



SUSTAINABILITY ANALYSIS OF DIRECT EVAPORATIVE COOLING SYSTEM

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ABSTRACT

In this paper exergy analysis of direct evaporative cooling system is presented. In this study ambient temperature, saturation specific humidity of the process and pressure at the end of the process is considered as the dead state. Variations in wet bulb saturation efficiency, Second Law Efficiency, Irreversibility, Entropy Generation, Sustainability Index, and Exergetic EER are analyzed for pads of different thickness with constant face velocity. It is observed that for a give thickness of pads Second Law Efficiency does not changes as wet bulb saturation efficiency changes. Irreversibility and entropy generation change almost same manner. Sustainability index curve is almost flat for pads of same thickness. However it increases slightly with the thickness of the pads.

Key words: Direct Evaporative Cooling, Exergy, Sustainability, EER, Exergy efficiency.

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INTRODUCTION

Evaporative cooling had its birth around one thousand years ago in ancient Egypt. At that time, porous pots and ponds covered with a wet cloth were often used to preserve food against hot weather and some water chutes were also integrated into walls to keep the inside space cool, due to the evaporation of water when air flowed through. This technique was soon spread into other hot and arid places of the world.

The principle underlying Evaporative Air Conditioning (EAC) is the conversion of sensible heat of hot air to latent heat of water. Part of the sensible heat of the air is transferred to the water and becomes latent heat and evaporates the water. The wetted medium for the evaporation of water could be a porous wetted pad consisting of fibres, cellulose papers or a spray of water.

Two common types of evaporative cooling systems are the direct and indirect evaporative systems. In the direct evaporative cooler (DEC), the air comes into direct contact with water. The direct evaporative cooling system adds moisture to the cool air, while an indirect evaporative cooling system (IEC) provides only sensible cooling to the processed air without any addition of moisture. Depending on the climatic conditions and the application, combining indirect and direct evaporative coolers might be appropriate. If a first indirect stage is added to a second direct stage, a two-stage indirect/direct cooler is obtained which cools the air more than a stand-alone DEC unit.

Besides reducing the temperature EAC supply fresh air, use water as the working fluid instead of CFCs, simple manufacturing, easy maintenance, low power consumption, ability of achieve suitable level of humidity in rather dry

regions. EAC technologies represent significant environmental benefits related to reducing CFC/HCFC use and for obviating CO₂ and other emissions, as well as for reducing peak electrical demand.

The minimum temperature that can be obtained is the wet bulb temperature of the entering air [1].

For the better understanding of EAC, exergy analysis method can be applied with energy analysis. Exergy analysis uses both conservation of mass and energy principles. This method is based on second law of thermodynamics for analysis, design and improvement of energy systems. Exergy is always evaluated with respect to a reference environment and it can be destroyed when the irreversibility process occurs. If an exergy analysis performed on a system, thermodynamic imperfections can be quantified as exergy destruction, which represent losses in energy quality or usefulness (Dincer and Rosen, 2007). The term exergy was introduced by Rant in 1953.

LITERATURE REVIEW

In the field of direct evaporative cooling several authors dedicated their researches. Watt [1] developed the first serious analyses of direct and indirect evaporative systems,

Halasz [2] presented a general dimensionless mathematical model to describe all evaporative cooling devices namely cooling water towers, evaporative condensers of fluid, air washes, dehumidification coils, etc. Camargo et al. [3] presented the principles of operation for direct and indirect evaporative cooling systems and the mathematical development of thermal exchanges equations, Koca et al. [4] have developed a procedure for testing evaporative cooling pads. Their results show that pad performance is affected by pad angle, pad thickness, face air velocity, and static pressure drop across the pad and can be expressed in terms of evaporative cooling efficiency and static pressure drop. Dai et al. [5] solved governing equations for cross-flow direct evaporative cooler using an integration method. They used honeycomb paper as packing material and assumed constant space between channels and

they simply modelled the thin water film on surfaces. Their results showed that the performance improve by optimizing length of the air channel of honeycomb paper, mass flow rates of air and feed water. Kruger [6] emphasized that the use of direct evaporative cooling system in humid places such as Maracaibo is not effective. In this way, indirect evaporative cooling system came to birth, gained its popularity and developed for more than a century. Liao et al. [7] developed a wind tunnel technique for measuring performance of the evaporative cooling pads. Liao et al. [8] investigated the effects of air velocity and pad thickness on the efficiency and pressure drop of evaporative cooling pads. Al-Sulaiman [9] experimentally evaluated the performance of three natural fibres (palm fibre, jute and luffa) as wetted pads in evaporating cooling. Gunhan et al. [10] experimentally evaluated the suitability of greenhouse shading net, pumice stones and volcanic tuff as pad materials for use in evaporative coolers. Khond [11] investigated the performance of evaporative cooler using four different pad materials i.e. stainless steel wire mesh, coconut coir, khus and wood wool. Dzivama et al. [12] they used ground sponge, stem sponge, jute fibre and charcoal as pads for an evaporative cooler

Kulkarni et al [13] analyzed the performance of jute fibre ropes as alternative cooling media as ropes are capable of retaining high moisture and have a large wetted surface area. Hot and dry air is allowed to flow over the wet jute rope bank tightly held between two plates which are integral part of two tanks.

Kulkarni et al [14] theoretically analyzed the performance of evaporative cooler pads of rigid cellulose, corrugated paper, high density polythene packing and aspen fibre having rectangular, cylindrical and hexagonal shape.

In the field of exergy analysis, Dincer [15] reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail. Chengqin et al. [16] analyze exergy changes in the HVAC systems. They presume an unusual dead state to eliminate the exergy calculation of water. Also, they break down the exergy of moist air

to three components: thermal, mechanical, and chemical components. By assuming efficiency for each scheme of evaporative cooling, the results have shown that the regenerative scheme has the best performance. Alhamzy [17] calculates the minimum work of dehumidification in an air-conditioning process based on the second law of thermodynamics. In his research, the state of environment was chosen as the dead state.

Qureshi et al. [18] carried out study of various psychrometric processes on the basis of second law of thermodynamics. The relation between work and changes in entropy generation arises from the simultaneous treatment of the first and second laws referred to as exergy analysis. The study of each of the processes is carried out to determine the variation of second-law efficiency as a function of mass flow rate, relative humidity and temperature. Other trends such as variation of temperature with relative humidity are also shown where applicable. Irreversible losses are calculated by applying an exergy balance on each system. Kanoglua et al.[19] had studied the effect of ambient conditions on the first and second law performance of an open desiccant cooling process. The cooling system consists of a desiccant wheel, a rotary regenerator, two evaporative coolers, and a heating unit. Certain ideal operating characteristics based primarily on the first law of thermodynamics are assumed for each component. Qureshi et al. [20] carried out second-law-based parametric study of performance evaluation of cooling towers and evaporative heat exchangers, to determine the variation of second-law efficiency as well as exergy destruction as a function of various input parameters. Irreversible losses are determined on each of the systems investigated. They noticed that an increase in the inlet wet bulb temperature invariably increases the second-law efficiency of all the heat exchangers. Taufiq et al. [21] study the exergy analysis of the direct evaporative cooling in a Malaysian building. The average temperature and relative humidity were considered as the dead state. The results obtained have shown that increase in relative humidity increases exergy efficiency. Muangnoi et al. [22] use an exergy analysis to

demonstrate exergy and exergy destruction of water and air flowing through the cooling tower. They show thermodynamics irreversibility is higher at bottom of a cooling tower. Kanoglu et al. [23] carried out studied on psychrometric processes on the basis of second law of thermodynamics. Mass, energy, entropy, and exergy balances and exergy efficiency relations are developed for common air-conditioning processes. The effects of air temperature and relative humidity at the inlet and exit, the temperature of steam used for humidification, and the dead state properties of exergy efficiency and exergy destruction are investigated. The results indicate that processes with low exergy efficiency and high exergy destruction have significant potential for improving performance. Chen et al. [24] analyzed and optimized several practical evaporative cooling systems based on the newly introduced moisture entransy theory. They realized that the most efficient evaporative cooling performance requires a minimum thermal resistance. Aforementioned research papers on exergy analysis have not examined exergetic efficiency on various climates. Indeed, multi-climate countries such as Iran necessitate an abroad consideration of exergy analysis on diverse environmental conditions.

Exergy analysis

The exergy balance of the evaporative cooling system for the control volume can be obtained by

$$\dot{E}x_{in} = \dot{E}x_{out} + \dot{E}x_{dest} + \dot{E}x_{lost} \quad (1)$$

where $\dot{E}x_{in}$, $\dot{E}x_{out}$, $\dot{E}x_{dest}$ and $\dot{E}x_{lost}$ are the exergy input rate, exergy output rate, exergy destruction rate and exergy loss rate, respectively.

The exergy input rate $\dot{E}x_{in}$, is defined by

$$\dot{E}x_{in} = \dot{E}x_{in,da} + \dot{E}x_{in,w} \quad (2)$$

$$\dot{E}x_{in} = \dot{E}x_{in,da} + \dot{E}x_{in,w} \quad (3)$$

$$\dot{E}x_{in,w} = \dot{m}_w e_w = \dot{m}_{da} \omega_{sl} e_w \quad (4)$$

Specific exergy rate of dry air is defined by

$$e_{da} = c_{pda} T_0 \left[\frac{T_{sl}}{T_0} - 1 - \ln \frac{T_{sl}}{T_0} \right] + R_a T_0 \ln \frac{P}{P_0} + R_a T_0 \ln(1 + \omega_0) \quad (5)$$

and specific exergy rate of water at ambient temperature is defined by

$$e_w = (h_{f(T_{SI})} - h_{g(T_0)}) - T_0(s_{f(T_{SI})} - s_{g(T_0)}) + (P - P_{sat(T_{SI})})v_{f(T_{SI})} - R_{wv}T_0 \ln \Phi \quad (6)$$

Where relative humidity is defined by

$$\Phi = \frac{P_0}{P_{sup\ ply}} \quad (7)$$

The exergy output rate $\dot{E}x_{out}$, is defined by

$$\dot{E}x_{out} = \dot{m}_{da} e_t \quad (8)$$

$$e_t = (c_{pda} + \omega_{SI}c_{pv})T_0 \left[\frac{T_{SI}}{T_0} - 1 - \ln \frac{T_{SI}}{T_0} \right] + (1 + \omega_{SI})R_a T_0 \ln \frac{P}{P_0} + R_a T_0 \left[(1 + \omega_{SI}) \ln \frac{(1 + \omega_0)}{(1 + \omega_{SI})} + \omega_{SI} \ln \frac{\omega_{SI}}{\omega_0} \right] \quad (9)$$

$$e_t = (c_{pda} + \omega_{SI}c_{pv})T_0 \left[\frac{T_{SI}}{T_0} - 1 - \ln \frac{T_{SI}}{T_0} \right] + (1 + \omega_{SI})R_a T_0 \ln \frac{P}{P_0} + R_a T_0 \left[(1 + \omega_{SI}) \ln \frac{(1 + \omega_0)}{(1 + \omega_{SI})} + \omega_{SI} \ln \frac{\omega_{SI}}{\omega_0} \right] \quad (10)$$

Rate of exergy loss is defined by

$$\dot{E}x_{loss} = \dot{Q}_{cooling} \left(1 - \frac{T_0}{T_{SI}} \right) \quad (11)$$

Rate of exergy destruction is defined by

$$\dot{E}x_{dest} = \dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{lost} \quad (12)$$

Rate of entropy generated

$$\dot{S} = \frac{\dot{E}x_{dest}}{T_0} \quad (13)$$

Exergy or second law of thermodynamics efficiency is defined by

$$\Psi = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = \frac{e_t}{e_{da} + \omega_{SI}e_w} \quad (14)$$

Thermal Specific exergy of moist air

$$ex_{th} = (c_{pa} + \omega c_{pv})T_0 \left[\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right] \quad (15)$$

Mechanical Specific exergy of moist air

$$ex_{mech} = (1 + 1.608\omega)R_a T_0 \ln \frac{P}{P_0} \quad (16)$$

Chemical Specific exergy of moist air

$$ex_{chem} = R_a T_0 \left[(1 + 1.608\omega) \ln \frac{(1 + 1.608\omega_0)}{(1 + 1.608\omega)} + 1.608\omega \ln \frac{\omega}{\omega_0} \right] \quad (17)$$

Total Specific exergy of moist air

$$ex = ex_{th} + ex_{mech} + ex_{chem} \quad (18)$$

Specific exergy of water

$$\psi_w = -R_v T_0 \ln \phi_0 \quad (19)$$

Exergy Analysis for DEC

$$\dot{m}_a \psi_{a1} + \dot{m}_w \psi_w - \dot{m}_a \psi_{a2} - \dot{I} = 0 \quad (20)$$

$$\dot{m}_w = \dot{m}_a (\omega_2 - \omega_1) \quad (21)$$

Sustainability assessment

Sustainability assessment is required the resources to be used efficiently, and also it is performed with sustainability index (SI) method which is related to exergy efficiency (Ψ). Exergy methods are essential in improving efficiency that allows society to maximize the benefits it derives from its resources while minimizing the negative impacts such as environmental damage (Rosen et al., 2008). So, SI method based on exergy efficiency is a useful tool to obtain sustainability assessment as follows:

$$SI = \frac{1}{1 - \Psi} \quad (22)$$

Variation in Saturation Efficiency

Wet-bulb saturation efficiency of DEC decreases with increase in the air mass flow rate. This is expected because with increase in air mass flow rate, air has lesser contact time with water layer causing less evaporation of water. Saturation efficiency of DEC increases with increase in the thickness of cooling pads. This is also expected because with increase in the thickness of the cooling air gets greater contact time with water layer causing higher evaporation of water. For 5 cm thick pads saturation efficiency varied from 48.7 to 59.6%, for 10cm thick pads saturation efficiency varied from 70.4 to 80.1% and for 15cm thick pads saturation efficiency varied from 81.9 to 88.5%. The overall variation in the saturation efficiency is from 48.7 to 88.5%.

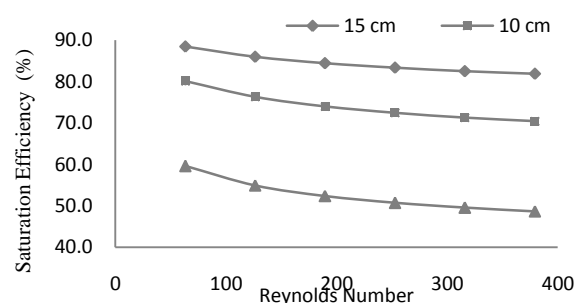


Fig. 1. Variations of saturation efficiency of pads of different thickness with Reynolds number.

Exergy Efficiency

For 5 cm thick pads Exergy Efficiency varied from 16.9 to 17.5 for 10cm thick pads Exergy Efficiency varied from 19.7 to 19.9 and for 15cm thick pads Exergy Efficiency varied from 21.4 to 22.1. The overall variation in the Exergy Efficiency is from 16.9 to 22.1.

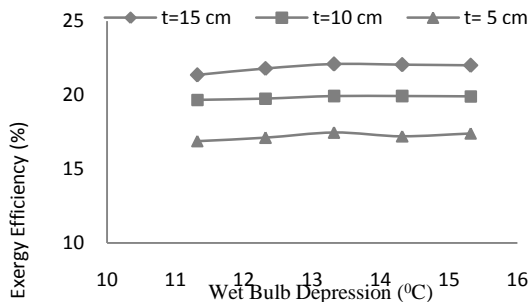


Fig. 2. Variations of Exergy Efficiency of DEC with Wet bulb Depression.

Irreversibility

For 5 cm thick pads Irreversibility varied from 391 to 983 for 10cm thick pads Irreversibility varied from 511 to 1273 and for 15cm thick pads Irreversibility varied from 580 to 1407. The overall variation in the Irreversibility is from 391 to 1407.

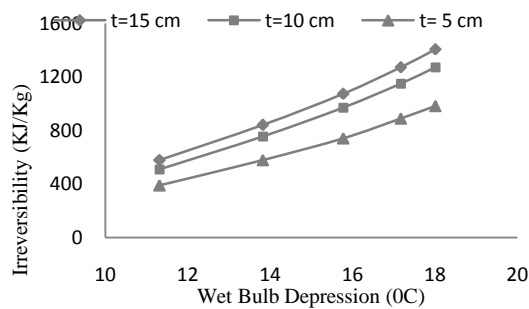


Fig. 3. Variations of Irreversibility in DEC with Wet bulb Depression.

Entropy Generation

For 5 cm thick pads Entropy Generation varied from 1.202 to 1.21for 10cm thick pads Entropy Generation varied from 1.252 to 1.26 and for 15cm thick pads Entropy Generation varied from 1.852 to 4.65. The overall variation in the Entropy Generation is from 1.202 to 4.65

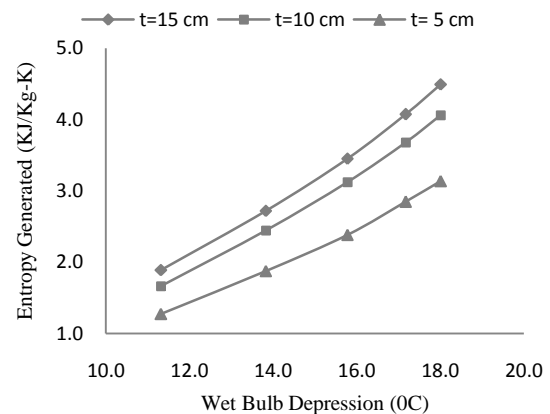


Fig. 4. Variations Entropy Generation during DEC with Wet bulb Depression.

Sustainability Index (SI)

For 5 cm thick pads SI varied from 1.202 to 1.21for 10cm thick pads SI varied from 1.252 to 1.26 and for 15cm thick pads SI varied from 1.852 to 4.65. The overall variation in the SI is from 1.202 to 4.65.

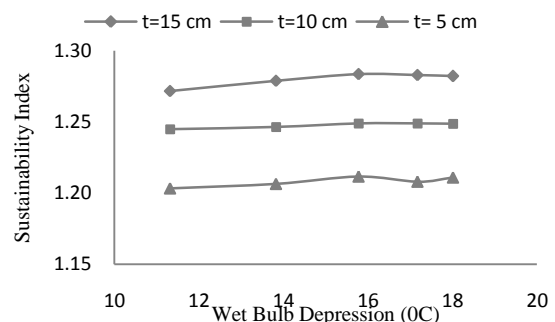


Fig. 5. Variations of Sustainability Index of DEC with Wet bulb Depression.

Exergetic EER

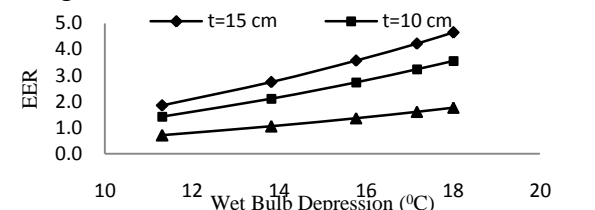


Fig. 6. Variations of Exergetic Energy Efficiency Ratio of DEC with Wet bulb Depression.

For 5 cm thick pads EER_{EX} varied from 0.712 to 1.76 for 10cm thick pads EER_{EX} varied from 1.422 to 3.56 and for 15cm thick pads EER_{EX} varied from 1.852 to 4.65. The overall variation in the EER_{EX} is from 0.712 to 4.65.

Conclusion

In this paper exergy analysis of direct evaporative cooling system is presented. Variations

in wet bulb saturation efficiency, Second Law Efficiency, Irreversibility, Entropy Generation, Sustainability Index, and Exergetic EER are analyzed for pads of different thickness with constant face velocity. **It is observed that for a give thickness of pads** Second Law Efficiency does not changes as wet bulb saturation efficiency changes. Irreversibility and entropy generation vary in same manner for given thickness of pads. Sustainability index curve is almost flat for pads of given thickness, however it increases slightly with the thickness of the pads.

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