A Review onPotential of Novel Energy-Efficient Dew-Point Evaporative Air Cooling System

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***Abstract*—Heating, Ventilation and Air Conditioning (HVAC) sector is responsible for consumption of most of the energy of the world. Main reason for the energy consumption in the cooling sector is reliability on conventional mechanical air conditioning system which consist of compressor, a high energy consuming device. Also, conventional mechanical air conditioning system uses refrigerant as working media, which if leaks will be harmful for the surrounding environment and humans. To overcome theselacking, evaporative cooling system is the suitable substitute. Direct evaporative cooling system cause fair drop in the temperature of air but at the same time it rises the humidity of the air, which is not desirable for human health. Whereas indirect evaporative cooling control the humidity rises but fails to drop temperature of air sufficiently. To utilize the advantages of both direct and indirect evaporative cooling Prof. ValeriyMaisotsenko introduced Maisotsenko Cycle (also called as M-Cycle). After reviewing the various literatures in the field of evaporative cooling it is found that wet bulb effectiveness greater than 100% could be achieved using M-Cycle also it approaches to dew-point temperature of inlet air. Counter flow configuration is more suitable than cross flow configuration. Aluminium dominates other materials in the construction of heat exchanger. M-Cycle has potential to substitute conventional mechanical air conditioning systems in many part of world where hot and dry climatic conditions prevail.**

***IndexTerms*—Dew point cooling, Maisotsenko Cycle, Indirect Evaporative cooling, Effectiveness**

Introduction

Cooling energy is one of the most important part of the energy required in buildings. Building sector consumes around 30 to 40% of the world's total energy. In the building sector, HVAC consumes around 50% of the total supplied energy. Main equipment in HVAC i.e. Air Conditioning System, is responsible for high energy consumption as it consists of compressor, high energy consuming device. Conventional mechanical air conditioning system is not only responsible for high energy consumption but also plays a vital role in raising global carbon emission. It is very much needed to seek way to reduce fossil fuel consumption and to utilize renewable energy sources. Because of this, evaporative cooling comes into picture. Direct evaporative cooling keeps air in direct contact with water and gives a fair drop in air temperature but at the same time it rises the humidity of the air, which is not always desirable. To overcome the drawbacks of direct evaporative cooling, indirect evaporative cooling is introduced, where the primary air (dry air) and the secondary air (moist air) are separated in heat and mass exchanger to gain a drop-in temperature of air without any rise in humidity. Although the humidity of air is controlled in indirect evaporative cooling the drop-in temperature of air is very less. In this context, a new thermodynamic cycle called as M-Cycle was developed by Professor ValeriyMaisotsenko to use the advantageous aspects of both cycle. This paper reviews the potential of M-Cycle, also known as Dew point evaporative cooler that can substitute conventional mechanical air conditioning system.

I. Evaporative Cooling

Evaporative cooling is one of the oldest methods used to cool the air, ancient Egyptians are the first who took advantage of evaporative cooling. Principle of evaporative cooling is used in evaporative coolers to reduce the temperature of air. It is the addition of water vapor into air resulting drop in temperature of air. The energy needed to evaporate the water is taken from the air in the form of sensible heat, which effects the temperature of the air, and converted into latent heat, the energy present in the water vapor component of the air, whilst the air remains at a constant enthalpy value. This conversion of sensible heat to latent heat is known as an adiabatic process because it occurs at a constant enthalpy value.Evaporative cooling therefore causes a drop-in temperature of air proportional to the sensible heat drop and an increase in humidity proportional to the latent heat gain.

A. Direct Evaporative Cooling (DEC)

In direct evaporating cooling system, evaporation of water take place by gaining the heat from the air as both air and water are kept in direct contact with each other and gives out cooling effect. As the evaporation takes place humidity is added into the air which is to be introduced as product air. Here the energy in the air does not change. Only transformation which takes place is conversion of warm dry air to cool moist air.Most common example of direct evaporative cooling are the evaporative coolers or desert coolers. Here the pad of DEC is kept wet by spraying water to it. Recirculation pump is used to circulate gravity driven water to water sump. Hot and dry air with high velocity is drawn into the wetted pad by the fan and at outlet cool and moist air is obtained.

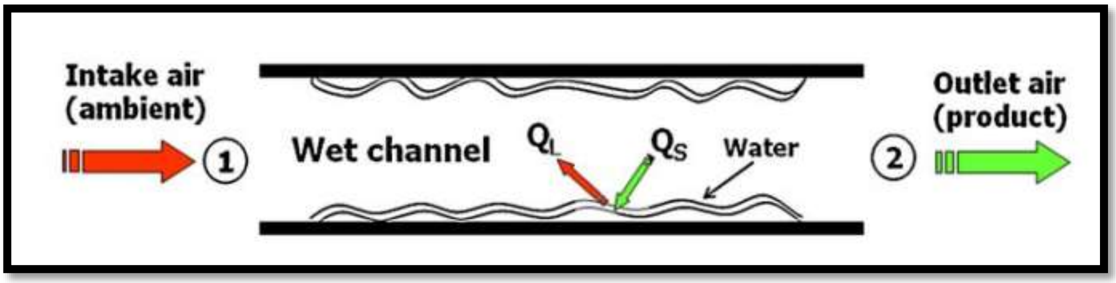

Figure 1 Direct evaporative cooling [14]

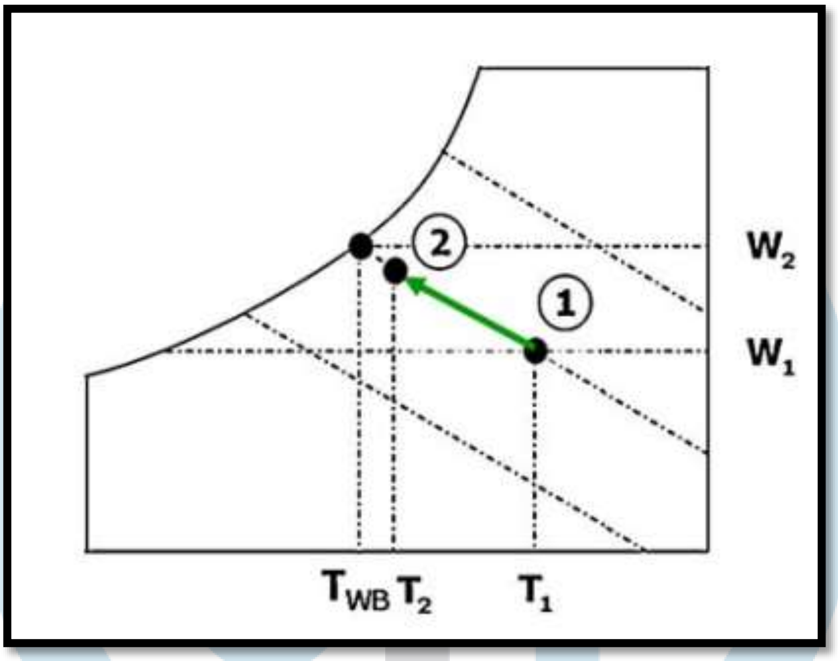

Figure 2 Direct Evaporative cooling on psychometry chart [14]

Figure 1 shows the process of direct evaporative cooling. Figure 2 shows the behavior of direct evaporative cooling on psychrometry chart.

This type of system gives sufficient cooling but at the same time the high humidity of it gives feeling of discomfort. Temperature to be achieved through direct evaporative cooling is limited up to the wet bulb temperature of the inlet air only. Also, evaporative cooling system consumes more water.

B. Indirect Evaporative Cooling (IEC)

Indirect evaporative cooling is a cooling process that uses direct evaporative cooling in addition to some type of heat-exchanger to transfer the cool energy to the supply air. The cooled moist air from the direct evaporative cooling process never comes in direct contact with the conditioned supply air. The moist air stream is released outside or used to cool other external devices such as solar cells which are more efficient if kept cool. While no moisture is added to the incoming air the relative humidity (RH) does rise a little according to the Temperature-RH formula. Indirect Cooling is an effective strategy for hot-humid climates that cannot afford to increase the moisture content of the supply air due to indoor air quality and human thermal comfort conditions.

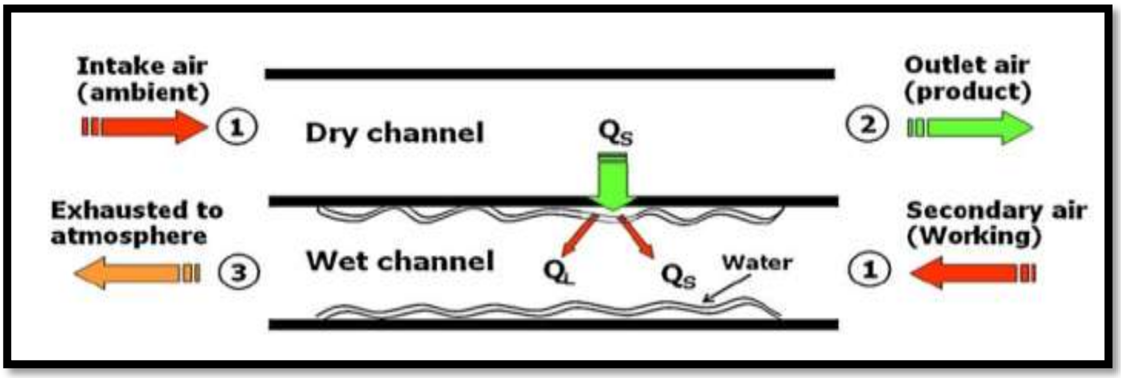

Figure 3 Indirect evaporative cooling [14]

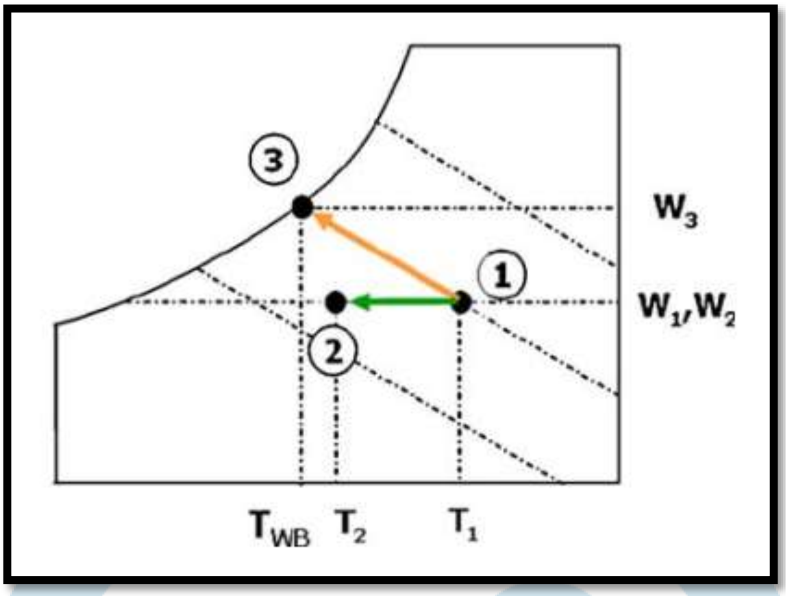

Figure 4 Indirect Evaporative cooling on psychometry chart [14]

Figure 3 shows the process of indirect evaporative cooling. Figure 4 shows the behavior of indirect evaporative cooling on psychrometry chart.

Comparatively it consumes less water than direct evaporative cooling. Main disadvantage of direct evaporative cooling, i.e. rise in humidity is overcome in indirect evaporative cooling. Although the rise in humidity is controlled in indirect evaporative cooling but this system is inefficient to give fair drop in temperature of product air.

II. Literature review

GhassemHeidarinejad et al. [1]: Novel modeling of an indirect evaporative cooling system with cross-flow configuration presented a new modeling with consideration of wall longitudinal heat conduction and effect of heat spray water temperature variation along the exchanger surface in a cross-flow configuration. The resultant equation of heat and mass transfer are discretized by finite difference method and solved by an iterative method. The numerical results of the simulation are compared with the experimental results and shows good agreement. Then the same model is used in two-stage system of indirect/direct evaporative cooling system and compared with one stage indirect evaporative cooling system and found indirect/direct evaporative cooling system has 50% higher wet-bulb effectiveness. And the numerical simulation of a counter-flow regenerative evaporative cooler shows 60% higher wet-bulb effectiveness.

X. Cui, K.J. Chua et al. [2]: Numerical simulation of a novel energy-efficient dew point evaporative air cooler. Theypresented thatthe novel evaporative air conditioner can cool air to temperature below ambient wet bulb temperature and approaching dew-point temperature. They also presented the simulation result of novel dew point evaporative air conditioner which was designed based on counter flow closed loop configuration. The simulation was carried out in ANSYS FLUENT and Eulerian-lagrangian approach was adopted in the numerical model. The author also gave the parameters range for analysis of counter flow plate type heat exchanger as follows: Product channel height: - 3-20 mm, Working channel height: - 1.5mm – 10 mm, Channel length: 300mm – 1000 mm, Inlet air temperature: 25 °C – 35 °C, Inlet air velocity: 0.3m/s – 4 m/s, Inlet air humidity ratio – 8-12 g/kg. The limiting air velocity is 1.5m/s. The channel length should be greater than 200 times the channel height of working air. The product channel height should be twice the working channel height. It is also suggested that the product to working air flow ratio should be less than 1.5.

Sergey Anisimov et al. [3]: Numerical study of the Maisotsenko cycle heat and mass exchanger. Theypresented the numerical modeling of heat and mass exchanger used for indirect evaporative cooling based on M-cycle. For that the numerical model is developed based on Ɛ-NTU method for performing thermal calculations. The model results are based on the experimental data from literature and the result of mathematical model was satisfactorily matched with experimental results. In this experiment, the fibre of the heat exchanger is 0.4 mm thick, height of channel is equal to 3.2mm, and width of channel is equal to 24mm.It is reviewed that wet bulb effectiveness of the mentioned unit is between 94 to 120%. Maximum dew point effectiveness that can be achieved was 88%. Maximum temperature difference that can be obtained was 20 °C and for secondary air stream, maximum humidity ratio difference was 10 g/kg.

X. Cui et al. [4]: Studying the performance of an improved due point evaporative design for cooling application. Here the novel dew point evaporative air cooler, based on the counter flow closed loop is used to cool air to temperature below ambient wet bulb temperature and approaching dew point temperature. A computational model for cooler has been developed.The key objectives of this work which differ from existing literature are: (1) M-cycle is as a basis, we introduce an improved dew point evaporative design for providing air cooling. (2) Developing a dew point evaporative cooling design which is completely separates working air from the product air.Model demonstrated closed agreement with the experimental findings to within +7.5% or -7.5%. They studied the cooler performance by considering effects of (1) varying channels dimension (2) room return air as a working fluid (3) installing physical ribs along the channel length. Operating under variant inlet air temperature and variant in humidity condition results showed that wet bulb effectiveness ranged from 122% to 132% and dew point effectiveness 31% to 93%.

ZhiyinDuan et al. [5]: Indirect evaporative cooling: past, present and future potentials presented an overview of indirect evaporative cooling system. The paper includes background, history, status, standard data, research and industrialization, market prospects and barriers, and future scope of current technology. They mentioned that IEC system has greater potential to be the best alternative of VCR based air conditioning systems for residential. They suggest that the new evaporative cooling technology approach to dew point temperature. The tested data of M cycle shows that the wet bulb effectiveness is 81-90% and dew point effectiveness is 50-60% which is 10 to 20 % higher than the effectiveness of conventional cooling system. He suggested that thermal properties and porosity is less important than shape formation, durability, compatibility and cost. He suggested that copper and aluminum are the best suitable materials compare to other.

Ala Hasan [6]: Going below the wet-bulb temperature by indirect evaporative cooling: Analysis using a modified ε-NTU method. In this paper, they developed an analytical model for indirect evaporative coolers based on modifications of the ε-NTU method. They suggested the method is universal and is applicable to any type of indirect evaporative cooler. They analyzed the performance of regenerative counter flow indirect evaporative cooler. The cooler was tested at inlet conditions: air temperature ranges from 30 to 34.2 °C, wet bulb temperature of 15 °C. The dimensions of cooler are: L_p=L_w= 0.5 m, Z = 0.5 m, H_p= 3.5 mm, H_w = 3.5 mm and d = 1.5 mm. The temperature difference obtained is of approximately 13 °C, wet bulb effectiveness of 93 to 120% and dew point effectiveness of 78 to 89%. The inlet velocity is suggested 0.7 m/s. The results are same as that obtained by numerical method that used finite difference method. Also, the results are validated with experiment results.

Chandrakant Wani et al. [7]: A Review on Potential of Maisotsenko Cycle in Energy saving Applications Using Evaporative Cooling. In this paper, they explained what Maisotsenko cycle is, its importance, performance parameters of M-Cycle and its underutilized applications. They explained its important properties like; it is energy efficient, it provides CFC-free cooling, water savings and competitive initial cost.

Changhong Zhan et al. [8]: Comparative study of the performance of the M – cycle counter flow and cross flow heat exchangers for indirect evaporative cooling – paving the path toward sustainable cooling of the buildings. In this paper, they compared both available structures of M-cycle i.e. cross flow and counter flow by theoretically and experimentally under the parallel operational conditions. The above is done by developing computer model. Parameters on which the study was done are Channel length – 1m, Channel height – 5 mm, Intake air flow rate-2000 m^3/hr., working to intake air ratio – 0.5, DBT - 28 °C and moisture content- 11.35g/kg. Result shows that counter flow exchanger offered 20% higher cooling capacity, 15-23% higher wet bulb and dew point effectiveness than cross flow exchanger of same physical size. However, cross flow exchanger had 10% higher Energy Efficiency.

B. Riangvilaikul et al. [9]: Numerical study of a novel dew point evaporative cooling system. They presented theoretical performance of a novel dew point evaporative cooling system operating under various inlet conditions of air and influence of major operating parameters. The simulation, results are compared with the experimental findings for various inlet air conditions and for different intake air velocities (1.5–6 m/s). Good agreement and trend can be observed from both simulation and experimental results. Operating under different climate, the simulation results show that the dew point effectiveness varies significantly from 65 to 86% when the inlet air humidity changes from 6.9 to 26.4 g/kg at the constant inlet temperature (35°C). Based on the analysis of influential parameters on the system performance, the system should be designed and operated at: intake air velocity below 2.5 m/s, channel gap less than 5mm, channel height larger than 1m and ratio of working air to intake around 35–60%, to obtain the wet bulb effectiveness greater than 100% for all typical inlet air conditions.

RabahBoukhanouf et al.[10]: Computer modelling and experimental investigation of building integrated sub-wet bulb temperature evaporative cooling system presents the computer modelling and the laboratory experiment results of evaporative cooling system for space cooling in buildings. Mathematical model developed is 1-dimensional and it is based on solving energy and mass conservation governing equations. The prototype constructed consists of 5 rows and each is built of 3 porous flat ceramic panels. The thermal performance of the system was evaluated for air inlet temperature of 35°C (22.9°C wet bulb) and relative humidity of 35%. The mass flow rate of air supplied in dry channel was of 0.03 kg/s and for wet channel it was 0.012 kg/s. The measurement shows the temperature of air dropped in dry channel was 12.4°C resulting in supply air temperature of 22. 6°C.There was good agreement between measured and computed results. Wet bulb effectiveness of 1.024 was achieved.

M. Jradi et al.[11]:Experimental and numerical investigation of a dew-point cooling system for thermal comfort in buildings. In this paper by modifying the indirect evaporative cooling system a new system is developed to achieve dew point temperature. Numerical analysis for cross-flow heat and mass exchanger is carried out. Model was developed in MATLAB. Equations were solved using a fully implicit accurate finite difference scheme. With intake air of 30°C temperature and relative humidity of 50% and a working to intake air flow ratio of 0.33 the system attained wet bulb effectiveness of 112% and dew point effectiveness of 78% with channel height of 5 mm and channel length of 500 mm. Also, experimental setup was built and tested under various operational and ambient conditions.

ZhiyinDuan et al.[12]: Experimental study of a counter-flow regenerative evaporative cooler investigated the operational performance and impact factors of a counter-flow regenerative evaporative cooler. From their earlier numerical work, the dedicated experimental model has been developed. The wet-bulb effectiveness of the cooler is observed in range from 0.55 to 1.06 with Energy Efficiency Ratio ranging from 2.8 to 15.5. From the study, it is concluded that cooling effectiveness of the module get improved through increasing intake wet-bulb depressions, reducing intake air velocity, or increasing working-to-intake air ratio respectively. On the other hand, low intake air velocity reduces the cooler’s cooling capacity. The working-to-intake air ratio range should be between 0.4 to 0.5 to achieve a compromise between effectiveness, cooling capacity and energy efficiency ratio.

Aftab Ahmad et al. [13]: Performance evaluation of an indirect evaporative cooler under controlled environmental conditions. The study investigated performance of a 5-ton capacity indirect evaporative cooler under controlled environmental conditions: 43.9◦C of dry-bulb temperature and 19.9% of relative humidity. The experimental results show that the intake air energy efficiency ratio of cooler varies from 7.1 to 55 depending on the test conditions. The power consumption of indirect evaporative cooler was found to vary from 68 to 746 watts. The results indicated that intake air energy efficiency ratio was directly proportional to wet-bulb depression.

Frank Bruno [14]: On-site experimental testing of a novel dew point evaporative cooler. In this paper, they developed indirect evaporative cooler and installed them in both commercial and residential application for a wide range of ambient conditions. Flow arrangement in the cooler is counter flow. In commercial application with inlet maximum temperature above 32°C, average EER is found in the range of 7.2 – 11.5 while in the warm days with a maximum inlet temperature around 27°C, average EER is found in the range of 4 – 5. The average temperature of the air delivered is at 17.3°C. In residential application, for inlet temperature 27.5 to 40.4°C the EER measured was in between 4.9 to 11.8. The average temperature of the air delivered was 14.9°C for average inlet of 34.7°C. In commercial application, the wet bulb effectiveness and dew point effectiveness ranges from 93 – 106% and 57 to 74% respectively and in residential application the same ranges from 118 – 129% and 65 – 83%. They concluded that the counter flow indirect evaporative cooler can supply air at a temperature comparable to conventional cooling system with high thermal efficiencies.

B. Riangvilaikul et al. [15]: An experimental study of a novel dew point evaporative cooling system. In this paper, they constructed novel dew point cooler and carried out experiments to investigate outlet air conditions and system performance at various inlet conditions. Parameters used are: Wall material – cotton sheet coated with polyurethane, Wall thickness – 0.5mm, Channel length – 1200 mm, Channel width – 80mm, Channel gap – 5mm, working air to intake air ratio – 0.33 kg/kg and Water supplied – 60 g/h. Wet bulb effectiveness and dew point effectiveness found 92-114% and 58-84% respectively. They suggested for inlet temperature above 30°C the velocity of intake should be kept less than 2.5 m/s.

Table 1Literature Summary

Parameters	**Sergey Anisimov et al. [3]**	**X. Cui et al.[4]**	**Ala Hasan[6]**	**M. Jradi et al. [11]**	**B. Riangvilaikul et al. [9,15]**
Type of analysis	*Simulation*	*Simulation*	*Modified Ɛ-NTU method*	*Simulation and Experiment*	*Simulation and Experiment*
Flow arrangement	*Cross flow, where primary and secondary air were separated but need more channels.*	*Counter flow, product air and working air were separated but need more channels.*	*Counter flow, working air is part of product air.*	*Cross flow; working air is part of product air*	*Counter flow; working air is part of the product air*
Inlet dry bulb temperature	*25 to 45 °C*	*25 to 35 °C*	*30 to 35 °C*	*30 °C*	*25 to 45 °C*
Temperature difference	*15 °C*	*13 °C*	*13 °C*	*13 °C*	*10 °C*
Inlet air humidity ratio	*10 g/kg*	*3.4 – 10.7 g/kg*	*9 g/kg*	*13.3 g/kg*	*7–26 g/kg*
Wet bulb effectiveness	*>100 %*	*>100 %*	*93 to 120%*	*112%*	*92 to 114%*
Dew point effectiveness	*Approach to 100 %*	*Approach to 100 %*	*78 to 89%*	*78%*	*58 to 84%*
Dry channel height (H_p)	*2.5 to 20 mm*	*3 to 20 mm*	*3.5 mm*	*5 mm*	*5 mm*
Wet channel height (H_w)	*0.5 H_p*	*0.5 H_p*	*3.5 mm*	*5 mm*	*5 mm*
Channel length	*0.25 to 1 m*	*200 H_p*	*500 mm*	*500 mm*	*1000 mm*
Inlet air velocity	*1.8 m/s to 7 m/s*	*Less than 1.5 m/s*	*0.7m/s*	*2 m/s*	*2.4 m/s*

III. Conclusion

Literatures related to simulations, mathematical models and experimental models of Maisotsenko Cycle based heat and mass exchangers are reviewed. It is concluded that novel energy efficient dew-point evaporative air cooling system (Maisotsenko Cycle) has various advantages over conventional cooling systems and has potential to substitute them in future.It is energy efficient, provides CFC free cooling and consumes less water. Counter flow arrangement has more advantages and is economical flow configuration.Aluminium is best suitable material for heat and mass exchanger because of its properties like light weight, corrosion resistance and good thermal conductivity.The novel dew-point evaporative air cooling system is able cool air to the temperature below its inlet wet bulb temperature and approaching dew-point temperature. To achieve temperature below wet bulb and to approach dew point, range of values of dimensions and parameters for heat and mass exchangers is found andsame are mentioned below:

Table 2 Range of dimension for design

Parameters	Value of dimension
Product channel height (H_p)	$2\ mm < H_p < 11\ mm$
Working channel height (H_w)	$2\ mm < H_w < 8\ mm$
Product channel length (L_p)	$700mm < L_p < 1300\ mm$
Working channel length (L_w)	$700mm < L_w < 1300\ mm$

Table 3 Range of parameter for design

Parameters	Value of parameters
Inlet air Velocity (V_{in})	$0.5 < (V_{in}) < 1.5\ m/s$
Inlet air temperature (T_{in})	$25 < (T_{in}) < 35°C$
Inlet air humidity ratio (X_{in})	$7 < (X_{in}) < 12\ g/kg$

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