Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 85 (2016) 461 – 471

Energy Procedia

Sustainable Solutions for Energy and Environment, EENVIRO - YRC 2015, 18-20 November 2015, Bucharest, Romania

A review of indirect evaporative cooling technology

Bogdan Porumb[a], Paula Ungureşan[a], Lucian Fechete Tutunaru[a], Alexandru Şerban[b], Mugur Bălan[a]*

[a] *Technical University of Cluj-Napoca, Bd. Muncii 103-105, Cluj-Napoca, 400641, Romania*
[b] *"Transilvania" University of Braşov, Str. Universităţii 1, Braşov 500068, Romania*

Abstract

The paper presents actual knowledge concerning the indirect evaporative cooling (IEC). This cooling technology is promising to develop in the near future due to its very low energy consumption and high efficiency in its range of applications. The review is presenting in details: theory, working principles, flow and construction. The IEC equipment and technology is suitable in different air conditioning applications: commercial, industrial, residential or data centres. The IEC technology is completely environmental friendly and has very low global warming impact. The single disadvantage of IEC is the water consumption.

Peer-review under responsibility of the organizing committee EENVIRO 2015

Keywords: Indirect evaporative cooling, regenerative cooling, dew point cooling, Maisotsenko cycle, energy efficiency

1. Introduction

The evaporative cooling (EC) technology is based on heat and mass transfer between air and cooling water. Direct evaporative cooling (DEC) is based on *mechanical and thermal contact* between air and water, while indirect evaporative cooling (IEC) is based on heat and mass transfer between two streams of air, separated by a *heat transfer surface* with a dry side where only air is cooling and a wet side where both air and water are cooling.

Both DEC and IEC are characterised by very high energy efficiency but also by significant water consumption rates.

---

* Corresponding author. Tel.: +4-026-440-1670; fax: +4-026-441-5490.
E-mail address: mugur.balan@termo.utcluj.ro.

Peer-review under responsibility of the organizing committee EENVIRO 2015
doi:10.1016/j.egypro.2015.12.228

In the case of IEC technology, on the dry side of the heat transfer surface (dry surface), is flowing the primary (or product) air that is cooling down. On the wet side of the heat transfer surface (wet surface), is flowing the secondary (or working) air in mixture with water.

The goal of this study is to present from both qualitative and quantitative point of view, the available scientific information concerning different aspects related to the IEC: construction principles, flow schemes and working processes.

2. Theory

2.1. Direct evaporative cooling (DEC)

The working principle scheme of the DEC equipment and a simplified flow scheme are presented in figure 1. The warm inlet air (1) enters in a pad which is sprayed with water at the wet bulb (WB) temperature of the inlet air. The heat transfer is realised from the warm air to the cold water. The heat is transferred by the air stream as sensible heat and is absorbed by the water as latent heat. Corresponding to the value of latent heat, a part of the water is evaporated being embedded by diffusion into the flowing air, increasing the moisture content of this air. The temperature of the outlet air (2) decreases due to the sensible heat transferred by the air, but the enthalpy of the outlet air will be the same with the enthalpy of inlet air as effect of the latent heat recovered into the air as moisture.

The working process of the DEC equipment is presented in the psychrometric chart in figure 2.

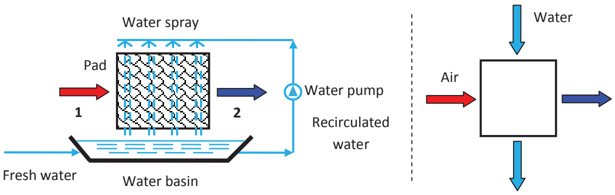


Fig. 1. Working principle scheme and simplified flow scheme of the DEC

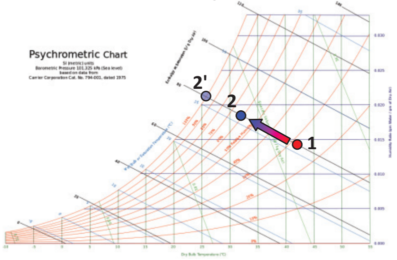


Fig. 2. The working process of the DEC

The working process (1-2) is realized at constant enthalpy as it can be observed on the chart. At limit, the cooling process could continue until the state of saturation (2').

The main advantage of DEC is represented by the very simple construction of the equipment. The main disadvantage of the DEC is represented by the increasing of the air moisture content which may be undesirable for certain applications.

2.2. Indirect evaporative cooling (IEC)

The working principle scheme of the IEC equipment [2], [3], [7], [11], [12], [15], [17], [18], [22], [24], [26], [30-33] is presented in the left side of figure 3. The warm primary (or product) air (1) is flowing inside the dry channels and transfers heat through the heat surface to the wet channels. At outlet, the primary (or product) air (2) will have a lower temperature as at inlet, due to the transferred heat. The secondary (working) air (3) is flowing inside the wet channels together with the water. The behaviour of the air and water in the wet channel is similar with the DEC process. The water temperature is the WB temperature of the secondary air. The heat transferred through the surface between the dry and wet channels is absorbed by the water as latent heat and a corresponding part of the water is evaporated being embedded by diffusion into the secondary air, increasing the moisture content of this air.

If the secondary air arrives at the saturation state, after this stage forward the heat from the primary air is split as latent heat absorbed by the water and as sensible heat absorbed by the secondary air. Thus, the temperature of the secondary air at the outlet (4) can be one of the following:

a. Lower than the WB temperature of the secondary air at the inlet (no saturation);

b. Equal with the WB temperature of the secondary air at the inlet (saturation is reached at the outlet);

c. Higher than the WB temperature of the secondary air at the inlet (saturation before the outlet).

A simplified flow scheme of the IEC equipment is presented in the right side of figure 3.

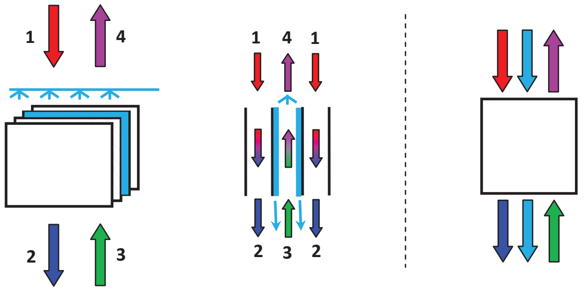


Fig. 3. Working principle scheme and simplified flow scheme of the **IEC** equipment

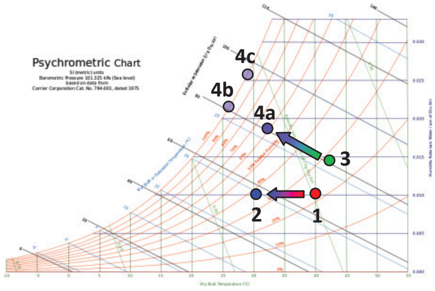


Fig. 4. The working process of the **IEC** in the psychrometric chart

The working process of the primary air (1-2) is realised at constant moisture content and the working process of the secondary air (3-4) is realised at constant enthalpy as it can be observed on the psychrometric chart. At limit, the cooling process of the primary air could continue until the WB temperature of the secondary air at the inlet.

The main advantage of the IEC is that primary air is cooled without modifying its moisture content. The main disadvantage of the IEC is that the cooling process of the primary air is limited by the WB temperature of the secondary air at the inlet. Because of this limitation, this type of equipment is also named *wet bulb IEC*.

2.3. Regenerative indirect evaporative cooling (R-IEC)

The regenerative indirect evaporative cooling (R-IEC) [4], [5], [19], [20], [25], [35] was developed to decrease the primary air temperature at the outlet, below the WB temperature of the secondary air at the inlet. The regeneration consists in extracting a part of the primary air at its outlet and using it as secondary air. In this case, because the secondary air is already cooled, the corresponding WB temperature is sensible lower than the WB temperature of regular (outside) secondary air and the limit at which the primary air can be cooled became considerably lower.

The working principle scheme of the R-IEC equipment is presented in the left side of figure 5.

The warm primary air (1) is flowing inside the dry channels and transfers heat through the heat surface to the wet channels. At its outlet, the primary air (2) will have a lower temperature than at inlet. A part of the outlet primary air is used as secondary air being introduced in the wet channels. The working process inside the wet channels is similar with the one described in the paragraph referring to the IEC with the single difference that in this case the secondary air is much cooler. A simplified flow scheme of the R-IEC equipment is presented in the right side of figure 5.

The corresponding working process of the R-IEC equipment is presented in figure 6.

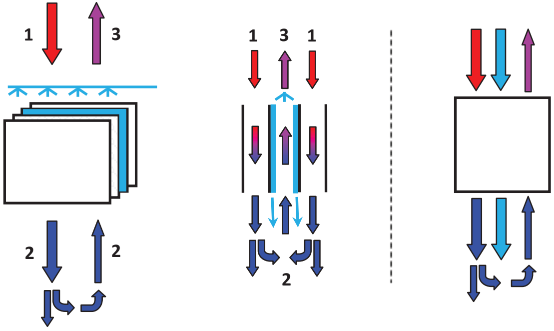


Fig. 5. Working principle scheme and simplified flow scheme of the R-IEC equipment

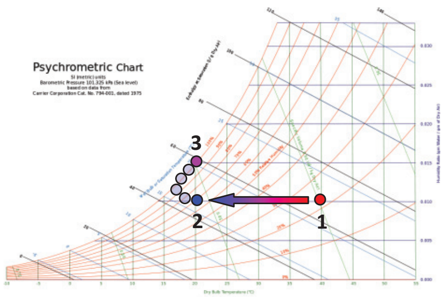


Fig. 6. The working process of the R-IEC in the psychrometric chart

The working process of the primary air (1-2) is realised at constant moisture content and the final dry bulb (DB) temperature of the primary air is considerable lower than in the case of classic IEC and below the WB temperature of the primary air at inlet. The working process of the secondary air (2-3) is represented on the psychrometric chart by the semi-transparent succession of circles. At limit, the cooling process of the primary air could continue until reaching the WB temperature of the secondary air at the inlet. This type of equipment is also named *sub wet bulb IEC*.

The main advantage of the R-IEC is that primary air is cooled at constant moisture content below the WB temperature of the primary air. The main disadvantage of the R-IEC is that the flow rate of the primary air is lower than in the case of classic IEC.

2.4. Dew point indirect evaporative cooling (D-IEC)

The dew point indirect evaporative cooling (D-IEC) [13] was developed to decrease the primary air temperature near the limit of the dew point (DP) temperature of the primary air at the inlet. The D-IEC consists in multiple stages of R-IEC equipment. The working principle of D-IEC equipment, with two stages of R-IEC is presented in figure 7 and the corresponding working process is presented in figure 8.

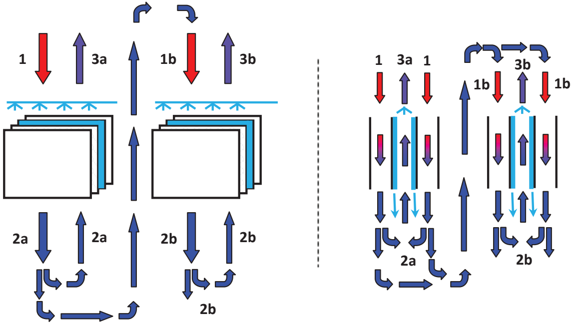


Fig. 7. Working principle scheme of D-IEC equipment; two stages R-IEC

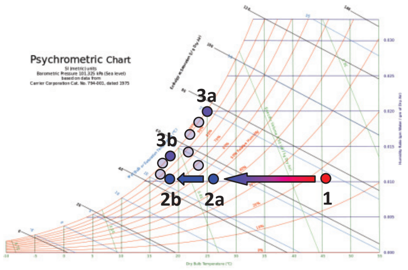


Fig. 8. The working process of the D-IEC

The warm primary air (1) is flowing inside the dry channels and transfers heat through the heat surface to the wet channels. At outlet, the primary air (2a) will have a lower temperature. A part of the outlet primary air of the first stage is used as secondary air of the first stage being introduced in the wet channels. The rest of the outlet primary air of the first stage is used as primary air of the second stage. The working process inside the wet channels of both stages is similar with the one described in the paragraph referring the classic IEC with the difference that in this case the secondary air is always much cooler.

The working process of the primary air (1-2a-2b) is realised at constant moisture and can approach the DP temperature of the primary air at the inlet on the first stage. The working process of the secondary air in all stages are (2a-3a), (2b-3b), etc., represented on the psychrometric chart. At limit, the cooling process of the primary air could continue near the DP temperature of the primary air at the inlet. This behaviour of the primary air is justifying why these equipment are also named *dry bulb IEC*.

The main advantage of the D-IEC is that primary air is cooled at constant moisture content almost near the DP temperature. The main disadvantage of the D-IEC is that flow rate of the primary air is decreasing with the number of stages.

2.5. Maisotsenko indirect evaporative cooling (M-IEC)

The indirect evaporative cooling system, developed by Valerij Maisotsenko [23] is representing an alternative possibility for cooling the primary air near the DP temperature of the inlet air. After the name of its inventor, the system was named M-IEC. The M-IEC [1], [6], [10], [34], [38], [39] has two types of dry channels, one for the primary air and one for the secondary air. The main characteristic of the system is that secondary air has multiple passages from its dry channels into the wet channels. The primary air is simply flowing into the dedicated dry channels.

The M-IEC are realised mainly from horizontal plates. The working principle scheme and a simplified flow scheme are presented in figure 9 while the corresponding working process is presented in figure 10.

The warm outside primary air (1) is flowing inside the dedicated dry channels and transfers heat through the heat surface to the wet channels. At outlet, the primary air (2) will have a temperature near the DP temperature of the primary air at inlet. The secondary air is the same outside air (1) and also flows inside dedicated dry channels, but having multiple passages into the wet channels were evaporated water is embed by diffusion as moisture into the secondary air. It can be considered that in each section of the equipment, the secondary air is constantly increasing its moisture until the outlet (3)..

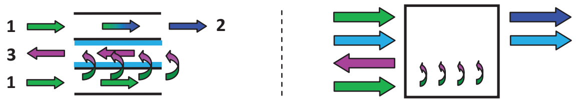


Fig. 9. Working principle scheme and simplified flow scheme of the M-IEC equipment

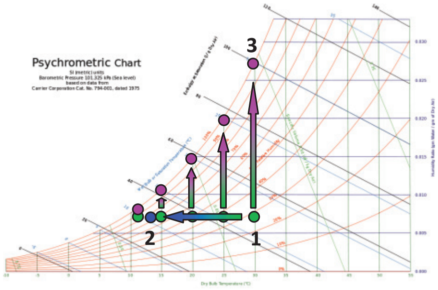


Fig. 10. The working process of the M-IEC in the psychrometric chart

The working process of the primary air (1-2) is realised at constant moisture. The working process of the secondary air (1-3) and the corresponding isothermal humidification processes inside the equipment are represented on the psychrometric chart by the corresponding states. At limit, the final DB temperature of the primary air at outlet can arrive near the DP temperature of the inlet primary air. This type of equipment is also a *dry bulb IEC*.

The main advantage of the M-IEC is that primary air is cooled without modifying the moisture content almost near the DP temperature. The main disadvantage of the M-IEC is the complex construction and flow scheme inside the equipment.

3. Scientific interest concerning IEC

The references, on which this study was based, were selected following a procedure that allowed the identification of representative scientific contributions in the field of study.

General information concerning the selected references, sorted by year of publication, are presented in Table 1, including the first author, location, construction type, flow type, nature of primary air inlet (PI), nature of secondary air inlet (SI), type of IEC and type of research methodology (Exp = Experiment; Sim = Simulation; Rev = Review).

Table 1. IEC references - general data

Ref. no.	Year	References first author	Location	Construction	Flow	PI	SI	Type	Obs.
[16]	1989	Hsu	USA	Horizontal plates	Cross flow	-	-	Multiple	Sim
[24]	1994	Mathews	ZAF	N/A	Multiple cases	-	-	IEC	Sim
[2]	1998	Alonso	ESP	Vertical plates	Cross flow	-	-	IEC	Sim
[3]	1998	Armbruster	DEU	Horizontal tubes	Cross flow	-	-	IEC	Exp; Sim
[12]	1998	Guo	HKG	Vertical plates	Cross flow	-	-	IEC	Sim
[31]	1998	Stoitchkov	BGR	Vertical plates	Cross flow	-	-	IEC	Sim
[22]	2001	Maheshwari	KWT	Vertical plates	Paralel flow	Outside	Outside	IEC	Exp; Sim
[30]	2001	Saman	AUS	Horizontal plates	Cross flow	-	-	IEC	Sim
[23]	2002	Maisotsenko	USA	Horizontal plates	Complex flow	-	-	M-IEC	Patent

Ref. no.	Year	References first author	Location	Construction	Flow	PI	SI	Type	Obs.
[27]	2004	Rey Martinez	ESP	Vertical plates and tubes	Cross flow	Outside	Inside	Multiple	Exp
[10]	2006	Elberling	USA	Horizontal plates	Complex flow	Outside	Outside	M-IEC	Exp
[26]	2006	Ren	CHN	Vertical plate	Paralel / Counter flow	-	-	IEC	Sim
[15]	2007	Hettiarachchi	USA	Horizontal plates	Cross flow	-	-	IEC	Sim
[39]	2008	Zhao	GBR	Horizontal plates	Complex flow	-	-	M-IEC	Sim
[7]	2010	Delfani	IRN	Vertical plates	Cross flow	-	-	IEC	Exp
[13]	2010	Hasan	FIN	Horizontal plates	Multiple cases	-	-	Multiple	Sim
[28]	2010	Riangvilaikul	THA	Vertical plates	Counter flow	Outside	-	R-IEC	Sim
[29]	2010	Riangvilaikul	THA	Vertical plates	Counter flow	Outside	-	R-IEC	Exp
[5]	2011	Bruno	AUS	Vertical plates	Counter flow	Outside	Supply	R-IEC	Exp
[6]	2011	Caliskan	TUR	Horizontal plates	Complex flow	Outside	Outside	M-IEC	Sim
[9]	2011	Dunnavant	USA	Horizontal tubes	Cross flow	Inside	Outside	IEC	Exp
[18]	2011	Kiran	IND	Vertical plates	Cross flow	Outside	-	IEC	Sim
[25]	2011	Miyazaki	JPN	Horizontal plates + solar	Counter flow	Inside	Inside	R-IEC	Sim
[38]	2011	Zhan	GBR	Horizontal plates	Complex flow	-	-	M-IEC	Sim
[8]	2012	Duan	GBR	Multiple cases	Multiple cases			Multiple	Rev
[11]	2012	Finocchiaro	ITA	Vertical plates	Cross flow	-	-	IEC	Exp
[14]	2012	Hasan	FIN	Horizontal plates	Counter flow	-	Supply	Multiple	Sim
[17]	2012	Khalajzadeh	IRN	Horizontal plates	Cross flow	Outside	Inside	IEC	Sim
[33]	2012	Velasco Gomez	ESP	Vertical plates	Cross flow	Outside	Inside	IEC	Exp
[34]	2012	Wani	IND	Vertical plates	Complex flow			M-IEC	Rev
[36]	2012	Xuan	CHN	Multiple cases	Multiple cases	-	-	Multiple	Rev
[37]	2012	Xuan	CHN	Multiple cases	Multiple cases	-	-	Multiple	Rev
[1]	2013	Ahmad	SAU	Horizontal plates	Complex flow	Outside	Outside	M-IEC	Exp
[4]	2013	Bellemo	DNK	Vertical plates	Counter flow	Outside	Supply	R-IEC	Sim
[19]	2013	Lee	KOR	Multiple cases	Counter flow	Outside	Supply	R-IEC	Sim
[20]	2013	Lee	KOR	Vertical plates	Counter flow	-	Supply	R-IEC	Exp; Sim
[21]	2013	Liu	USA	Vertical plates	Counter flow	Inside	Outside	Multiple	Sim
[32]	2013	Tejero-Gonzalez	ESP	Vertical plates	Cross flow	Outside	Inside	IEC	Exp
[35]	2013	Woods	USA	Vertical plates	Counter flow	Outside		R-IEC	Exp; Sim

The interest concerning IEC in the scientific community had increased constantly and this is proved by the disappearance of gaps between references after 2010, and by the increased number of references in the last years.

The wide interest concerning IEC is proved by the number of 20 countries worldwide, covered by the references: USA (7 references), SPA (4 references), GBR (3 references), CHN (3 references), etc.

The most common flow pattern is the cross flow in 38.5% of the references. The counter flow is met in 25.6% of the references and the parallel flow in a single reference (2.6%). Complex flow situations are met in 17.9% of the references and are typical for the M-IEC equipment. Multiple flow patterns are presented in 12.8% of the selected references and a single reference (2.6%) is presenting both counter flow and parallel flow.

Classical IEC equipment are the most studied (in 41.0% of the selected references). Almost similar number of references is dedicated to the R-IEC equipment (20.5%) and M-IEC equipment (17.9%). Multiple types of equipment are studied in 20.5% of the references.

Simulations are presented in more than half of the selected references (51.3%). Experiments are presented in about a quarter of the references (25.6%). Both simulation and experiment are presented in 10.3% of the references. The same 10.3% of the references are reviews and one reference (2.6%) is presenting a patent (of the M-IEC).

4. Integration of IEC in applications

The IEC equipment can be used in different applications, in different arrangements, according to the characteristics of each application. In Table 2 are presented some basic schemes of coupling the IEC with the served spaces, together with typical applications and a brief description of each situation.

Table 2. Basic arrangements of IEC equipment and served spaces

Typical applications	Description
- Office buildings	- Outside air is the inlet of primary air.
- Industrial buildings	- Outside air is the inlet of secondary air.
- Supermarkets	- Counter flow
- Cinemas	- Large range of cooling power
- Sport facilities	
- Etc.	
- Office buildings	- Outside air is the inlet of primary air.
- Industrial buildings	- Outside air is the inlet of secondary air.
- Supermarkets	- Cross flow
- Cinemas	- Large range of cooling power
- Sport facilities	
- Etc.	
- Data centres	- Inside air is the inlet of primary air.
	- Outside air is the inlet of secondary air.
	- Counter flow
	- High cooling power
- Special applications	- Both outside air and inside air can be the inlet of primary air.
	- Outlet primary air is divided in inlet of secondary air and supply air.
	- Counter flow
	- Low cooling power

The most common applications for the IEC technology are office and industrial buildings, supermarkets, cinemas, sport facilities or similar. This type of applications can be designed for a large range of cooling power.

A particular case is represented by the cooling of data centres where the main stream of cooling air is compulsory and entirely recirculated mainly due to data security and data transactions reasons. The cooling with fresh air is not allowed in this application, because accidental impurities could cause damages on processors or computers and data or data transfer integrity could be affected.

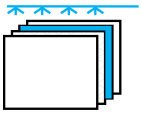
Special applications of laboratory are typical for R-IEC equipment.

5. Construction and flow

The most common construction of IEC equipment is based on plates, this situation being met in 79.5% of the references, with vertical plates representing 46.2% and horizontal plates representing 33.3%.

IEC constructions based on vertical plates are presented in Table 3. These constructions can be realised in a large range of cooling power. The water is distributed by spraying.

Table 3. IEC constructions based on vertical plates and sprayed water

Ref.	Year	First author	Ref.	Year	First author	Ref.	Year	First author	Construction
[16]	1989	Hsu	[27]	2004	Rey Martinez	[11]	2012	Finocchiaro	
[24]	1994	Mathews	[26]	2006	Ren	[33]	2012	Velasco Gomez	
[2]	1998	Alonso	[7]	2010	Delfani	[37]	2012	Xuan	
[12]	1998	Guo	[18]	2011	Kiran	[21]	2013	Liu	
[31]	1998	Stoitchkov	[8]	2012	Duan	[32]	2013	Tejero-Gonzalez	
[22]	2001	Maheshwari							

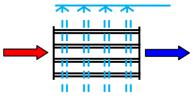
IEC constructions based on horizontal plates are presented in Table 4. In these constructions the water is distributed by atomisation at high pressure with higher efficiency because small water drops can better interact with the air particles in the wet channels, but are also characterised by higher energy consumption with the high pressure water.

Table 4. IEC constructions based on horizontal plates and atomised water

Ref.	Year	First author	Ref.	Year	First author	Construction
[30]	2001	Saman	[8]	2012	Duan	
[13]	2007	Hasan	[15]	2012	Hettiarachchi	
[14]	2010	Hasan	[17]	2012	Khalajzadeh	

IEC based on horizontal tubes are found only in 5.1% of the studied references. The constructions are presented in Table 5.

Table 5. IEC constructions based on horizontal tubes

Ref.	Year	First author	Construction
[3]	1998	Armbruster	
[9]	2011	Dunnavant	
[8]	2012	Duan	
[37]	2012	Xuan	

This construction is characterised by lower intensity of the heat transfer comparing with the heat transfer intensity in plates based equipment.

The R-IEC constructions are based on horizontal plates (presented in Table 6) or vertical plates (presented in Table 7).

Table 6. R-IEC constructions based on horizontal plates

Ref.	Year	First author	Ref.	Year	First author
[16]	1989	Hsu	[14]	2012	Hasan
[13]	2010	Hasan	[19]	2013	Lee
[25]	2011	Miyazaki			

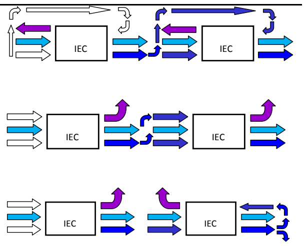
Table 7. R-IEC constructions based on vertical plates

Ref.	Year	First author	Ref.	Year	First author
[2]	1998	Alonso	[21]	2013	Liu
[28]	2010	Riangvilaikul	[35]	2013	Woods
[19]	2013	Lee	[5]	2013	Bruno
[20]	2013	Lee	[4]	2013	Bellemo

The R-IEC equipment is typical for low cooling power, mainly because of the low flow rate of the supply air.

The D-IEC constructions are derived by R-IEC coupled in two or many modules as suggested in Table 8.

Table 8. D-IEC constructions

Ref.	Year	First author	Construction
[13]	2010	Hasan	

The M-IEC constructions are mainly based on horizontal plates as indicated in Table 9, but construction based on vertical plates are also reported as indicated in Table 10.

Table 9. M-IEC flow scheme and construction - Horizontal plates

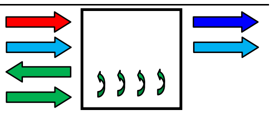
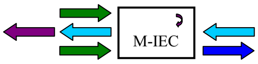
Ref.	Year	First author	Ref.	Year	First author	Construction
[10]	2006	Elberling	[34]	2012	Wani	
[39]	2008	Zhao	[36]	2012	Xuan	
[38]	2011	Zhan	[1]	2013	Ahmad	
[8]	2012	Duan				

Table 10. M-IEC flow scheme and construction - Vertical plates

Ref.	Year	First author	Construction
[39]	2008	Zhao	
[8]	2012	Duan	

Due to the construction complexity the M-IEC equipment are met only at low or average cooling power.

Table 11. IEC Plates geometry

Ref.	First author	Year	Type	Channel height [m]	Channel length [m]	Channel gap [mm]	Material type	Wall thickness [mm]	Fin pitch [mm]	Obs.
[2]	Alonso	1998	Vertical	0.6	0.3	3.0	N/A	N/A	N/A	R-IEC
[12]	Guo	1998	Vertical	N/A	N/A	2...10	N/A	N/A	N/A	IEC
[31]	Stoitchkov	1998	Vertical	N/A	0.4...0.7	3.5	N/A	N/A	N/A	IEC
[30]	Saman	2001	Horizontal	0.6	0.6	3	Polyethylene	0.2	N/A	IEC
[39]	Zhao	2008	Horizontal	0.002…0.01	0.25…3.5	N/A	N/A	<0.5	N/A	M-IEC
[13]	Hasan	2010	Horizontal	0.5	0.5	3.5	N/A	0.5	N/A	R-IEC
[28]	Riangvilaikul	2010	Vertical	0.045	1.2	5	N/A	N/A	N/A	R-IEC
[29]	Riangvilaikul	2010	Vertical	0.08	1.2	5	Polyurethane, Cotton	N/A	N/A	R-IEC
[38]	Zhan	2011	Horizontal	N/A	1.2	4	Fibres; Polyethylene	N/A	N/A	M-IEC
[4]	Bellemo	2013	Vertical	1.5	1.38	3.8/3	Polypropylene	0.25	N/A	R-IEC
[19]	Lee	2013	Multiple cases	1.46 … 3.84	0.2 … 1.83	3.54 … 20	Al; Polypropylene	0.2	N/A	R-IEC
[20]	Lee	2013	Vertical	0.69	0.35	20	Al; Coating 20µm	0.3	1.5	R-IEC
[32]	Tejero-Gonzalez	2013	Vertical	0.18	0.62	4 / 9	Polycarbonate	0.1	N/A	IEC
[35]	Woods	2013	Vertical	0.43	0.56	1.85/2	Polypropylene	0.25	N/A	R-IEC

Geometric elements of IEC tubes are not presented in any references.

It can be observed that less than 36% of the total number of considered references is presenting concrete data concerning materials and geometry of the studied IEC construction. None of the studies related to the horizontal tubes based construction, is presenting geometric characteristics of tubes bundles.

6. Conclusions

Indirect evaporative cooling (IEC) is a promising technology based on complex heat transfer between air on one side and air-water on other side.

The study presents theoretical and practical aspects related with the IEC including: theory, construction principles; flow schemes; working conditions and parameters of performance.

From the geometry point of view, were identified constructions based on horizontal and vertical plates, but also based on horizontal tubes.

The different flow schemes allow the use of outside and inside air both as primary and as secondary air, in applications based on (0…100)% fresh air. It was identified as very common the use of regeneration, consisting in recirculating a part of the cooled primary air, as secondary air, in R-IEC equipment. Many references are dedicated to the study of complex flow M-IEC devices.

Acknowledgements

This study was financially supported by Emerson Network Power, Italy.

References

[1]. Ahmad, A., Rehman, S., Al-Hadhrami, L.M., 2013. Performance evaluation of an indirect evaporative cooler under controlled environmental conditions. Energy and Buildings 62, 278-285. doi: 10.1016/j.enbuild.2013.03.013.

[2]. Alonso, J.F.S.J., Martíez, F.J.R., Gómez, E.V., Plasencia, M.A.A.-G., 1998. Simulation model of an indirect evaporative cooler. Energy and Buildings 29, 23-27. doi: 10.1016/S0378-7788(98)00014-0.

[3]. Armbruster, R., Mitrovic, J., 1998. Evaporative cooling of a falling water film on horizontal tubes. Experimental Thermal and Fluid Science 18, 183-194. doi: 10.1016/S0894-1777(98)10033-X.

[4]. Bellemo, L., Elmegaard, B., Reinholdt, L.O., Kaern, M.R, 2013. Modeling of a regenerative indirect evaporative cooler for a desiccant cooling system. 4th IIR Conference Thermophysical Properties and Transfer Processes of Refrigerants, Delft, The Netherlands 9. http://orbit.dtu.dk/files/56233310/MODELING_OF_A_REGENERATIVE.pdf [accessed 14.11.2013].

[5]. Bruno, F., 2011. On-site experimental testing of a novel dew point evaporative cooler. Energy and Buildings 43, 3475-3483. doi: 10.1016/j.enbuild.2011.09.013.

[6]. Caliskan, H., Hepbasli, A., Dincer, I., Maisotsenko, V., 2011. Thermodynamic performance assessment of a novel air cooling cycle. International Journal of Refrigeration 34, 980-990. doi: 10.1016/j.ijrefrig.2011.02.001.

[7]. Delfani, S., Esmaeelian, J., Pasdarshahri, H., Karami, M., 2010. Energy saving potential of an indirect evaporative cooler as a pre-cooling unit for mechanical cooling systems in Iran. Energy and Buildings 42, 2169-2176. doi: 10.1016/j.enbuild.2010.07.009.

[8]. Duan, Z., Zhan, C., Zhang, X., Mustafa, M., Zhao, X., Alimohammadisagvand, B., Hasan, A., 2012. Indirect evaporative cooling: Past, present and future potentials. Renewable and Sustainable Energy Reviews 16, 6823-6850. doi: 10.1016/j.rser.2012.07.007.

[9]. Dunnavant, K., 2011. Data Center Heat Rejection. ASHRAE Journal 53, 44-54.

[10].Elberling, L., 2006. Laboratory Evaluation of the Coolerado Cooler-Indirect Evaporative Cooling Unit. Pacific Gas and Electric Company.

[11].http://www.etcc-ca.com/sites/default/files/OLD/images/stories/pdf/ETCC_Report_304.pdf [accessed 14.11.2013].

[12].Finocchiaro, P., Beccali, M., Nocke, B., 2012. Advanced solar assisted desiccant and evaporative cooling system equipped with wet heat exchangers. Solar Energy 86, 608-618. doi: 10.1016/j.solener.2011.11.003.

[13].Guo, X.C., Zhao, T.S., 1998. A parametric study of an indirect evaporative air cooler. International Communications in Heat and Mass Transfer 25, 217-226. doi: 10.1016/S0735-1933(98)00008-6.

[14].Hasan, A., 2010. Indirect evaporative cooling of air to a sub-wet bulb temperature. Applied Thermal Engineering 30, 2460-2468. doi: 10.1016/j.applthermaleng.2010.06.017.

[15].Hasan, A., 2012. Going below the wet-bulb temperature by indirect evaporative cooling: Analysis using a modified ε–NTU method. Applied Energy 89, 237-245. doi: 10.1016/j.apenergy.2011.07.005.

[16].Hettiarachchi, H.D.M., Golubovic, M., Worek, W.M., 2007. The effect of longitudinal heat conduction in cross flow indirect evaporative air coolers. Applied Thermal Engineering 27, 1841-1848. doi: 10.1016/j.applthermaleng.2007.01.014.

[17].Hsu, S.T., Lavan, Z., Worek, W.M., 1989. Optimization of wet-surface heat exchanger. Energy 14, 757-770. doi: 10.1016/0360-5442(89)90009-1.

[18].Khalajzadeh, V., Farmahini-Farahani, M., Heidarinejad, G., 2012. A novel integrated system of ground heat exchanger and indirect evaporative cooler. Energy and Buildings 49, 604-610. doi: 10.1016/j.enbuild.2012.03.009.

[19].Kiran, T.R., Rajput, S.P.S., 2011. An effectiveness model for an indirect evaporative cooling (IEC) system: Comparison of artificial neural networks (ANN), adaptive neuro-fuzzy inference system (ANFIS) and fuzzy inference system (FIS) approach. Applied Soft Computing Journal 11, 3525-3533. doi: 10.1016/j.asoc.2011.01.025.

[20].Lee, J., Choi, B., Lee, D.-Y., 2013. Comparison of configurations for a compact regenerative evaporative cooler. International Journal of Heat and Mass Transfer 65, 192-198. doi: 10.1016/j.ijheatmasstransfer.2013.05.068.

[21].Lee, J., Lee, D.-Y., 2013. Experimental study of a counter flow regenerative evaporative cooler with finned channels. International Journal of Heat and Mass Transfer 65, 173-179. doi: 10.1016/j.ijheatmasstransfer.2013.05.069.

[22].Liu, Z., Allen, W., Modera, M., 2013. Simplified thermal modeling of indirect evaporative heat exchangers. HVAC and R Research 19, 257-267. doi: 10.1080/10789669.2013.763653.

[23].Maheshwari, G.P., Al-Ragom, F., Suri, R.K., 2001. Energy-saving potential of an indirect evaporative cooler. Applied Energy 69, 69-76. doi: 10.1016/S0306-2619(00)00066-0.

[24].Maisotsenko, V., Gillan, L.E., Heaton, T.L., Gillan, A.D., 2002. Method and apparatus of indirect-evaporation cooling. US6497107 B2 Patent.

[25].Mathews, E.H., Kleingeld, M., Grobler, L.J., 1994. Integrated simulation of buildings and evaporative cooling systems. Industrial and Engineering Chemistry Research 33, 197-206. doi: 10.1016/0360-1323(94)90070-1.

[26].Miyazaki, T., Akisawa, A., Nikai, I., 2011. The cooling performance of a building integrated evaporative cooling system driven by solar energy. Energy and Buildings 43, 2211-2218. doi: 10.1016/j.enbuild.2011.05.004.

[27].Ren, C., Yang, H., 2006. An analytical model for the heat and mass transfer processes in indirect evaporative cooling with parallel/counter flow configurations. International Journal of Heat and Mass Transfer 49, 617-627. doi: 10.1016/j.ijheatmasstransfer.2005.08.019.

[28].Rey Martinez, F.J., Velasco Gomez, E., Herrero Martin, R., Martinez Gutierrez, J., Varela Diez, F., 2004. Comparative study of two different evaporative systems: an evaporative cooler and a semi-indirect evaporative cooler. Energy and Buildings 36, 696-708. doi: 10.1016/j.enbuild.2003.10.010.

[29].Riangvilaikul, B., Kumar, S., 2010. Numerical study of a novel dew point evaporative cooling system. Energy and Buildings 42, 2241-2250. doi: 10.1016/j.enbuild.2010.07.020.

[30].Riangvilaikul, B., Kumar, S., 2010. An experimental study of a novel dew point evaporative cooling system. Energy and Buildings 42, 637-644. doi: 10.1016/j.enbuild.2009.10.034.

[31].Saman, W.Y., Alizadeh, S., 2001. Modelling and performance analysis of a cross-flow type plate heat exchanger for dehumidification/cooling. Solar Energy 70, 361-372. doi: 10.1016/S0038-092X(00)00148-1.

[32].Stoitchkov, N.J., Dimitrov, G.I., 1998. Effectiveness of crossflow plate heat exchanger for indirect evaporative cooling. International Journal of Refrigeration 21, 463-471. doi: 10.1016/S0140-7007(98)00004-8.

[33].Tejero-Gonzalez, A., Andres-Chicote, M., Velasco-Gomez, E., Rey-Martinez, F.J., 2013. Influence of constructive parameters on the performance of two indirect evaporative cooler prototypes. Applied Thermal Engineering 51, 1017-1025. doi: 10.1016/j.applthermaleng.2012.10.054.

[34].Velasco Gómez, E., Tejero González, A., Rey Martínez, F.J., 2012. Experimental characterisation of an indirect evaporative cooling prototype in two operating modes. Applied Energy 97, 340-346. doi: 10.1016/j.apenergy.2011.12.065.

[35].Wani, C., Ghodke, S., Shrivastava, C., 2012. A Review on Potential of Maisotsenko Cycle in Energy Saving Applications Using Evaporative Cooling. International Journal of Advance Research in Science, Engineering and Technology 1, 15-20.

[36].http://www.coolerado.com/pdfs/M-CycleCoolingIndiaArticle.pdf [accessed 14.11.2013].

[37].Woods, J., Kozubal, E., 2013. A desiccant-enhanced evaporative air conditioner: Numerical model and experiments. Energy Conversion and Management 65, 208-220. doi: 10.1016/j.enconman.2012.08.007.

[38].Xuan, Y.M., Xiao, F., Niu, X.F., Huang, X., Wang, S.W., 2012. Research and application of evaporative cooling in China: A review (I) – Research. Renewable and Sustainable Energy Reviews 16, 3535-3546. doi: 10.1016/j.rser.2012.01.052.

[39].Xuan, Y.M., Xiao, F., Niu, X.F., Huang, X., Wang, S.W., 2012. Research and applications of evaporative cooling in China: A review (II) - Systems and equipment. Renewable and Sustainable Energy Reviews 16, 3523-3534. doi: 10.1016/j.rser.2012.02.030.