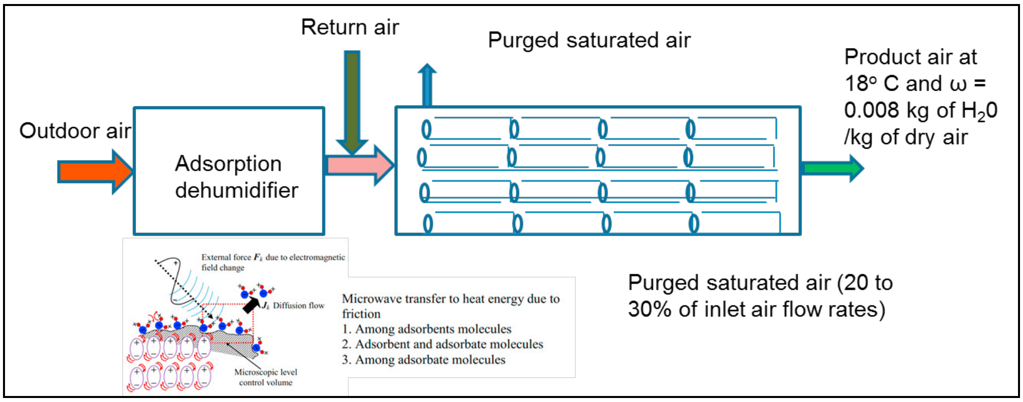


Fig. 3. Innovative Low Energy DH-IEC Technology

4. Results and Discussion

Fig. 4 shows the variation of COP of proposed DH-IEC based cooling system to the COP of dehumidified (DH) system alone. It can be seen that the performance of the DH-IEC based cooling system is entirely based upon the COP of dehumidification system. Higher the COP of DH system, higher is the COP of DH-IEC system. For proposed microwave based dehumidification system, an overall COP of 16 can be achieved for DH-IEC system, which is more than the twice of mechanical chiller-based cooling systems. Such performance improvement in COP is due to decoupling of latent and sensible heat as microwave based DH system requires three time less energy for desorption than other conventional thermal dehumidification systems.

In order to compare the overall energy saving by replacing the conventional chiller-based cooling system with the proposed DH-IEC based cooling system, a simple case study of Singapore is presented in Fig. 5 and a similar study of Saudi Arabia is presented in Fig. 6. Given the annual (2015) cooling loads of both economies and their relative percentage proportions in conventional and district cooling, the cooling energy analyses are performed by a top-down approach using the average COP improvement of a successful DH-IEC over the mechanical chillers. For such an approach, one needs the annual cooling load as well as the relative distributions of the technology types employed, i.e., the percentages of mechanical vapor compressors, the heat-driven chillers and the tonnage of district cooling plants. The scenario-I is based upon business as usual (BAU) case in the total cooling load requirements are fulfilled with conventional chiller based cooling system. However, in scenario-II, the proposed DH-IEC system is introduced to replace the convention system, either alone as MVC or in form of district cooling (DC). The results are presented for different cases with different proportion mix of DH-IEC system and conventional chiller systems. On the other hand, two different COPs of DH-IEC system is investigated to see overall effect on the energy savings against the COP of DH-IEC system. It can be seen that 80-85% overall energy, fuel cost and emissions can be saved by replacing the conventional chillers with proposed DH-IEC based system. In addition, about 50% water can also be save with proposed cooling configuration.

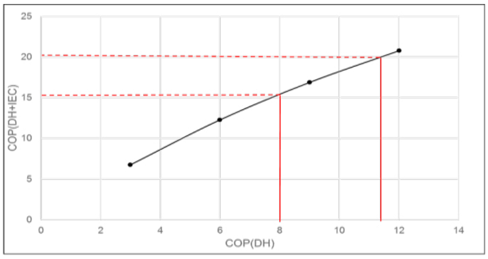
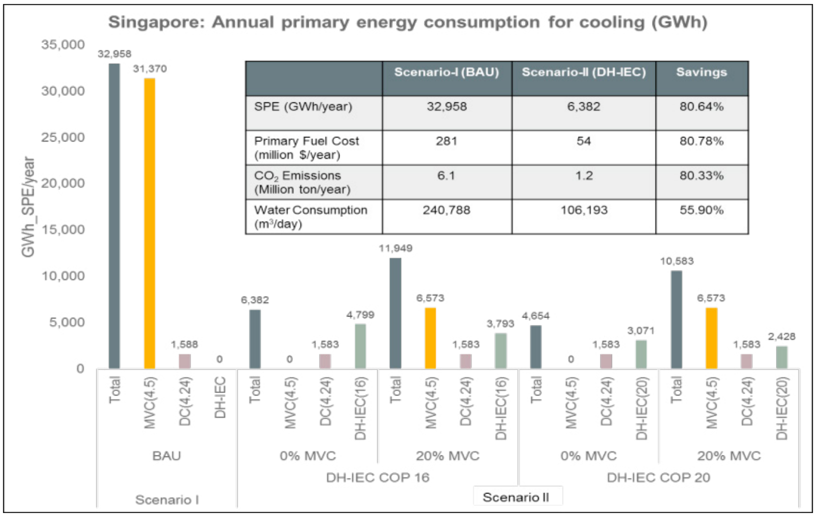


Fig. 4. Overall COP (DH+IEC) Versus DH COP



	Scenario-I (BAU)	Scenario-II (DH-IEC)	Savings
SPE (GWh/year)	32,958	6,382	80.64%
Primary Fuel Cost (million $/year)	281	54	80.78%
CO_2 Emissions (Million ton/year)	6.1	1.2	80.33%
Water Consumption (m^3/day)	240,788	106,193	55.90%

Fig. 5. Energy scenario between BAU and DH-IEC for Singapore

5. Conclusion

An all-weather low energy cooling system is proposed based upon the DH-IEC based design in which the latent and sensible cooling loads are decoupled. An overall COP of 16 to 20 can be achieved with proposed DH-IEC based cooling system. Such low energy consumption is due innovative microwave based dehumidification system which requires 3 times less energy than conventional systems due to the efficient method of water vapor molecules being dislodged from the surface sorption forces by micro-wave energy. The present case study of Singapore shows that an overall improvement of 4-6 times in energy consumption can be made if such proposed system is replaced by the conventional MVC chiller based systems. Also, the avoided equipment of conventional chillers, such as mechanical chillers, cooling towers, chilled and cooling water distribution pipes, plant room, refrigerants, etc., implies significant savings in the capex. For a sustainable future, such proposed system can fulfill all the cooling needs of the growing global population of these countries.

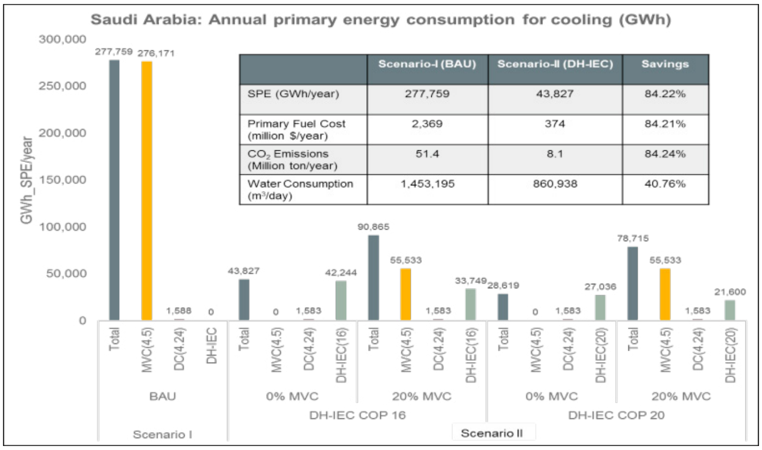


Fig. 6. Energy scenario between BAU and DH-IEC for Saudi Arabia

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