CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A number of studies have been conducted on the direct, indirect, and regenerative evaporative cooler. A wide range of investigations has been done in past on the different configurations, material selection, dimensions, and optimization of the evaporative coolers. The analysis of various evaporative coolers available in literature includes energy, exergy, economic and environmental aspects. The present literature review is broadly divided into two parts (numerical and experimental studies). Various review papers such as Cuce and Riffat (2016), Amer et al. (2015), Sajjad et al. (2021), Porumb et al. (2016) are available on the evaporative coolers. The recent studies in the literature are focused mostly on regenerative evaporative coolers.

2.2 Numerical studies:

The direct evaporative coolers are almost mature technology. So only a few recent studies are available related to direct evaporative coolers. The indirect evaporative coolers are still not that much popular and commercialised in the market. A lot of work has been done on the direct and indirect evaporative cooler. Some work has been done on the two-stage (Indirect + direct) evaporative coolers such as Heidarinejad and Moshari, (2015), Gilani and Poshtiri, (2017). The studies related to Numerical analysis which includes the energy, exergy, environmental, sustainability, and statistical analysis are listed in Table 2.1.

Table 2.1: Summary of the different numerical studies on evaporative cooling

Study	Method	Configuration	conclusion
Maclaine-cross and Banks (1981)	Numerical	IEC	For the study of IEC systems, a linear approximation heat and mass transport model was devised.
Hsu et al. (1989)	Numerical	Counter and cross flow REC	They discovered that moderate flow rates and simple geometries may obtain temperatures significantly lower than the intake wet bulb temperature.
Erens and Dreyer (1993)	Numerical	IEC	They discovered that in REC systems, the best extraction ratio is determined by plate spacing. They advised a 36 percent extraction ratio for plate

			spacing of 3 mm for optimal REC system performance.
Halasz (1998)	Numerical	IEC and REC	This model was simplified by replacing a straight saturation line for the real one, and it produces a fairly realistic model for evaporative cooler rating.
Abbassi and Aliehyaei, (2004)	Numerical	IEC	The entropy generation principle used to obtain the optimum external dimension of the device and search method is used to investigate the different cooling capacities of wavy plate IEC

Chengqin and Hongxing (2006)	Analytical solution	IEC with parallel- and counter-flow	Obtained best performing configurations with assumed surface wettability
Zhao et al. (2008)	Numerical investigation	REC	The channel gap should be set to 6 mm or below, and the length of the passage should be 200 times the height; the working-to-intake-air ratio should be around 0.4
Eslamian et al. (2009)	Numerical	IEC	Minimization of entropy generation principle used to optimize the length of channels
Riangvilaikul and Kumar, (2010)	Numerical modeling	REC	Obtained dew point effectiveness in the range of 65 to 86 %

	(finite difference method)		
Hasan (2010)	Numerical	Single-stage and two-stage counterflow, two-stage parallel flow, and combined parallel-regenerative cooler	Single-stage effectiveness of 1.16 while the maximum for the combined parallel-regenerative cooler of 1.31
Caliskan et al. (2011)	Numerical	M-cycle-based IEC	Obtained maximum efficiency of 19.14 % at the ambient temperature reference conditions
Hasan, (2012)	Numerical ξ-NTU method	IEC and regenerative IEC	General method showed good agreement with the experimental result
Farmahini-Farahani et al., (2012)	Numerical	IEC and DEC	Exergy efficiency of indirect/direct evaporative cooling is on average 22%

			higher than that of IEC
Caliskan et al. (2012a)	Numerical	M cycle REC	Varied dead state temperatures from 10-35 ºC, they concluded that irreversibility increases with an increase in the dead state temperature
Caliskan et al., (2012b)	Numerical	M-cycle REC	Exergoeconomic economic and sustainability analyses of the evaporative cooler
Lee et al. (2013)	Numerical	Flat plate type, the corrugated plate type, and the finned channel type	Finned channel type regenerative cooler found to give the most compact structure under a limit of the pressure drop
Cui et al. (2014a)	Numerical (CFD)	REC	To achieve below wet bulb cooling, the intake velocity

			should be less than 1.5 m/s
Cui et al., (2014b)	Numerical (CFD)	REC with ribs	Achieved wet bulb effectiveness of up to 132%, and dew-point effectiveness of up to 93%
Pandelidis et al., (2015a)	Numerical	Regenerative indirect evaporative air	Perforated regenerative exchangers show higher temperature efficiency than the typical regenerative units
Pandelidis et al., (2015b)	Numerical	Counter-flow indirect evaporative air cooler	Modified exchanger (recirculation and exhaust airflow in wet channel) produce low outlet temperature and high cooling capacity

Heidarinejad and Moshari, (2015)	2d Numerical modeling	Cross-flow and counter flow configuration	Counter-flow regenerative evaporative cooler which shows around 60% higher wet-bulb effectiveness in comparing to a one-stage IEC
Anisimov and Pandelidis,(2015)	2d and 3d numerical	Parallel-flow, counter-flow, cross-flow, and regenerative	The parallel flow configuration validate lewis number unity while it violates other configurations
Bolotin et al. (2015)	Numerical ξ-NTU method	Cross-flow indirect evaporative cooler units	The regenerative exchanger provides lower outlet supply air temperature, higher COP, and lower water usage, while the typical cross flow exchanger is characterized by

			greater cooling capacity
Moshari and Heidarinejad, (2015)	Numerical simulations	Cross and counter flow REC	Counter flow REC can produce the lowest temperature as compared to cross flow REC (30% higher) and four stage IEC for the same air and heat exchanger parameter
Cui et al. (2015)	Numerical	Combines IEC and a vapor compression	Product air can be cooled and dehumidified simultaneously in the channel due to the lower plate temperature
Elgendy et al. (2015)	Numerical	DEC and REC	Configuration which adds two direct/indirect evaporative cooling after rotating heat exchanger shows

			54% higher exergy efficiency
Lin et al. (2016a)	Mathematical model	Dew point evaporative cooler	Longitudinal heat conduction is accounted in the analysis
Lin et al., (2016b)	Transient model	IEC	Average transient wet bulb effectiveness found to be higher than steady state response
Moshari et al. (2016)	Numerical	Two stages IEC	Obtained 31% higher effectiveness than that of the one stage IEC
Cui et al. (2016)	Non-dimensional numerical analysis	Counter-flow regenerative IEHX	Low supply air temperature is achieved by increasing non-dimensional group
Kabeel and Abdelgaied, (2016)	Numerical	REC with internal baffles	wet bulb effectiveness increases with the

			increase in the number of baffles
Xu et al. (2016a)	Numerical	Irregular REC with corrugation	Achieved low flow resistance and high heat transfer. 37% higher wet bulb effectiveness than flat plate
Ham and Jeong (2016)	Numerical	REC	The liquid desiccant and IEC unit can reduce electricity consumption by 67.8%
Fakhrabadi and Kowsary (2016a)	Numerical	REC	Optimal design of the REC by simplified conjugate gradient method and recommended the extraction ratio of 0.4 and channel height of 4-6 mm
Ham et al. (2016)	Numerical	REC	REC with liquid desiccant syatem

			can save 12% of primary energy compared to a conventional variable air volume system.
Fakhrabadi and Kowsary, (2016b)	Numerical	REC	Conjugate gradient method is utilized to optimize the hybrid liquid desiccant-REC system
Pandelidis et al. (2017)	Numerical	M-cycle cross flow and combination of cross-counter	Combination of cross flow and regenerative counter flow HMX performed best
Kabeel et al. (2017)	Numerical	REC with internal baffles	Wet bulb effectiveness increases with the increase in the number of baffles
Moshari and Heidarinejad, (2017)	Numerical	IEC	The supply air temperature decreases with the

			fin height reduction and increases with the increase in the volume flow rate
Gilani and Poshtiri (2017)	Numerical	Two-stage indirect/direct evaporative cooler	Thermal comfort can be achieved when outdoor temperature 34–54 °C and relative humidity 10–60 % range
Lin et al. (2017a)	2-D mathematical model	REC	Scaling analysis is used to obtain the dimensionless groups, which controls the operating and geometric parameters
Jafarian et al. (2017)	Numerical	REC	Difference between the maximum prediction errors of 2D and 3D models were less than 4.5%

Wan et al. (2017)	Numerical (CFD)	IEC	Minimum set of grouped dimensionless factors are obtained from the 2D model
Jafarian et al. (2017)	Numerical (neural network)	REC	Optimizatised coefficient of performance and specific area for the system were improved 36.3% and 30.9%, respectively
Sadighi Dizaji et al. (2018)	Analytical	Perforated (multi-stage) regenerative M-cycle exchanger.	An accurate and fast model is proposed for the cooler
Zhu et al. (2017)	Numerical (artificial neural network)	REC	Optimal extraction ratio (0.3 to 0.36.) decreased with the outdoor temperature and relative humidity
Sohani et al. (2018)	Numerical	REC	The counter flow configuration is

			best for hot and dry areas whereas cross flow configuration is best for other investigated climates
Tariq et al. (2018)	Numerical	Cross-flow (HMX)	Performance improved with the use of alumina-based Nano fluid in the water
Wan et al. (2018)	Numerical	REC	CFD results are used to get outlet data for the NTU _ Le _ R model
Baakeem et al. (2018)	Numerical	DEC	Energy, exergy, and economic analyses for Riyadh city and concluded it archives comfort cooling at low cost
Wang et al. (2019)	Numerical	M cycle IEC	They concluded that HMX performance influenced by

			outdoor conditions mostly and length of HMX should be in the range of 1-1.75 m
Sadighi Dizaji et al. (2019)	Numerical	REC	They investigated operating parameters of a cooler at the fixed structure. They suggested that velocity in channels is a very important parameter to reduce exergy loss
Oh et al. (2019)	Mathematical model	Combined HMX with purged holes	Single-purge configuration produced higher cooling capacity (around 20% higher)
Liu et al. (2019b)	2-D numerical model	REC	Water inlet temperature is higher than a fixed

			temperature of 23.1 °C for REC, the temperature of supply air increases with the increasing water mass flow rate
Lin et al. (2018a)	Numerical	REC	Exergy destruction in a REC accounts for 10-25%.
Ng et al. (2019)	Numerical	IEC combined with dehumidification	Used microwave-based regeneration and get the COP up to 20
Nada et al. (2019)	Numerical	DEC	Exergetic analysis of the DEC with four different pad thicknesses. The exrgetic performance improves with an increase in the pad thickness and water flow rate. The highest COP of 281

			is obtained at 2 m/s air velocity
Katramiz et al. (2020)	Numerical	REC integrated with hydronic radiative cooling	Found a 44.2% reduction in water consumption

Most of the numerical studies in the evaporative cooling field are related to cooling performance investigation. Different research such as Hasan (2010), Riangvilaikul and Kumar (2010), Cui et al. (2014b), Lin et al. (2016a), Wang et al. (2019) obtained below wet bulb temperature cooling from regenerative coolers. The channel gap, extraction ratio, intake air velocity, channel length, water flow rate, and water temperature are found to be important parameters that affect the performance of the device. Riangvilaikul and Kumar, (2010), recommended a channel length greater than 1m for sub wet cooling. The COP is a very important performance parameter and many literate such as Duan,(2011) in the range of 100-800, Wang et al. (2019) in the range of 100-900 and Zhan et al. (2011) in the range of 300-1200 claims much higher value. The extensive exergetic study performed by different researcher such as Chengqin et al. (2002), Caliskan et al. (2012a), Farmahini-Farahani et al. (2012), Lin et al. (2018a), Wang et al. (2019), and Sadighi Dizaji et al. (2019) to optimize the cooling device. However limited studies involved in the economic and environmental study, such as Caliskan et al. (2012b), Sohani and Sayyaadi (2018), and Baakeem et al. (2018). The computational fluid dynamics analysis of the regenerative evaporative coolers are also performed in the literature such as Cui et al. (2014a), Wan et al. (2017). The cooling device is numerically evaluated by 3d (Anisimov and Pandelidis, 2015), 2d (Heidarinejad and Moshari, 2015), (Lin et al., 2017a), (Liu et al., 2019b), and one-dimensional models by many researchers. However, Pakari and Ghani, (2019) evaluated one-dimensional and three-dimensional REC models to experimental results and found that the one-dimensional model is justified enough to predict performance.

2.3 Experimental studies:

The experimental analysis of the coolers includes the counterflow, cross flow, and M-cycle configurations of the regenerative evaporative coolers. The literature related to the experimental analysis is listed in Table 2.2.

Table 2.2: Summary of the different experimental studies on evaporative cooling

Study	Method	Configuration	conclusion
Zhan et al. (2011)	Experimental	Cross flow and counter flow dew point evaporative cooler	Counter flow exchanger offer higher (around 20%) cooling capacity as well as greater(15%-23% higher) dew point and wet bulb effectiveness
Lee and Lee (2013)	Experimental	Finned channels REC	Obtained below wet bulb temperature
Woods and Kozubal (2013)	Experimental	Two-stage (REC + dehumidifier)	Found wet-bulb effectiveness up to 125% and dew point effectiveness up to 82%

Jradi and Riffat (2014)	Numerical and experimental	Cross flow REC	Attained 112% wet-bulb effectiveness and 78% dew-point effectiveness
Gao et al. (2015)	Experimental	M cycle IEC and liquid dessicant	Water flow rate needs to be five times greater than the water evaporation rate
Xu et al. (2016b)	Experimental	IEC	Bamboo coolpass bird eye mesh fabric is the best fabric for evaporative cooling application
De Antonellis et al. (2016)	Experimental	Cross-flow IEC	Achieved up to 85 % wet bulb effectiveness.
Duan et al. (2016)	Experimental	Counter flow REC	Wet bulb effectiveness from 0.55 to1.06, 31% higher than IEC
Khalid et al. (2016)	Experimental	IEC	New designe for width to height

			ratio and efficient moisture absorbing material (felt) obtained
Kim et al. (2017)	Experimental	Cross flow IEC	Normal cross flow IEC perform better than regenerative IEC for use in a 100% outdoor air
Boukhanouf et al. (2017)	Experimental	REC with the hollow porous ceramic container as a wetting material	Obtained wet bulb effectiveness up to 1.024
Xu et al. (2017)	Experimental	REC	Achieved wet bulb cooling effectiveness of 114% and dew point cooling of 75%
Lin et al. (2017b)	Experimental	Cross flow REC	Achieved dew point effectiveness up to 0.85
Duan et al. (2017)	Experimental and numerical	REC	Obtained effectiveness of

			0.96 to 1.07 and cooling capacity of 3.9 to 8.5 kW
Khalid et al. (2017)	Experimental	REC Cross flow (M cycle)	Achieved 5% more effective compared to the previous design by improving the width to height ratio and wetting paper quality
Lin et al. (2018b)	Experimental and numerical	REC	They obtained wet bulb effectiveness in the range of 0.89-1.44 and dew point effectiveness in 0.6-0.97
Li et al. (2018)	Numerical and experimental	IEC	The supply air temperature of the vertical IEC is 2 ºC cooler and has 29.97% more cooling capacity than horizontal IEC

Pakari and Ghani (2019)	Numerical and experimental	REC	Compared the 1D and 3D model with experimental results and concluded that 1D modeling is justified in REC analysis
Liu et al. (2019a)	Experimental	REC	Obtained COP up to 42.8
Jia et al. (2019)	Experimental	REC	Lightweight REC cooler that contains nylon fibers in the wet channels, and this cooler reduces the size of the device for the same cooling performance.
Arun and Mariappan (2019)	Experimental	REC with the water mist which is created by the ultrasonic transducers	Obtained below wet bulb cooling and more than 10ºC temperature drop

Shahzad et al. (2019)	Experimental	REC with multi-point injection	Obtained COP up to 78 and suggested integrating it with the dehumidification
Sellami et al. (2019)	Experimental	DEC using a ceramic wet porous layer	Cooling efficiency increases with an increase in porous layer thickness and is more pronounced for large thicknesses.
Ali et al. (2021)	Experimental	cross-flow REC	Obtained an 18% increment in the cooling capacity of the cooler when compared to the without fin cooler.

The majority of REC investigations in the literature are conducted on a flat plate. However, few studies on the performance of regenerating HMX with surface changes have been conducted. The polygonal-sheets-stacked structure HMX was employed by Zhao et al. (2008), while Lee et al. (2013) designed and tested a finned channel regenerative cooler. Lee et al. (2013) investigated three regenerative HMX configurations: flat, corrugated, and finned. Pandelidis et al. (2015) investigated perforated heat and mass exchangers while Kabeel et al. (2016) examined the performance of the REC with baffles. Boukhanouf et al. (2017) tested REC with hollow porous ceramic (a water-holding medium) to achieve comfort cooling. According to the above-mentioned experimental literature review, a single regenerative evaporative cooling system has been extensively investigated in recent years.

2.4 Research gaps

Based on the above literature review, the following research gaps have been identified

- Limited regenerative evaporative cooler configurations are investigated in the literature. However, a lot of scopes exist for all other configurations. Based on primary air, secondary air, and water flow directions, several configurations are possible for both parallel/counter and cross-flow regenerative evaporative coolers. However, to the best of the author's knowledge, only a few configurations were tested. So there is a need to do a comparative analysis of all the possible configurations of a regenerative evaporative cooler considering water and air flow directions to get the best one.
- Only limited studies are available on the performance improvement of regenerative evaporative coolers using various surface modifications and nanofluids. The regenerative evaporative cooler is studied with corrugated, finned, and baffled surfaces, as mentioned in the literature. A wide number of investigations have been reported on the plate-type heat exchangers by altering the profile of the plates. But, these surface modifications have not been investigated for a regenerative evaporative cooler. Moreover, the binary hybrid nanofluids have shown promising results in the field of heat transfer; however,

these have not been used in the regenerative evaporative cooler for performance improvement.

- Different evaporative coolers have been investigated for individual suitable climatic conditions. No attempt was made to develop a single cooling device that operates depending upon the suitability for the climatic conditions. The climatic conditions of a city keep on changing throughout the year, so a single device which is suited best for different climatic conditions needs to be investigated.
- The regional acceptability of evaporative cooler is investigated for country-specific or climate-specific conditions. None of the studies is done to investigate the suitability of modes of evaporative cooler. The suitability and mode-specific (direct or regenerative) study for different global climatic conditions and zonal conditions are not available in the literature.
- No study is available, which focuses on the future performance prediction and suitability of the evaporative cooling devices.