A Detail Review of an Indirect Evaporative Cooling System Using M – Cycle

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Abstract— A large part of the world's energy is consumed by ventilation and air-conditioning. One of the most energy-intensive processes in the ventilation and air-conditioning is the process of air cooling. Traditional systems based on the compressor cycle consume a lot of energy. Refrigerants contained in compressor circuits are often very harmful to the environment. These factors led to the active development of evaporative coolers. And the former soviet scientist Valery Maisotsenko improved evaporative cooling technology and called the resulting cycle as Maisotsenko-cycle. Direct evaporative cooling is associated with the increased humidity though it gives a fair drop in temperature. On the other hand, humidity is controlled by the indirect evaporative cooling but the temperature drop is not sufficient. Both the systems are coupled in Maisotsenko cycle to form a new system. Opportunities for energy saving will be provided if this newly formed system is utilized properly. After reviewing the various literature in the field of evaporative cooling, scope of Maisotsenko cycle in energy saving applications is discussed. Maisotsenko Cycle find a multiclimate application like dry and humid like India.

Key words: Dew point cooling, Effectiveness, Evaporative Cooling, Maisotsenko Cycle.

I. INTRODUCTION

The conventional evaporative cooling system (e.g. water cooler) is used for the cooling purposes in the dry and hot regions. This type of system gives the sufficient cooling, but the increased humidity of the air gives the feeling of discomfort. The other way to overcome the problem of increased humidity is use of indirect evaporative cooling system. This system though handles the humidity properly, but the cooling obtained with the said system is less. On the other hand, vapour compression refrigeration systems consume more electricity and some of the systems carry the potential to pollute the environment. Also cost of such systems is on the higher side. In this context, a new system which uses the advantageous aspect of both the evaporative cooling system and minimises the drawbacks has been put forward by Valeriy Maisotsenko. He developed a new thermodynamic cycle known as "Maisotsenko Cycle". It is also called as the "M-cycle" which uses the simple cross flow heat exchanger and indirect evaporative coolers, but with a much different airflow.

II. EVAPORATIVE COOLING SYSTEM

A. *Direct Evaporative Cooling (Dec):*

Direct evaporative cooling adds moisture to the process air. The working diagram of direct evaporative cooling and the working process representing on the psychrometric chart are shown in Fig. 1.

Evaporative coolers have been used to lower the temperature of air by using the latent heat of evaporation; changing water to vapor. In this process, the energy in the air does not change. Warm dry air is changed to cool moist air. Heat in the air is used to evaporate water; no heat is added or removed making it an adiabatic process (Fan heat gain or pump energy is ignored in this evaluation.) This also assumes the water entering the system is to be evaporated at the wet bulb temperature of the entering air, and that there is no excess water. Therefore the water has a negligible effect on the adiabatic process.

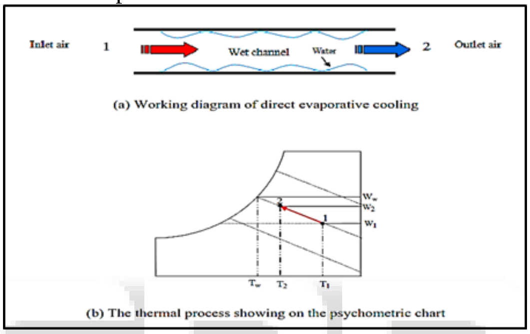

Fig. 1: Working diagram of (a) direct evaporative cooling and (b) thermal process showing on the psychometric chart [19]

B. *Indirect Evaporative Cooling (IEC):*

Indirect Evaporative Cooling (IEC) systems can lower air temperature without adding moisture into the air, making them the more attractive option over the direct ones. In an indirect evaporative air cooling system, the primary (product) air passes over the dry side of a plate, and these working air passes over the opposite wet side. The wet side air absorbs heat from the dry side air with aid of water evaporation on the wet surface of the plate and thus cools the dry side air; while the latent heat of the vaporized water is transmitted into the working air in the wet side. Fig. 2 presents the working principle and psychometric illustration of the air treatment process relating to an indirect evaporative cooling operation.

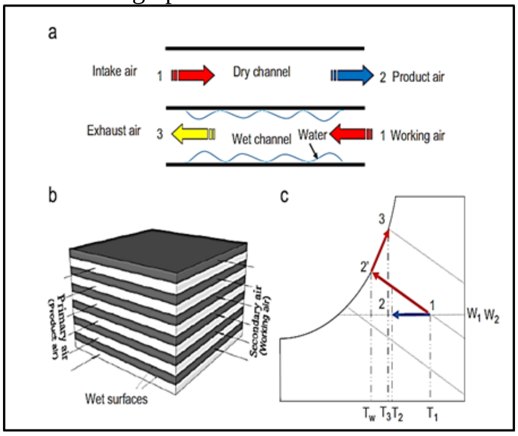

Fig. 2: Conventional IEC heat and mass exchanger. (a) Working principle of the indirect evaporative cooling, (b) Configuration of the type IEC heat and mass exchanger and (c) Psychrometric illustration of the air treatment process in the IEC heat and mass exchanger [1]

III. M-CYCLE IEC SYSTEMS

To enhance cooling performance of the IEC heat exchanger, a novel thermodynamic cycle, known as the M-cycle, was proposed by Professor Valeriy Maisotenko as the new approach of making and operating a heat exchanger. This cycle was claimed to enable harnessing extra amount of energy from the ambient using a dedicated flat plate, cross-flow and perforated heat exchanger, as shown schematically in Fig. 3 and 4.

During operation, all part of air is initially brought into the dry channels of the heat exchanger, and cooled when moving along the flow path owing to the established temperature difference between the dry and wet side of the exchanger plates. When passing across the perforated holes, part of the air, known as the 'working (or secondary) air', is diverted into the adjacent wet channels. Within the wet channels, the air travels in normal direction to the dry channel air, taking away the evaporated water from the saturated wet surface of the plate and receiving the sensible heat transferred across the plate. As a result, the working (secondary) air is gradually saturated and heated when travelling across the flow paths, and finally discharged to ambient, leading to the state change from point3', 3'' to 3. Meanwhile, the remaining air in the dry channel continues to move forward and at the end of its flow path, is cooled to a state below its relative wet bulb and close to its dew point.

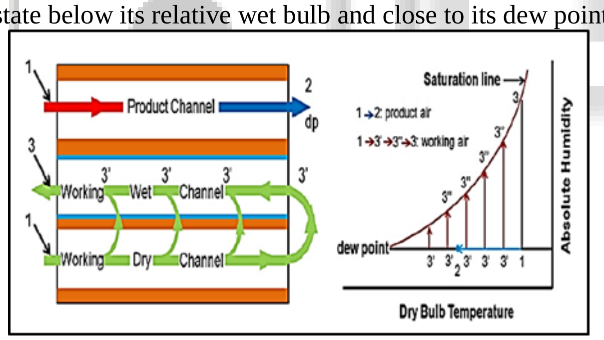

Fig. 3: Principle of the heat and mass exchanger based on M- cycle and its representation on psychrometric chart [1]

Compared to the conventional IEC heat exchanger, this M-cycle exchanger will produce a much colder air flow to be delivered to the room space, thus generating the increased cooling output. Due to its potential in reaching the dew point of the product air, the approach is also known as 'dew point (M-cycle) cooling'. A test indicated that the M-cycle based heat exchanger could obtain a wet bulb effectiveness of 81–91% and dew point effectiveness of 50–60%, which is 10–30% higher than that of the conventional IEC heat exchangers.

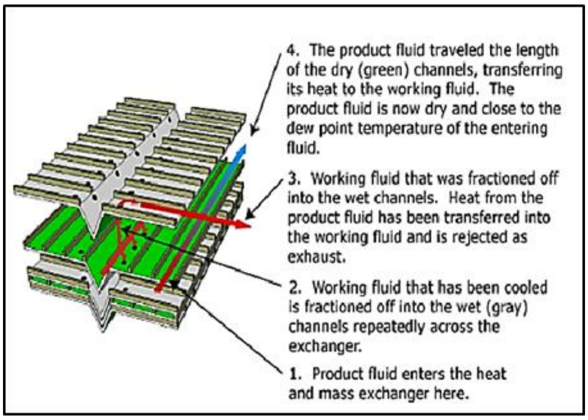

Fig. 4: Schematic of a heat and mass exchange module based on M-cycle [19]

To further enhance the cooling effectiveness of the IEC systems, a M-cycle counter-flow heat exchanger was recently developed. The structure and operation of this type of exchanger is shown schematically in Fig. 5. Unlike the M-cycle cross-flow exchanger that has the perforated holes widely spreading across the flow paths, the new exchanger positions those holes to the end of the flow channels (end side of the exchanging sheet). During operation, both the product and working air are directed into the dry channels, losing heat to the adjacent wet channels and at the end of each channel, all parts of air are cooled to a level approaching the inlet air's dew point. At this end, part of the air (product air) is delivered to the building space and the remaining air (working air) is diverted to the adjacent wet channels, where it travels on an opposite direction to the dry channel air.

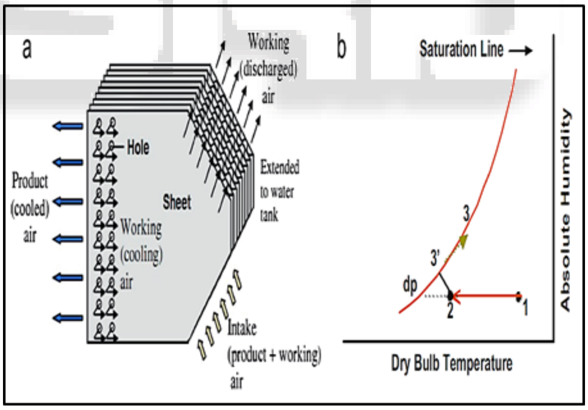

Fig. 5: Structure and operation of the M-cycle counter-flow heat exchanger for indirect evaporative cooling. (a)Structure illustration and (b) air treatment process—psychometric [1]

Compared to the cross-flow heat exchanger, the M-cycle counter-flow heat exchanger was found several advantages: (1) the working air travels to the end of the dry channels and therefore could be fully cooled, leading to increased temperature difference and heat transfer between the two air streams, and (2) counter-air- flow pattern could be created to enable enhanced heat transfer between the product and working air streams. Both simulation and experiments indicated that the M-cycle counter-flow exchanger offered greater (around 20% higher) cooling capacity, and greater (15–23% higher) dew-point and wet-bulb effectiveness than the M-cycle cross-flow exchanger of the same physical size and under the same operating conditions.

IV. LITERATURE REVIEW

This chapter can be broadly classified under two categories. The first part of the survey deals with analytical and numerical studies. The second part of the survey deals with the experimental studies.

A. Analytical & Numerical Studies:

Zhiyin Duan, et al,[1] presented Indirect evaporative cooling: past, present and future. This paper reported a review based study into the Indirect Evaporative Cooling (IEC) technology which indicated that the IEC technology has potential to be an alternative to conventional mechanical vapour compression refrigeration systems to take up the air conditioning duty for buildings. Due to the continuous progress in technology innovation, particularly the M-cycle development and associated heat and mass transfer and material optimisation, the IEC systems have obtained significantly enhanced cooling performance with the wet-bulb effectiveness of greater than 90% and energy efficiency ratio (EER) up to 80. Structure of the IEC heat and mass exchanger varied from flat-plate-stack, tube, heat pipe and potentially wave-form. Materials used for making the exchanger elements (plate/tube) included fibre sheet with the single side water proofing, aluminium plate/tube with single side wicked setting (grooved, meshed, toughed etc), and ceramic plate/tube with single side water proofing. Counter-current water flow relevant to the primary air is considered the best choice.

Chandrakant wani, et al.,[2] presented A Review on Potential of Maisotsenko Cycle in Energy Saving Applications Using Evaporative Cooling. The limitations of the conventional vapor compression system are overcome by the use of Maisotsenko Cycle. Direct evaporative cooling is associated with the increased humidity though it gives a fair drop in temperature. While, humidity is controlled by the indirect evaporative cooling but the temperature drop is not sufficient. Both the systems are coupled in Maisotsenko cycle to form a new efficient system. Also, tendency of conventional refrigerants to create pollution is vomited as the said system uses water as a cooling agent. For the better performance, use of different cooling pad materials is also suggested. Systems using Maisotsenko Cycle find the application in a multi climate means dry and humid country like India.

X. Cui, et al.,[3] presented Numerical simulation of a novel energy-efficient dew-point evaporative air cooler. Novel dew-point evaporative air conditioner which was designed based on a counter-flow closed-loop configuration consisting of separated working channels and product channels. ANSY FLUENT was employed to predict heat and mass transfer process in evaporative cooler. For investigate the performance of the evaporative air cooler under a variety of conditions, the Eulerian–Lagrangian computational fluid dynamics (CFD) model was adopted. Simulation results have indicated that the novel dew-point evaporative air conditioner is able to achieve a higher wet-bulb and dew-point effectiveness with lower air velocity, smaller channel height, larger length-to-height ratio, and lower product-to-working air flow ratio. The mesh for computational domain was created using Gambit. The finite volume method is employed to discretize the governing equations. The simple algorithm is used to couple the pressure and velocity.

Sergey Anisimov, et al.,[4] presented Numerical study of the Maisotsenko cycle heat and mass exchanger. Cross flow finned surface heat and mass exchanger (HMX) based on Maisotsenko cycle is used for indirect evaporative cooling. For this purpose numerical model is developed based on the modified Ɛ-NTU method to perform thermal calculations of the indirect evaporative cooling process, thus quantifying overall heat exchanger performance. From analysis, heat and mass transfer performance strongly depends on inlet air temperature and humidity, geometrical size of the channels, type of plate-fin surface, uniformity of water distribution, intake air velocity, secondary to primary air mass flow ratio, but depends less on the conductive conductance through the fin. Heat exchanger can be relatively long in the direction of product air flow, while its length in the direction of secondary air flow should not become excessive and The primary to secondary air flow rate ratio should be close to 1, while velocity values in channels should remain relatively low.

X. Cui, et al.,[5] presented the performance of an improved dew-point evaporative design for cooling application. The novel dew-point evaporative air cooler, based on a counter-flow closed-loop configuration, is able to cool air to temperature below ambient wet bulb temperature and approaching dew-point temperature. ANSYS FLUENT 14.0 was employed to predict the heat and mass transfer process in evaporative cooler. For investigate the performance of the evaporative air cooler under a variety of conditions, the Eulerian–Lagrangian computational fluid dynamics (CFD) model was adopted. The main air flow was treated as a continuum by solving Naviere Stokes equations (Eulerian approach) and the water droplets were solved as a discrete phase using the Lagrangian approach. Simulation results showed that the wet bulb effectiveness ranged from 122% to 132% while dew-point effectiveness spanned 81% - 93%.

Ala Hasan,[6] presented Going below the wet-bulb temperature by indirect evaporative cooling: Analysis using a modified Ɛ-NTU method. An analytical model is developed based on the effectiveness-NTU method (Ɛ-NTU) for sensible heat exchangers. For achieving a sub-wet bulb temperature by indirect evaporative cooling of air is by indirectly pre-cooling the working air before it enters the wet passage. This modified model is used to find the performance of a regenerative indirect evaporative cooler. The model results show very good agreement with results from experimental measurements and a numerical model.

Changhong Zhan, et al.,[7] presented Numerical study of a M-cycle cross-flow heat exchanger for indirect evaporative cooling. The numerical model was established for heat and mass transfer between the product and working air, using the finite-element method. The model was developed using the EES (Engineering Equation Solver). The air flow and exchanger parameters were analysed and suggested in terms of cooling effectiveness and system COP. It is found that lower channel air velocity, lower inlet air relative humidity, and higher working-to-product air ratio yielded higher cooling effectiveness. The recommended average air velocities in dry and wet channels should not be greater than 1.77 m/s and 0.7 m/s, respectively. The optimum flow ratio of working-to-product air for this cooler is 50%. Longer channel length and smaller channel height contribute to increase of the system cooling effectiveness but lead to reduced system COP.The recommend channel height is 4 mm and the dimensionless channel length, i.e., ratio of the channel length to height, should be in the range 100 to 300. Numerical study results indicated that this new type of M-cycle heat and mass exchanger can achieve 16.7% higher cooling effectiveness compared with the conventional cross-flow heat and mass exchanger for the indirect evaporative cooler.

B. Riangvilaikul, et al.,[8] presented Numerical study of a novel dew point evaporative cooling system. He performed numerical study for counter flow regenerative IEC. Here, the governing equations were solved by employing finite differential approach and newton iterative method to obtain temperature and humidity values of the air across the whole channel space. They analysed the effect of various parameters on the effectiveness of the exchanger such as inlet air conditioning, air velocity, channel gap, channel length, extraction ratio. The heat exchanger was able to achieve dew point effectiveness from 58 to 84 % and wet bulb effectiveness from 92 to 114%.

Emmanuel D. Rogdakis, et al.,[9] presented An Energy Evaluation of a Maisotsenko Evaporative Cooler Based on Cylinder Geometry. M-cycle based systems are generally constructed by using a plate heat and mass exchanger considered to be capable of cooling building rooms keeping the humidity ratio constant, as they work as indirect evaporative coolers. Using a smart network of air channels, a wet bulb efficiency of about 120% is achieved. The efficiency of the proposed system has been estimated to be about 105%, while the product air temperatures satisfy the cooling demands of buildings at regions of low relative humidity (specifically, the proposed geometry simulating Athens downtown environmental conditions). The simulation results have shown that such geometries are of lower water consumption than of standard plate geometry, while they produce fresh air at about 21°C and consume less than 2 kg of water per cooling kWh.

Leland Gillan,[10] presented Maisotsenko cycle for cooling processes. The Maisotsenko Cooling cycle combines the thermodynamic processes of heat exchange and evaporative cooling in a unique indirect evaporative cooler resulting in product temperatures that approach the dew point temperature (not the wet bulb temperature) of the working gas. This cycle utilizes the enthalpy difference of a gas, such as air, at its dew point temperature and the same gas saturated at a higher temperature. This enthalpy difference or potential energy is used to reject the heat from the product. Here the cooling gas to be air and the liquid to be water; the Maisotsenko Cycle allows the product fluid to be cooled in temperature ideally to the dew point temperature of the incoming air. This is due to the precooling of the air before passing it into the heat rejection stream where water is evaporated. Here, the product fluid is air. When exhausted, the heat rejection air stream or exhaust air is saturated and has a temperature less than the incoming air, but greater than the wet bulb temperature. This cycle is realized in a single apparatus with a much higher heat flux and lower pressure drop than has been realizable in the past due to its efficient design.

M. Shariaty-Niassar, et al.,[11] presented An Investigation of Indirect Evaporative Coolers, IEC With Respect to Thermal Comfort Criteria. The effects of air stream direction in the channels of indirect evaporative cooler (IEC) on system performance have been investigated. In addition, the dependence of system performance on outdoor air temperature and relative humidity has been studied to determine the allowable conditions for proper operation of the system, with respect to thermal comfort criteria. For this; the different types of IECs were investigated using the CFD technique. Several codes were defined in MATLAB for modeling the parallel flow, counter flow and cross flow layout. The CFD program was validated against theoretical data from the literature and good agreement between the prediction and measurement was achieved. The calculated results show that when the air relative humidity is lower than 70%, the system can prepare a good indoor condition even at 50°C, and a higher performance is achieved by using the IEC with counter current configuration. The results showed that IECs can be successfully used in hot and humid climates to fulfill the indoor thermal comfort conditions.

B. Experimental Studies:

M. Jradi, et al.,[12] presented Experimental and numerical investigation of a dew-point cooling system for thermal comfort in buildings. A numerical analysis is carried out for a modified dew point cooling system based on a proposed psychrometric energy core (PEC) with a cross-flow heat and mass exchanger for buildings air-conditioning applications. A detailed numerical model was developed for the energy core with the cross-flow exchanger using Matlab. The coupled heat and mass transfer equations were solved using 2nd order fully implicit accurate finite difference scheme to predict air temperature and humidity distribution throughout the dry and wet channels with newton raphson method. With an intake air of 30°C temperature and 50% relative humidity and a working-to-intake air flow ratio of 0.33, the system attained a wet bulb effectiveness of 112% and a dew point effectiveness of 78% with 5 mm channel height and 500 mm channel length. In addition, an experimental setup was built and a dew-point cooler with a cross-flow heat and mass exchanger was tested to assess the feasibility of using such dew point cooling systems under various operational and ambient conditions.

Emmanuel D. Rogdakis, et al.,[13] presented Experimental an computational evaluation of a Maisotsenko evaporative cooler at Greek climate. In order to determine the efficiency and consumption of an evaporative cooler, which follows the Maisotsenko cycle, an experimental installation was constructed, able to provide multiple options of inlet conditions and supported by measurement systems. The degree to which it is possible to achieve the nominal efficiency levels as well as the effect of the ambient conditions on water consumption were examined, and it was discovered that under different conditions and in the optimization mode, the efficiency levels vary between 97% and 115%, while water consumption varies between 2.5 kgwkWhc−1 and 3.0 kgwkWhc−1. The experimental procedure and the measurement processing are analyzed in detail and finally, it is ascertained that Maisotsenko cycle based coolers can satisfy the cooling demand with high efficiency in the hot and arid Mediterranean climate.

Joohyun Lee, et al.,[14] presented Experimental study of a counter flow regenerative evaporative cooler with finned channels. A regenerative evaporative cooler has been fabricated and tested for the performance evaluation The air flowing through the dry channels is cooled without any change in the humidity and at the outlet of the dry channel a part of air is redirected to the wet channel where the evaporative cooling takes place. The regenerative evaporative cooler fabricated consists of the multiple pairs of finned channels in counter flow arrangement. The fins and heat transfer plates were made of aluminum and brazed for good thermal connection. Thin porous layer coating was applied to the internal surface of the wet channel to improve surface wettability. The cooling performance is found greatly influenced by the evaporative water flow rate. To improve the cooling performance, the evaporative water flow rate needs to be minimized as far as the even distribution of the evaporative water is secured. At the inlet condition of 32°C and 50% RH, the outlet temperature was measured at 22°C which is well below the inlet wet-bulb temperature of 23.7°C.

Aftab Ahmad, et al.,[15] presented Performance evaluation of an indirect evaporative cooler under controlled environmental conditions. The study investigated the performance of a 5-ton capacity indirect evaporative cooler under controlled environmental conditions (43.9°C dry-bulb temperature and 19.9% relative humidity) but for different air flow rates (631 to 2388 m3/h). The experimental results showed that the intake air energy efficiency ratio of the cooler varied from 7.1 to 55.1 depending on test conditions and air flow rate. The power consumption of indirect evaporative cooler was found to vary from 68.3 to 746 watts. Water consumption was found to vary between 0.0160 and 0.0598 m3/h. At full fan speed, an average of 58.7% of the total water consumed by indirect evaporative cooler was evaporated. The results indicated that intake air energy efficiency ratio was directly proportional to the wet-bulb depression. The study also showed that the indirect evaporative cooler is suitable for hot and dry climatic conditions.

Frank Bruno,[16] presented On-site experimental testing of a novel dew point evaporative cooler installed in both commercial and residential application. The systems use a counter flow regenerative plat heat exchanger. The paper presents results obtained from testing a prototype cooler installed in both a commercial and residential application in a wide range of ambient conditions. Cooler can produce supply air at a temperature as low as it provided by conventional mechanical VCR if the cooler operates at high efficiency. When outside weather conditions were hot and dry, the cooling effectiveness of the cooler would increase. It was shows that ,by comparing with mechanical VCR, the annual energy saving by using the evaporative cooler was between 50 to 56 %. The cooler in commercial application, average WB effectiveness was 106% and in residential application 124 %.

B. Naticchia, et al.,[17] presented Energy performance evaluation of a novel evaporative cooling technique. A preliminary experimental evaluation of the energy performance of a new technology which is capable of canceling conduction gains through walls: “water-evaporative walls”, which are not only able to prevent the entrance of energy fluxes from the exterior to the interior, but also to reduce wall temperatures to below the values found indoors. This solution basically suggests equipping standard ventilated facades with a proper water-evaporative system, which exploits the latent heat of water evaporation, in order to absorb summer cooling loads. From the technological point of view, it requires the insertion of a water spraying system and a proper insulating layer in the ventilated air chamber. The insulation will act not only as a standard insulating material, but also as a porous surface to store water sprayed by the system and then gradually release it when needed for cooling. The experimental analyses showed the effectiveness of this technology, which decreases the overall summer energy load in buildings by canceling conduction loads.

B. Riangvilaikul, et al.,[18] presented An experimental study of a novel dew point evaporative cooling system. Counter flow regenerative heat and mass exchanger employed in a novel dew point evaporative cooling system for sensible cooling of the ventilation air for air conditioning application. The results showed that wet bulb effectiveness ranged between 92 and 114% and the dew point effectiveness between 58 and 84%. A continuous operation of the system during a typical day of summer season in a hot and humid climate showed that wet bulb and dew point effectiveness were almost constant at about 102 and 76%, respectively.

	X. Cui, et al.,[5]	Zhan et al. [9]	B.Riangvilaikul et al. [10,21]	Lee and Lee [17]
Study method	Simulation	Simulation	Simulation, Experiment	Experiment
Type of the cooler	Plate heat exchanger	Plate heat exchanger	Plate heat exchanger	Plate heat exchanger
Flow arrangement	Counter flow; product air and working air are separated	Cross flow; one inlet for both the product air and the working air	Counter flow; working air is part of the product air	Counter flow; working air is part of the product air
Product channel height	3–20 mm	5 mm	5 mm	20 mm
Working channel height	1.5–10 mm	5 mm	5 mm	10 mm
Channel length	300–1500 mm	1000 mm	1200 mm	200 mm
Inlet air temperature	25–35 °C	28 °C	25–45 °C	27.5–32 °C
Inlet air humidity ratio	8–12 g/kg	11.35 g/kg	7–26 g/kg	9.19–18.11 g/kg
Inlet air velocity	0.3–4.0 m/s	1 m/s	2.4 m/s	1 m/s
Wet bulb effectiveness	1.22 - 1.32	1.16	0.92 - 1.14	1.18–1.22
Dew point effectiveness	0.81 - 0.93	0.81	0.58 - 0.84	0.75–0.9

V. CONCLUSION

From this study, concludes that a new dew point indirect evaporative cooler for buildings which consumes very little energy for the system operation and the constraints set by the conventional vapor compression system are overcome by the use of Maisotsenko Cycle. Also, Pollution is vomited as the uses water as a cooling agent. The counter-flow exchanger offered greater (around 20% higher) cool- ing capacity, greater (15–23% higher) dew-point and wet-bulb effectiveness, and lower (around 90%) energy efficiency than the equivalent cross-flow heat exchanger. So, development would allow consumption of fossil fuels in cooling buildings to be reduced substantially or avoided.

A. *Energy Saving Application:*

Evaporative cooling M-cycle cools down the product air without any rise in humidity. This principle of M-cycle can find a very vital role in many applications of cooling. It may be directly or indirectly. This includes air conditioning, water cooler, some turbines, heat exchangers, etc.

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