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Evaporative Cooling Technologies: Conceptual Review Study

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Abstract: The technical advantages of using evaporative cooling have drawn the attention of many researchers and industrialist in the world. Moreover, evaporative cooling techniques have been found to be most promising alternative to the HVAC methods in various building applications such as residential, commercial, agricultural, institutional and industrial buildings. An extensive literature review on latest developments of evaporative cooling that might deliver efficient cooling relief, reduce carbon emission and energy utilization in the buildings was carried out in the present paper. Also, the paper contains study of working principle of evaporative cooling, various types such as direct evaporative cooling (DEC), indirect evaporative cooling (IEC) and combined (IDEC) evaporative cooling system. Evaporative cooling makes the air cooler by increasing its humidity level. Thereby, it can be observed from the paper that the evaporative cooling provides a promising way to reduce the energy consumption in hot and arid climate conditions. Also, it seems to be an economical and environment friendly cooling compared to conventional HVAC methods which will ensure a substantial saving of fossil fuel (coal, petroleum and natural gas) utilization and reduction of carbon emission allied to the buildings.

Keywords: Evaporative cooling; Building applications; HVAC; Cost effective

1. Introduction

The ever-rising energy demand for skyscrapers cooling across the world has led many researchers and industrialists to look out for alternate energy efficient cooling techniques. The rise in energy demand leads to the deterioration of energy assets and further increment to the global warming throughout the world. In order to provide conditioned air and thermal comfort to the people, the space air conditioning systems play a vital role. However, the highest share of the total energy is being consumed by traditional HVAC systems for space/building air conditioning[1]. Almost all the HVAC systems mainly work upon vapour compression cycles along with their massive power consumption quality[2][3]. Although the impact of conventional and new generation refrigerants on the environment was reviewed by[4]. These traditional HVAC systems perform poorly generally in hot climate countries and with huge electricity bills[5][6]. Therefore, evaporative cooling systems are most environment friendly due to their less energy consumption and high-performance quality[7–12]. Evaporative cooling performance increases when air temperature rises and the humidity reduces. A suitable validation for the coefficient of performance of various cooling systems is shown by [13]. The total primary energy supplied by several fuels such as natural gas, oil, coal/peat, and biofuels and nuclear is shown in Fig. 1(a). While according to the Energy Agency, the total energy consumed and CO2 emissions by those fuels in 2012 are compiled in Fig. 2. According to the experts, the total final energy utilization will increase massively by 2035 as shown in Fig. 1(b). Therefore, it is necessary to emphasis on energy proficient techniques and results not only in newly constructed buildings, also in the existing buildings. Hence, this paper aims to provide an extensive literature review on recent developments of evaporative cooling systems in building applications which further helps to improve the performance of evaporative cooling.

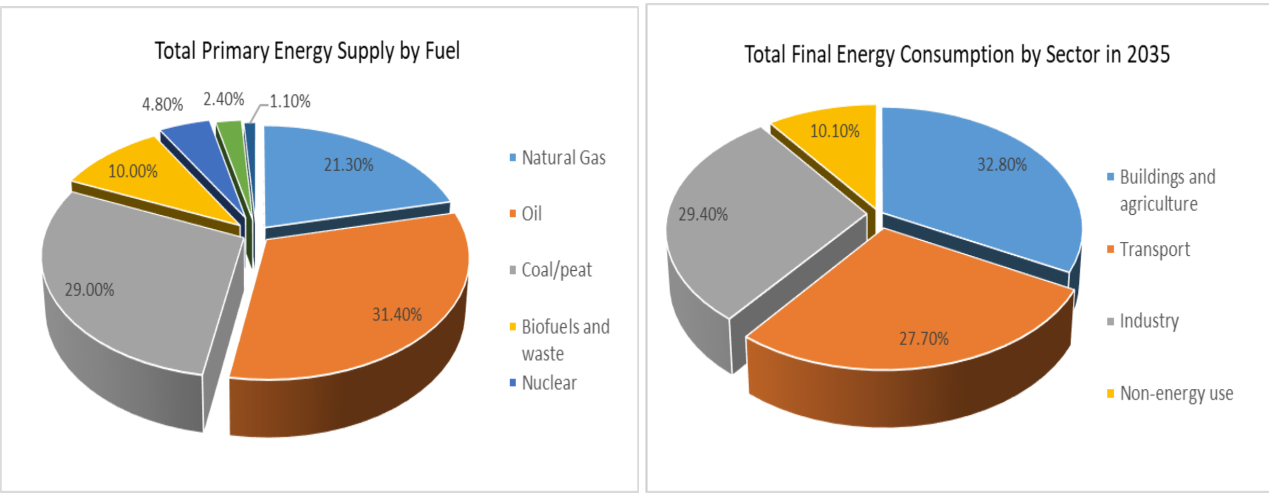


Fig. 1: Total primary energy supply by several fuel in 2012 [14)]

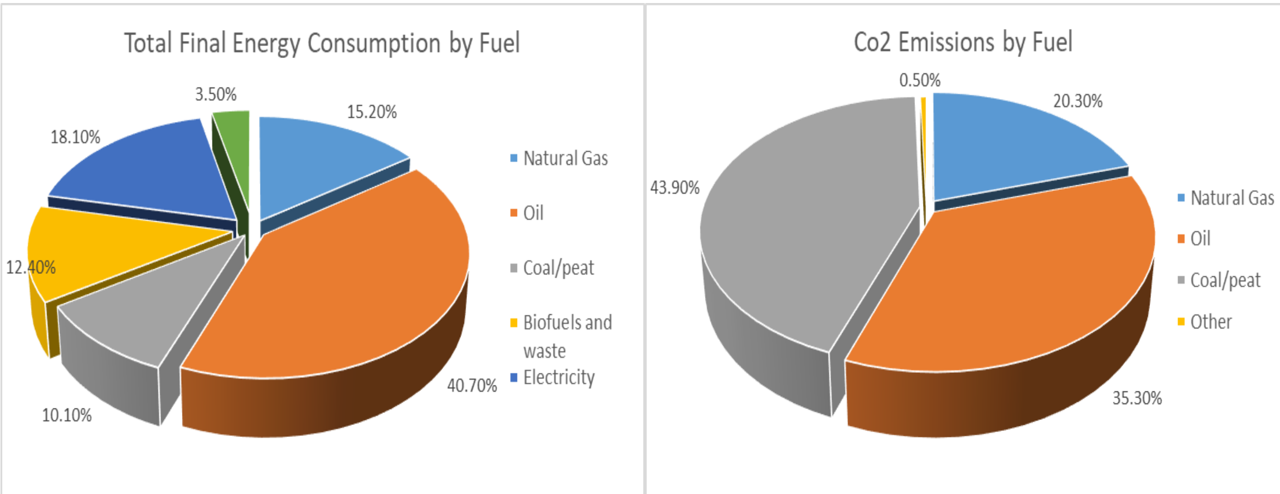


Fig. 2: Total final energy consumption (a) by fuel (b) CO2 emissions by fuel [14)]

1.1 Working Principle

Evaporative cooling is a technique of heat and mass transfer based on the principle of water evaporation in which heat is transported from air to water which further leads to reduce the air temperature[15–17)]. The removal of latent heat of evaporation takes place either from water, air or both of them. Owing to the transfer of water vapour, the latent heat of air increases and thus the air gets cooled and humidified[18)]. Therefore, thermal comfort can be provided using cooled and humidified air. The main driving force of the evaporative cooling is the difference between dry bulb temperature and wet bulb temperature of ambient air. Thus greater the difference between these two temperatures, greater will be the evaporative cooling effect[19)]. Further evaporative cooling can be categorized in three main parts such as (i) Direct evaporative cooling (ii) Indirect evaporative cooling (iii) Combined evaporative cooling (DEC/IEC)[3)20)21)]. A typical classification of evaporative cooling for building applications is illustrated in Fig. 3. Evaporative cooling is one of the old-style air conditioning methods that provides efficient cooling comfort, reduce carbon emission and energy consumption in the hot climates with low humidity. Moreover, evaporative cooling have been widely used in cooling towers to dissipate the industrial heat for better thermal effectiveness. This study on thermal effectiveness in cooling towers was carried out by [8)].

1.2 Direct evaporative cooling (DEC)

Direct evaporative cooling is one of the oldest and simplest cooling techniques. The ambient air brought directly in contact with water for cooling by conversion of sensible heat into latent heat. DEC involves the water (with spray or wetted media) into the air mainstream to absorb the heat from air. The dry bulb temperature is lowered whereas wet bulb temperature remains constant in DEC[22,23)]. The main advantage of DEC as compared of other cooling techniques is less energy intensive and saves up to 90% of the energy [24)25)26)]. Direct evaporative cooling systems can be further classified as: Active DECs which are electricity operated and Passive DECs which are naturally operated without any consumption of power[27)28)]. The overall efficiency of active DEC depends upon the pad media used into it. Various types of cooling/wet media are shown in Fig. 4 and their features and effectiveness are compiled in Table 1 from ASHRAE handbook[29)]. These media have a significant effect on the efficiency of the active DECs[19)30)]. In addition, the water distribution system in active DEC can be categorized into various parts such as spray (air wash), slinger (spinning wheel) and dripping (mist) [31)].

On the other hand passive cooling are naturally driven building cooling techniques without electricity and mechanical power[32)33)]. This technique is quite effective to decrease the space temperature up to 9^{0}C. The common types of passive DEC systems are The Mashrabiya, Wind Towers and Roof-pound[34)35)].

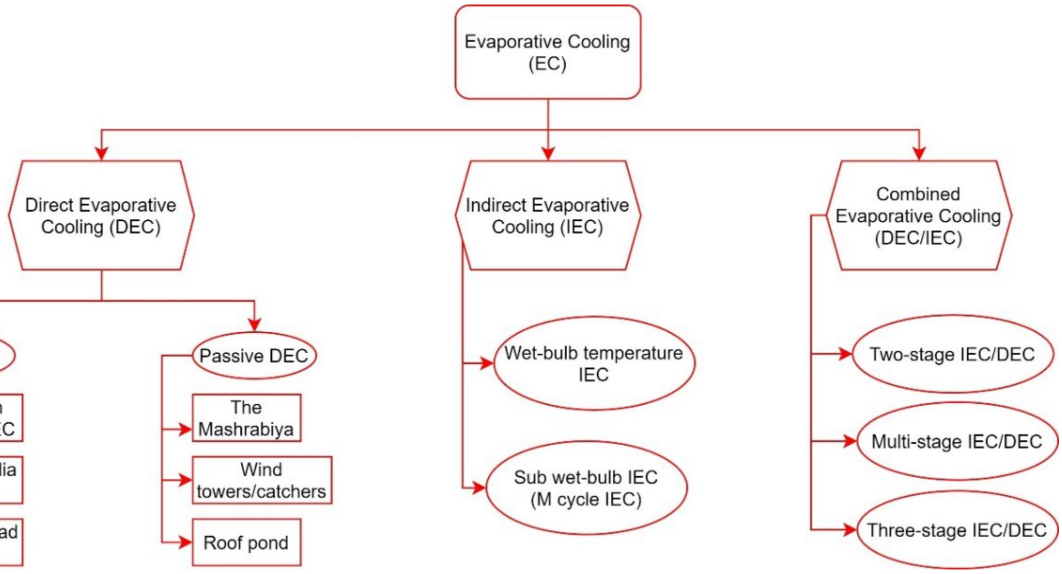
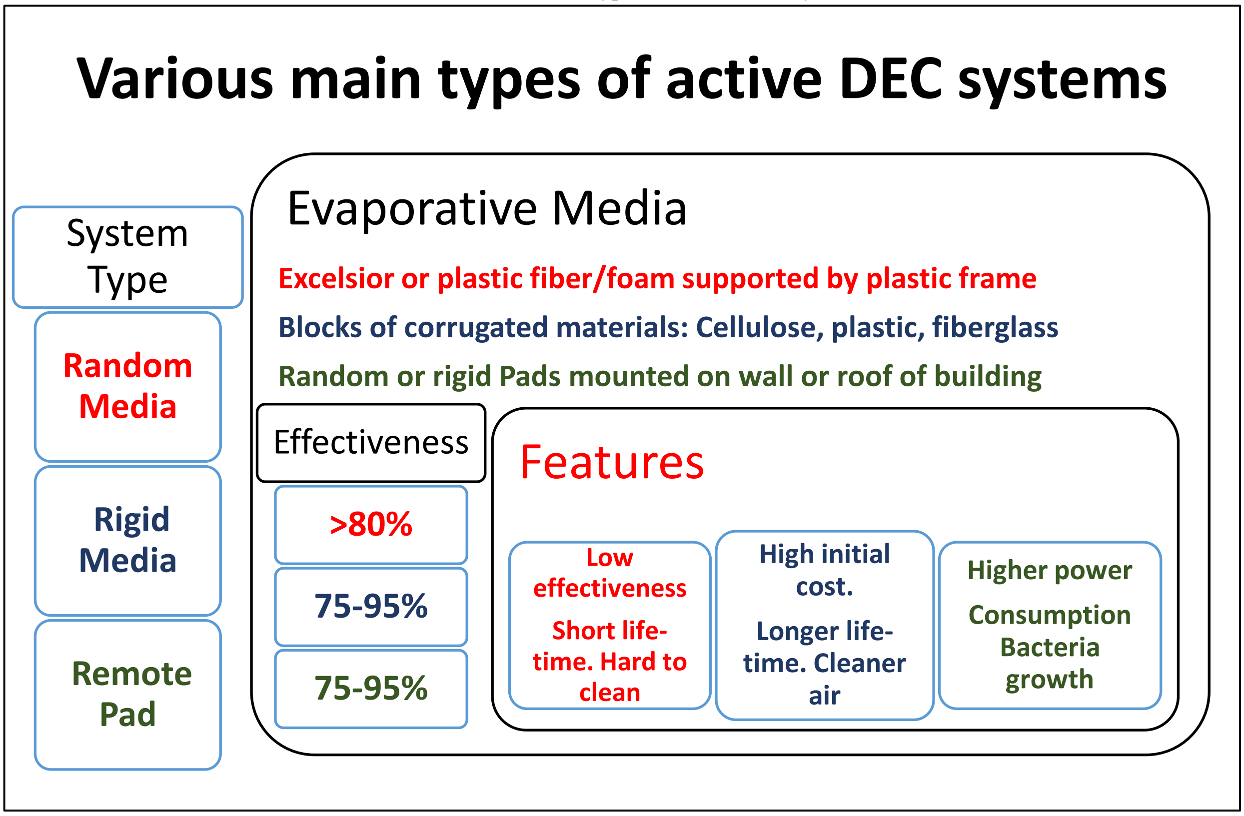


Fig. 3: A typical classification of evaporative cooling system [36)]

Table 1. Various main types of active DEC systems



Various main types of active DEC systems

System Type	Evaporative Media	Effectiveness	Features
Random Media	Excelsior or plastic fiber/foam supported by plastic frame	>80%	Low effectiveness Short life-time. Hard to clean
Rigid Media	Blocks of corrugated materials: Cellulose, plastic, fiberglass	75-95%	High initial cost. Longer life-time. Cleaner air
Remote Pad	Random or rigid Pads mounted on wall or roof of building	75-95%	Higher power Consumption Bacteria growth

Fig. 4: Types of various pads used in DEC [29)37)]

1.3 Indirect evaporative cooling (IEC)

Indirect evaporative cooling is one of the promising techniques to reduce air temperature without altering its humidity. This cooling technique introduces a unit of heat exchanger (Plate type), fan, pump and water tank with water circulation lines. Unlike the DEC this technique works on heat and mass transfer between two airstreams separated by heat exchanger.

The warm ambient air is cooled in dry channel via heat exchange to wet channel through heat exchanger[38–42)]. The cooled ambient air certainly not comes directly in contact with water or environment and directly sent to the required space[43–45)]. The temperatures such as (dry bulb and wet bulb) are decreased in an indirect evaporative cooling system. The key feature of IEC is that reduction in the temperature of ambient air without adding any moisture content into it[46)]. The main disadvantage of an indirect evaporative cooling is the high operating cost and lower efficiency than DEC. Moreover, the cooling of main air stream in IEC is dependent on the wet bulb temperature of secondary air stream[47)48)].

1.4 Combined/Indirect-Direct evaporative cooling (IDEC)

Combined evaporative cooling is the combination of Indirect and Direct cooling techniques in order to attain the best features such as higher cooling and lower relative humidity of both the systems. This cooling method comprises of total two stages[50–52)]. In first stage the warm ambient air is passed through one side of heat exchanger which is cooled by evaporation at the other side of air stream and water spray. In second stage, pre-cooled air circulates via a wetted media (pad) and add humidity when it cools more[51)]. Thus this cooling method provides cooler air than either direct or indirect cooling methods individually. In many of the cases this combined evaporative cooling perform better than mechanically compressor based systems due to their more favorable humidity range[53)]. The key components of combined system are plate type heat exchanger, unit of IEC, wet/evaporative media of DEC, fan, and water tank with recirculation system. However, the higher initial cost of the system and design complexity are the main weaknesses of the system.

2. Literature Review

This section involves a comprehensive review of recent developments and innovations on various types of evaporative cooling in numerous applications. The researchers have pertained various approaches such as performance of evaporative coolers, material of cooling pads and heat and mass transfer study to make the evaporative cooling more efficient. The outcomes of the different approaches for all reviewed articles in this paper are compiled in the Table 2.

Table 2. Recent reviewed developments of Evaporative systems

Authors	Method	System Type	Key findings
Chen et al.[55)] (2010)	Theory	Evaporative cooling	In extension to the entransy theory, few new concepts such as moisture entransy, moisture entransy dissipation and thermal resistance have been introduced and studied theoretically to confront the process of conjugate heat and mass transfer so as to optimize the performance of evaporative cooling systems.
Andresen et al.[56)] (2010)	Experiment	Evaporative cooling of	Studied and introduced a concept of evaporative cooling of antiprotons at cryogenic temperature using liquid helium as coolant.

		antiprotons	
Miyazaki et al.[57] (2011)	Simulation	Passive solar based evaporative cooling	Studied air flow induced by solar chimney and cooling performance of dew-point evaporative cooler implemented in the ceiling of a room using mathematical model.
Jain et al.[58] (2011)	Experiment	Evaporative cooling	Experimentally tested the two different cooling pads (coconut and palash fibers) and found better performance and lower pressure drop to be used in EC.
Sultan et al.[59] (2014)	Experiment	Greenhouse dehumidification using Carbon based adsorbent	Experimentally examined the water vapors into silica gel and carbon based adsorbents for the air-conditioning application of greenhouse. CBA was found to be most prominent greenhouse dehumidification.
Montazeri et al.[60] (2015)	Simulation	Evaporative cooling using mist spray system	Examined the influence of several physical parameters on the performance of evaporative cooling consisting mist spray system along with hollow-cone nozzle.
Heidarinejad et al.[61] (2015)	Theory	Indirect evaporative cooling	Introduced and presented a novel model of an IEC with wall longitudinal heat conduction in a cross-flow regenerative evaporative cooler along with the variation of spray water temperature.
Xu et al.[62] (2015)	Experiment	Evaporative cooling pads	Studied about the performance of EC cellulose paper pads for a 2304m^2 glass multi-span greenhouse in Shanghai, China.
Tominaga et al.[17] (2015)	Simulation and experiment	Evaporative cooling	Predicted the evaporative cooling effect and the thermal environment from water surfaces of residential buildings and land neighborhood with a pond or small river (micro-scale urban environment) using CFD.
Porumb et al.[63] (2016)	Theory	Indirect evaporative cooling	Studied the capability of indirect evaporative cooling to mitigate the energy consumption of an office building in climate conditions of Cluj-Napoca, Romania and validated with the conventional air conditioning system.
Mahmood et al.[8] (2016)	Experiment	Desiccant Air-Conditioning	Desiccant Air-Conditioning system was investigated to analyze three different humid environmental level for fruits and vegetables storage in Pakistan.
Antonellis et al.[64] (2016)	Experiment	Cross glow EC	The influence of varying mass flow rate of water, humidification nozzle and air temperature have been investigated using cross flow heat exchanger in an IEC.
Xu et al.[65] (2016)	Experiment	Fabrics of Indirect evaporative cooling	Several textile fabrics {coolpass (bird eye mesh fabric, knitted pique mesh), Bamboo charcoal, Topcool, 320D Supplex, and 228T Supplex} were tested experimentally and found the superior properties as compared with Kraft paper.
Aljubury et al.[66] (2017)	Experiment	Two-stage evaporative cooling	Feasibility of greenhouse cooling using geothermal energy in IDEC (two stage evaporative cooling) was carried out during summer season of Baghdad with four different types of shading.
Sultan et al.[67] (2017)	Simulation	Desiccant Air-Conditioning system	Evaluated the performance of two different types of cross-linked hydrophilic organic polymer sorbents for cooling applications using MATLAB numerical simulations.
Eidan et al.[68] (2017)	Experiment	Direct evaporative cooling	Four several parameters such as coefficient of performance, energy saving, cooling capacity and compressor auto shut down were studied experimentally to improve the performance of an air conditioning system using DEC in hot climates.
Chen et al.[69] (2017)	Experiment	Polymer hollow fiber integrated EC	The influence of several parameters such as air velocities, heat & mass transfer coefficients and pressure drop through the polymer hollow fiber integrated EC system were examined.
Haidar et al.[70] (2018)	Experiment	Passive evaporative cooling	Studied about the cooling of solar photovoltaic (PV) panel using evaporative cooling technique.
Wang et al.[71] (2018)	Experiment	Passive evaporative cooling	Studied about the effect of evaporative cooling on the permeable pavements on outdoor thermal environment to reduce the overall heat.

Dhamneya et al.[25] (2018)	Theory	Direct evaporative cooling	The influence of various parameters such as inlet air temperature, humidity and mass flow rate of air were studied using six different cooling media configurations.
Zheng et al.[72] (2019)	Theory	Direct evaporative cooling	The influence of DEC on the performance of thermoelectric generator (TEG) by considering the temperature dependent material properties and effect of conduction, heat loss by radiation and Thomson phenomenon are studied.
Tewari et al.[21] (2019)	Experiment	Evaporative cooling	In order to study the indoor thermal comfort in composite climate of Jaipur, a multiyear field study under evaporative cooling system using Griffith's method at ten office buildings was performed.
Dogramaci et al.[73] (2020)	Experiment	Direct evaporative cooling	Five new porous natural and organic materials such as Eucalyptus fibers (EF), Ceramic pipes (CP), dry bulrush basket (DBB), and Yellow stone (YS), Cyprus marble (CM) were tested at various air velocities in a wind pipe tunnel to make evaporative cooling more feasible in hot and dry climate.
Kashyap et al.[74] (2020)	Simulation	Regenerative evaporative cooling	Regenerative evaporative cooler were examined using configuration specific boundary conditions and set of generalized governing equations and all the configurations were compared based on parameters such as cooling capacity, coefficient of performance and effectiveness[74-75].

3. Conclusion and Future Outlook

This paper stated a review on all types of evaporative cooling and the recent developments that could offer efficient cooling comfort, reduce carbon emission and energy consumption in hot climate was carried out. It is observed from the reviewed articles that the efficacy of evaporative cooling depends on the many factors such as velocity of inlet air, thickness of evaporative media and most importantly environmental conditions i.e. temperature and humidity level. Evaporative cooling is found to be one of the promising technologies to minimize the energy consumption in hot and dry climate conditions. Therefore, IEC and IDEC systems are recommended in such conditions but their system's design complexity and high initial cost are major drawbacks. Hence, more attention is required in the future to reduce the complexity, noise level and initial cost of IEC and IDEC and to enhance efficacy of the systems for humid climates.

References

1) L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy Build.*, **40** (*3*) 394–398 (2008). doi:10.1016/j.enbuild.2007.03.007.
2) S. Noor, H. Ashraf, M. Sultan, and Z.M. Khan, "Evaporative cooling options for building air-conditioning: a comprehensive study for climatic conditions of multan (pakistan)," *Energies*, **13** (*12*) (2020). doi:10.3390/en13123061.
3) Y. Yang, G. Cui, and C.Q. Lan, "Developments in evaporative cooling and enhanced evaporative cooling - a review," *Renew. Sustain. Energy Rev.*, **113** (*June 2016*) 109230 (2019). doi:10.1016/j.rser.2019.06.037.
4) A. Pal, K. Uddin, K. Thu, and B.B. Saha, "Environmental assessment and characteristics of next generation refrigerants," *Evergreen*, **5** (*2*) 58–66 (2018). doi:10.5109/1936218.
5) G.Q. Qiu, and S.B. Riffat, "Novel design and modelling of an evaporative cooling system for buildings," *Int. J. Energy Res.*, **30** (*12*) 985–999 (2006). doi:10.1002/er.1199.
6) P. Kowalski, and D. Kwiecień, "Evaluation of simple evaporative cooling systems in an industrial building in poland," *J. Build. Eng.*, **32** (*July*) (2020). doi:10.1016/j.jobe.2020.101555.
7) J. Chu, and X. Huang, "Research status and development trends of evaporative cooling air-conditioning technology in data centers," *Energy Built Environ.*, (*May*) (2021). doi:10.1016/j.enbenv.2021.08.004.
8) M.H. Mahmood, M. Sultan, T. Miyazaki, and S. Koyama, "Desiccant air-conditioning system for storage of fruits and vegetables: pakistan preview," *Evergreen*, **3** (*1*) 12–17 (2016). doi:10.5109/1657381.
9) S. Onmura, M. Matsumoto, and S. Hokoi, "Study on evaporative cooling effect of roof lawn gardens," *Energy Build.*, **33** (*7*) 653–666 (2001). doi:10.1016/S0378-7788(00)00134-1.
10) A.P. da Veiga, S. Güths, and A.K. da Silva, "Evaporative cooling in building roofs: local parametric and global analyses (part-2)," *Sol. Energy*, **207** (*February*) 1009–1020 (2020). doi:10.1016/j.solener.2020.05.091.
11) Z. Pan, Q. Meng, Q. Li, J. Xie, and J. Liu, "Evaporative cooling of porous tiles with seawater in a tropical climate with salty humid air," *Constr. Build. Mater.*, **204** 727–739 (2019). doi:10.1016/j.conbuildmat.2019.01.031.
12) A. Alharbi, A. Almaneea, and R. Boukhanouf, "Integrated hollow porous ceramic cuboids-finned heat pipes evaporative cooling system: numerical modelling and experimental validation," *Energy Build.*, **196** 61–70 (2019). doi:10.1016/j.enbuild.2019.05.012.
13) Z. Duan, C. Zhan, X. Zhang, M. Mustafa, and X.

Zhao, "Indirect evaporative cooling : past , present and future potentials," *Renew. Sustain. Energy Rev.*, **16** (*9*) 6823–6850 (2012). doi:10.1016/j.rser.2012.07.007.

14) "Key world energy statistics," International Energy Agency, 2020.
15) S. Anisimov, and D. Pandelidis, "Numerical study of the maisotsenko cycle heat and mass exchanger," *Int. J. Heat Mass Transf.*, **75** 75–96 (2014). doi:10.1016/j.ijheatmasstransfer.2014.03.050.
16) B. Riangvilaikul, and S. Kumar, "Numerical study of a novel dew point evaporative cooling system," *Energy Build.*, **42** (*11*) 2241–2250 (2010). doi:10.1016/j.enbuild.2010.07.020.
17) Y. Tominaga, Y. Sato, and S. Sadohara, "CFD simulations of the effect of evaporative cooling from water bodies in a micro-scale urban environment: validation and application studies," *Sustain. Cities Soc.*, **19** 259–270 (2015). doi:10.1016/j.scs.2015.03.011.
18) Q. Chen, N. Pan, and Z.Y. Guo, "A new approach to analysis and optimization of evaporative cooling system ii: applications," *Energy*, **36** (*5*) 2890–2898 (2011). doi:10.1016/j.energy.2011.02.031.
19) F. Al-Sulaiman, "Evaluation of the performance of local fibers in evaporative cooling," *Energy Convers. Manag.*, **43** (*16*) 2267–2273 (2002). doi:10.1016/S0196-8904(01)00121-2.
20) E.H. Mathews, M. Kleingeld, and L.J. Grobler, "Integrated simulation of buildings and evaporative cooling systems," *Build. Environ.*, **29** (*2*) 197–206 (1994). doi:10.1016/0360-1323(94)90070-1.
21) P. Tewari, S. Mathur, J. Mathur, S. Kumar, and V. Loftness, "Field study on indoor thermal comfort of office buildings using evaporative cooling in the composite climate of india," *Energy Build.*, **199** 145–163 (2019). doi:10.1016/j.enbuild.2019.06.049.
22) A. Laknizi, M. Mahdaoui, A. Ben Abdellah, K. Anoune, M. Bakhouya, and H. Ezbakhe, "Performance analysis and optimal parameters of a direct evaporative pad cooling system under the climate conditions of morocco," *Case Stud. Therm. Eng.*, **13** (*October 2018*) 100362 (2019). doi:10.1016/j.csite.2018.11.013.
23) W. Ketwong, T. Deethayat, and T. Kiatsiriroat, "Performance enhancement of air conditioner in hot climate by condenser cooling with cool air generated by direct evaporative cooling," *Case Stud. Therm. Eng.*, **26** (*May*) 101127 (2021). doi:10.1016/j.csite.2021.101127.
24) N. Lechner, "Heating, Cooling, Lighting: Sustainable Design Methods for Architects," 4th ed., Willey, New Jersey, U.S.A, 2014.
25) A.K. Dhamneya, S.P.S. Rajput, and A. Singh, "Thermodynamic performance analysis of direct evaporative cooling system for increased heat and mass transfer area," *Ain Shams Eng. J.*, **9** (*4*) 2951–2960 (2018). doi:10.1016/j.asej.2017.09.008.
26) K. Sellami, M. Feddaoui, N. Labsi, M. Najim, M. Oubella, and Y.K. Benkahla, "Direct evaporative cooling performance of ambient air using a ceramic wet porous layer," *Chem. Eng. Res. Des.*, **142** 225–236 (2019). doi:10.1016/j.cherd.2018.12.009.
27) A. Malli, H.R. Seyf, M. Layeghi, S. Sharifian, and H. Behravesh, "Investigating the performance of cellulosic evaporative cooling pads," *Energy Convers. Manag.*, **52** (*7*) 2598–2603 (2011). doi:10.1016/j.enconman.2010.12.015.
28) J. Lv, J. Yi, Y. Fu, and H. Liu, "Experimental and numerical study of a multi-unit evaporative cooling device in series," *Case Stud. Therm. Eng.*, **21** (*April*) 100727 (2020). doi:10.1016/j.csite.2020.100727.
29) A. Handbook, "HVAC systems and equipment," American Society of Heating, Refrigerating, and Air Conditioning Engineers, Etlanta, GA, 1996.
30) W. He, L. Xilian, S. Yuhui, Z. Min, and G. Zhaolin, "Research of evaporative cooling experiment in summer of residential buildings in xi'an," *Energy Procedia*, **152** 928–934 (2018). doi:10.1016/j.egypro.2018.09.095.
31) D. Kolokotsa, M. Santamouris, A. Synnefa, and T. Karlessi, "Passive solar architecture," Elsevier Ltd., 2012. doi:10.1016/B978-0-08-087872-0.00320-6.
32) D.K. Bhamare, M.K. Rathod, and J. Banerjee, "Passive cooling techniques for building and their applicability in different climatic zones—the state of art," *Energy Build.*, **198** 467–490 (2019). doi:10.1016/j.enbuild.2019.06.023.
33) V.K. Firfiris, A.G. Martzopoulou, and T.A. Kotsopoulos, "Passive cooling systems in livestock buildings towards energy saving: a critical review," *Energy Build.*, **202** 109368 (2019). doi:10.1016/j.enbuild.2019.109368.
34) F.A. Obando, A.P. Montoya, J.A. Osorio, F.A. Damasceno, and T. Norton, "Evaporative pad cooling model validation in a closed dairy cattle building," *Biosyst. Eng.*, **198** 147–162 (2020). doi:10.1016/j.biosystemseng.2020.08.005.
35) A.P. da Veiga, S. Güths, and A.K. da Silva, "Evaporative cooling in building roofs: theoretical modeling and experimental validation (part-1)," *Sol. Energy*, **207** (*February*) 1122–1131 (2020). doi:10.1016/j.solener.2020.06.081.
36) O. Amer, R. Boukhanouf, and H.G. Ibrahim, "A review of evaporative cooling technologies," *Int. J. Environ. Sci. Dev.*, **6** (*2*) 111–117 (2015). doi:10.7763/ijesd.2015.v6.571.
37) A. Tejero-González, and A. Franco-Salas, "Optimal operation of evaporative cooling pads: a review," *Renew. Sustain. Energy Rev.*, **151** (*July*) (2021). doi:10.1016/j.rser.2021.111632.
38) H. Zhang, H. Ma, and S. Ma, "Investigation on indirect evaporative cooling system integrated with liquid dehumidification," *Energy Build.*, **249** 111179

(2021). doi:10.1016/j.enbuild.2021.111179.

39) J. Lv, H. Xu, M. Zhu, Y. Dai, H. Liu, and Z. Li, "The performance and model of porous materials in the indirect evaporative cooling system: a review," *J. Build. Eng.*, **41** (*May*) 102741 (2021). doi:10.1016/j.jobe.2021.102741.
40) H. Yang, W. Shi, Y. Chen, and Y. Min, "Research development of indirect evaporative cooling technology: an updated review," *Renew. Sustain. Energy Rev.*, **145** (*April*) 111082 (2021). doi:10.1016/j.rser.2021.111082.
41) K. Yang, X. Hao, Y. Lin, Q. Xing, H. Tan, J. Hu, and X. Liu, "An integrated system of water-cooled vrf and indirect evaporative chiller and its energy saving potential," *Appl. Therm. Eng.*, **194** (*April*) 117063 (2021). doi:10.1016/j.applthermaleng.2021.117063.
42) A.Y.T. Al-Zubaydi, and G. Hong, "Experimental study of a novel water-spraying configuration in indirect evaporative cooling," *Appl. Therm. Eng.*, **151** (*November 2018*) 283–293 (2019). doi:10.1016/j.applthermaleng.2019.02.019.
43) X. Cui, K.J. Chua, M.R. Islam, and K.C. Ng, "Performance evaluation of an indirect pre-cooling evaporative heat exchanger operating in hot and humid climate," *Energy Convers. Manag.*, **102** 140–150 (2015). doi:10.1016/j.enconman.2015.02.025.
44) Y. Al Horr, B. Tashtoush, N. Chilengwe, and M. Musthafa, "Operational mode optimization of indirect evaporative cooling in hot climates," *Case Stud. Therm. Eng.*, **18** (*December 2019*) 100574 (2020). doi:10.1016/j.csite.2019.100574.
45) S. Pedrazzi, G. Allesina, and A. Muscio, "Indirect evaporative cooling by sub-roof forced ventilation to counter extreme heat events," *Energy Build.*, **229** 110491 (2020). doi:10.1016/j.enbuild.2020.110491.
46) Y. Min, Y. Chen, and H. Yang, "A statistical modeling approach on the performance prediction of indirect evaporative cooling energy recovery systems," *Appl. Energy*, **255** (*April*) 113832 (2019). doi:10.1016/j.apenergy.2019.113832.
47) S. Moshari, G. Heidarinejad, and A. Fathipour, "Numerical investigation of wet-bulb effectiveness and water consumption in one-and two-stage indirect evaporative coolers," *Energy Convers. Manag.*, **108** 309–321 (2016). doi:10.1016/j.enconman.2015.11.022.
48) U. Agrobusiness, "Development of sustainable hydroponics technique for urban agrobusiness," *Evergreen*, **09** (*03*) 629–635 (2022).
49) B. Riangvilaikul, and S. Kumar, "An experimental study of a novel dew point evaporative cooling system," *Energy Build.*, **42** (*5*) 637–644 (2010). doi:10.1016/j.enbuild.2009.10.034.
50) F.A. Al-Sulaiman, P. Gandhidasan, and S.M. Zubair, "Liquid desiccant based two-stage evaporative cooling system using reverse osmosis (ro) process for regeneration," *Appl. Therm. Eng.*, **27** (*14–15*) 2449–2454 (2007). doi:10.1016/j.applthermaleng.2007.02.010.
51) G. Heidarinejad, M. Bozorgmehr, S. Delfani, and J. Esmaeelian, "Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions," *Build. Environ.*, **44** (*10*) 2073–2079 (2009). doi:10.1016/j.buildenv.2009.02.017.
52) X. Cheng, D. Peng, Y. Yin, S. Xu, and D. Luo, "Experimental study and performance analysis on a new dehumidifier with outside evaporative cooling," *Build. Environ.*, **148** 200–211 (2019). doi:10.1016/j.buildenv.2018.11.006.
53) K. Panchabikesan, V. Antony Aroul Raj, S. Abaranji, P. Vellaichamy, and V. Ramalingam, "Effect of direct evaporative cooling during the charging process of phase change material based storage system for building free cooling application—a real time experimental investigation," *Energy Build.*, **152** 250–263 (2017). doi:10.1016/j.enbuild.2017.07.037.
54) P. Mert, and S. Riffat, "A state of the art review of evaporative cooling systems for building applications," *Renew. Sustain. Energy Rev.*, **54** 1240–1249 (2016). doi:10.1016/j.rser.2015.10.066.
55) Q. Chen, K. Yang, M. Wang, N. Pan, and Z.Y. Guo, "A new approach to analysis and optimization of evaporative cooling system i: theory," *Energy*, **35** (*6*) 2448–2454 (2010). doi:10.1016/j.energy.2010.02.037.
56) G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, J. Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A. Humphries, R. Hydomako, S. Jonsell, L. Kurchaninov, R. Lambo, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D.M. Silveira, C. So, J.W. Storey, R.I. Thompson, D.P. Van Der Werf, D. Wilding, J.S. Wurtele, and Y. Yamazaki, "Evaporative cooling of antiprotons to cryogenic temperatures," *Phys. Rev. Lett.*, **105** (*1*) 1–5 (2010). doi:10.1103/PhysRevLett.105.013003.
57) T. Miyazaki, A. Akisawa, and I. Nikai, "The cooling performance of a building integrated evaporative cooling system driven by solar energy," *Energy Build.*, **43** (*9*) 2211–2218 (2011). doi:10.1016/j.enbuild.2011.05.004.
58) J.K. Jain, and D.A. Hindoliya, "Experimental performance of new evaporative cooling pad materials," *Sustain. Cities Soc.*, **1** (*4*) 252–256 (2011). doi:10.1016/j.scs.2011.07.005.
59) M. Sultan, I.I. El-Sharkawl, T. Miyazaki, B.B. Saha, and S. Koyama, "Experimental study on carbon based adsorbents for greenhouse dehumidification," *Evergreen*, **1** (*2*) 5–11 (2014). doi:10.5109/1495157.
60) H. Montazeri, B. Blocken, and J.L.M. Hensen, "CFD analysis of the impact of physical parameters on

evaporative cooling by a mist spray system," *Appl. Therm. Eng.*, **75** 608–622 (2015). doi:10.1016/j.applthermaleng.2014.09.078.
61) G. Heidarinejad, and S. Moshari, "Novel modeling of an indirect evaporative cooling system with cross-flow configuration," *Energy Build.*, **92** 351–362 (2015). doi:10.1016/j.enbuild.2015.01.034.
62) J. Xu, Y. Li, R.Z. Wang, W. Liu, and P. Zhou, "Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates," *Appl. Energy*, **138** 291–301 (2015). doi:10.1016/j.apenergy.2014.10.061.
63) B. Porumb, M. BĂlan, and R. Porumb, "Potential of indirect evaporative cooling to reduce the energy consumption in fresh air conditioning applications," *Energy Procedia*, **85** (*November 2015*) 433–441 (2016). doi:10.1016/j.egypro.2015.12.224.
64) S. De Antonellis, C.M. Joppolo, P. Liberati, S. Milani, and L. Molinaroli, "Experimental analysis of a cross flow indirect evaporative cooling system," *Energy Build.*, **121** 130–138 (2016). doi:10.1016/j.enbuild.2016.03.076.
65) P. Xu, X. Ma, X. Zhao, and K.S. Fancey, "Experimental investigation on performance of fabrics for indirect evaporative cooling applications," *Build. Environ.*, **110** 104–114 (2016). doi:10.1016/j.buildenv.2016.10.003.
66) I.M.A. Aljubury, and H.D. a. Ridha, "Enhancement of evaporative cooling system in a greenhouse using geothermal energy," *Renew. Energy*, **111** 321–331 (2017). doi:10.1016/j.renene.2017.03.080.
67) M. Sultan, T. Miyazaki, S. Koyama, and Z.M. Khan, "Performance evaluation of hydrophilic organic polymer sorbents for desiccant air-conditioning applications," *Adsorpt. Sci. Technol.*, **36** (*1–2*) 311–326 (2018). doi:10.1177/0263617417692338.
68) A.A. Eidan, K.J. Alwan, A. Alsahlani, and M. Alfahham, "Enhancement of the performance characteristics for air-conditioning system by using direct evaporative cooling in hot climates," *Energy Procedia*, **142** 3998–4003 (2017). doi:10.1016/j.egypro.2017.12.311.
69) X. Chen, Y. Su, D. Aydin, X. Zhang, Y. Ding, D. Reay, R. Law, and S. Riffat, "Experimental investigations of polymer hollow fibre integrated evaporative cooling system with the fibre bundles in a spindle shape," *Energy Build.*, **154** 166–174 (2017). doi:10.1016/j.enbuild.2017.08.068.
70) Z.A. Haidar, J. Orfi, and Z. Kaneesamkandi, "Experimental investigation of evaporative cooling for enhancing photovoltaic panels efficiency," *Results Phys.*, **11** (*May*) 690–697 (2018). doi:10.1016/j.rinp.2018.10.016.
71) J. Wang, Q. Meng, K. Tan, L. Zhang, and Y. Zhang, "Experimental investigation on the influence of evaporative cooling of permeable pavements on outdoor thermal environment," *Build. Environ.*, **140** (*May*) 184–193 (2018). doi:10.1016/j.buildenv.2018.05.033.
72) L.J. Zheng, D.H. Kang, N.K. Kim, Y.J. Youn, and H.W. Kang, "Theoretical analysis of natural evaporative cooling to enhance the efficiency of thermoelectric devices," *Int. J. Heat Mass Transf.*, **143** 118512 (2019). doi:10.1016/j.ijheatmasstransfer.2019.118512.
73) P.A. Doğramacı, and D. Aydın, "Comparative experimental investigation of novel organic materials for direct evaporative cooling applications in hot-dry climate," *J. Build. Eng.*, **30** (*February 2020*) (2020). doi:10.1016/j.jobe.2020.101240.
74) S. Kashyap, J. Sarkar, and A. Kumar, "Comparative performance analysis of different novel regenerative evaporative cooling device topologies," *Appl. Therm. Eng.*, **176** (*May*) 115474 (2020). doi:10.1016/j.applthermaleng.2020.115474.
75) P. Byrne, N. Putra, T. Mare, N. Abdallah, P. Lalanne, I. Alhamid, P. Estelle, A. Yatim, and A.L. Tiffonnet, "Design of a solar ac system including a pcm storage for sustainable resorts in tropical region," Evergreen, **6** 143–148 (2019). doi:10.5109/2321009