Original Research Article

Investigation of evaporative cooling pad material from Hyphaene thebaica fibers

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ABSTRACT

Evaporative coolers are technologies highly used as a source of thermal comfort in terms of fresh air provider in areas where weather conditions are harsh and people living standard goes from medium to low earnings. This technology being environmentally friendly still requires a certain minimum maintenance, mostly the change of pads. This paper presents the performance of a cost-effective cooling pad made from the fibers of *hyphanene thebaica* (wood wool) as an alternative pad to the commercial ones rendering this technology more accessible and affordable for all social classes. The experiment was done in an insulated duct whereby thermodynamic parameters of locally made pad such as temperature, pressure, relative humidity and velocity, were recorded, and effect of physical properties on performances were analyzed. Compared to the commercial pad, the proposed local pad presented the lowest minimum outlet dry bulb temperature (20.00^{o}C), a saturation efficiency of 78.80% with the highest cooling capacity of 0.1867 kW, the highest heat transfer coefficient of 7.3497 kW/m^{2} ^{o}C, the best cost-to-efficiency ratio (CER) and coefficient of performance (COP). By studying and improving the pads thermophysical characteristics, performance could be improved opening ways towards industrial production of such pads for a sustainable development.

Keywords*: Direct evaporative cooling, desert air conditioners, cellulosic pad materials, cost-effective cooling, sub-Saharan area.*

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1 INTRODUCTION

Providing a comfort zone for crop production or even humans' living is one of the major concerns these days in areas where climate change is causing a persevering heat stress (Raymond et al., 2020). Cooling systems are usually used as a temporary direct remedy. Although effective, conventional air conditioners (ACs) were reported to emit greenhouse gases (GHGs) responsible for this global rise in average temperature, global warming (Matthews and Raymond, 2020; Raymond et al., 2020). Many research and technologies were developed in order to find an alternative cooling device to help reduce GHGs emissions among which evaporative cooling systems emerged as one of the best cost-effective systems and environmentally friendly (Chijioke, 2017; Hassanien et al., 2016). Evaporative coolers are based on evaporative cooling principle which creates a cooler and more humid air when a dry and hot air come into contact with water medium in the presence of a cellulosic materials. During this process, water gets latent heat of evaporation and evaporates while air absorbs sensible heat and decreases in dry bulb temperature. This cooling process is more effective in regions with a dry and hot weather condition (Chijioke, 2017; Khobragade and Kongre, 2016). To date, Aspen pad made from wood shavings of *propulus tremuloides* and Celdek (Trade name) paper pad are the commercially available high-performance pad on our market. Research has been conducted in finding news cooling pads from indigenous plants. In fact, fibers-derived cooling pads have been performing well as alternative materials towards cost-effectiveness, even better than the other industrial pads especially in the cost efficiency ratio aspect (Chijioke, 2017). Since then, deeper research has been conducted in order to improve their efficiency and stability towards commercial production of fibers pad technologies.

The purpose of this paper is to investigate the performance of an evaporative cooling pad made from the fibers of *Hyphaene thebaica*.

Nomenclature

eff = Evaporative saturation efficiency, %

T_{db1}, T_{db2} = inlet and outlet dry bulb temperature, ^oC

T_{wb} = wet bulb temperature, ^oC

q and q_{pad} = Cooling capacity of the pad, kW

ma = air mass flow rate, kg/s

mv = mass flow rate of water vapour, kg/s

W = humidity ratio, kg of air/kg of water

ha_1, ha_2 = inlet and outlet enthalpy of air, kJ/kg of dry air

hw = enthalpy of water, kJ/kg of dry air

q = heat loss by the pads, kJ/s

RH = relative humidity, %

v = frontal/inlet velocity, m/s

v_{out} = outlet velocity, m/s

me = mass of water evaporated, kg/s

W = humidity ratio, kg moisture/kg dry air

h_H = heat transfer coefficient, $kW/m^2\,^oC$

h_M = mass transfer coefficient, kg/s

A_s = total wetted surface area of the pad used, m^2

ΔT = log mean temperature difference, ^oC

$\Delta\rho_v$ = log mean mass density difference of water vapour, Kg/m^3

ρ_{v1}, ρ_{v2} and ρ_{vwb} = mass density of water vapour at inlet, outlet and wet bulb conditions, Kg/m^3

ρvw = actual density of water vapour from saturated water table, Kg/m^3

Er = amount of water evaporated, L/h

ΔPv = pressure drop across the pad, kPa

Pv_2, Pv_1 = vapour pressures at outlet and inlet temperature respectively, kPa

Ps_2, Ps_1 = saturated vapour pressures at outlet and inlet temperature respectively, kPa

P_{fan}, P_{pump} = power of fan and pump respectively, kW

$□_{fan}$ and $□_{motor}$ = fan and motor efficiencies, %

COP = coefficient of performance

CER = cost-to-efficiency ratio

K = coefficient of permeability

Cost = cost of material in US Dollars, $

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Experimental setup

The experimental setup used in this experiment was made up of an aluminium duct of 120 cm length with a fan at the entrance and a circulating pump to drip water on the pads as shown in figure 2. The pad section is removable. Three sensors for measuring inlet and outlet relative humidity, temperature and wind speed, are placed 40 cm before and after the pad in order to measure inlet and outlet parameters. This distance keeps sensors at equidistance from pads to be analyse while allowing accurate and stable readings.

Wood wool pad was made from wood wool fibers packed to fill a rectangular aluminium structure of width (W) x height (H) x thickness (□) = 0.47 x 0.41 x 0.05 m. A commercial pad (Celdek) was acquired from local market (Katako market) and compared with our wood wool pad.

2.1.2 Measuring instruments

The inlet air velocity and dry bulb temperature were measured using HoldPeak HP-856A. Digital multimeter HoldPeak HP-90EPC was used to measure outlet dry bulb temperature. Inlet wet bulb temperature was measured using another HoldPeak HP-90EPC by covering its probe with a wetted cotton wool. The temperature of the circulated water was measured with a TP101 thermometer.

Figure 1 Commercial Celdek pad (left) against locally made wood wool pad (right)

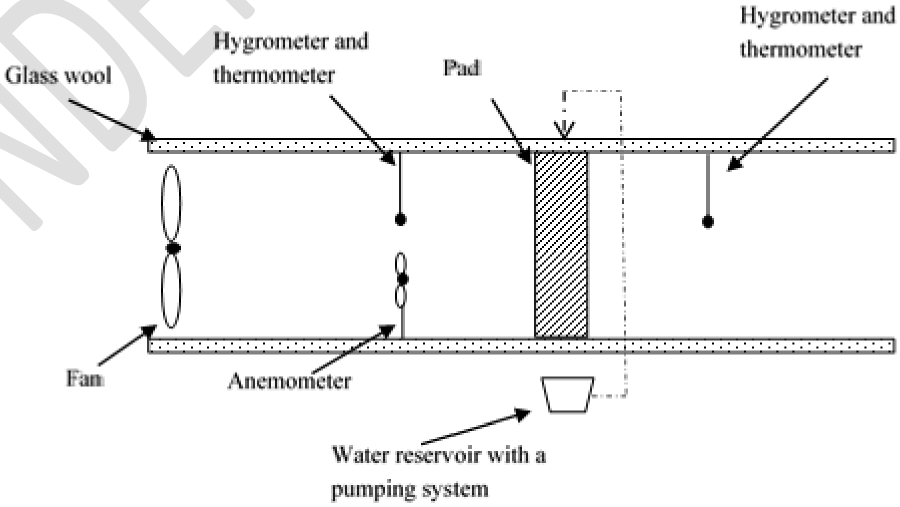

Figure 2 Schematic diagram of Cross-sectional view of experimental setup

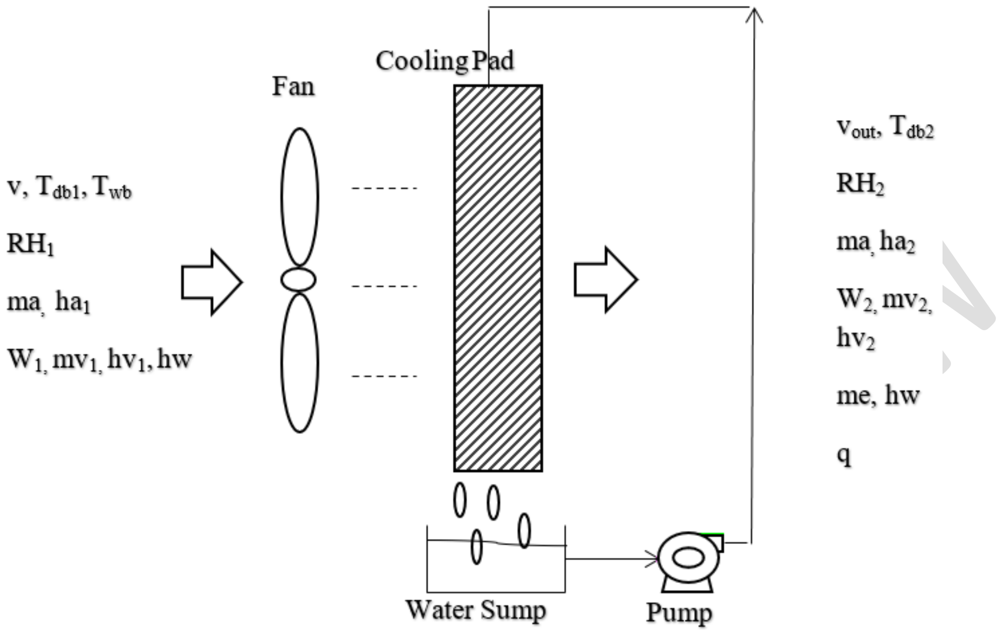

Figure 3 Diagram of a balance around the pad

2.2 Methods

The characterization of our local pad started by applying its saturation efficiency (equation 1) and its cooling capacity (equation 2).

Saturation efficiency is given by: $\text{eff} = \frac{T_{db1} - T_{db2}}{T_{db1} - T_{wb}}$ Equation 1

Cooling capacity is given by: $q = m_a Cp_a (T_{db1} - T_{db2})$ Equation 2

2.3 Energy balance

When thermal equilibrium is reached, the energy balance for air/water vapour mixture across the pads can be written as:

$maha_1 + mv_1hv_1 + mv_1hw - maha_2 - mv_2hv_2 - mv_2hw - q = 0$

$maha_1 + mv_1hv_1 + mv_1hw = maha_2 + mv_2hv_2 + mv_2hw + q$ Equation 3

where the indices 1 and 2 indicate inlet and outlet parameter respectively.

Let $me = mv_2 - mv_1$ Equation 4

$W = mv/ma$ Equation 5

$q = ma\ Cpa\ (T_{db1} - T_{db2})$ Equation 6

⇨ $ma\ (ha_1 - ha_2) + mehw + mv_1hv_1 + mv_2hv_2 = q$ Equation 7

⇨ $ha_1 - ha_2 + W_1(hv_1 + hw) - W_2\ (hv_2 - hw) = Cpa\ (T_{db1} - T_{db2})$ Equation 8

2.4 Heat and mass transfer coefficients

The heat loss (q) is also known as the heat transferred which is carried by the cool air serving as a comfort. The heat transferred can also be expressed as:

$$q = h_H A_s \Delta T$$ Equation 9 (Jain and Hindoliya, 2011)

$$\Delta T = \frac{T_{db2} - T_{db1}}{ln((T_{db2} - T_{wb})/(T_{db1} - T_{wb}))}$$ Equation 10

And the mass of water evaporated (me) or mass transferred through the evaporative cooling process can be expressed as:

$$me = h_M A_s \Delta \rho_v$$ Equation 11 (Jain and Hindoliya, 2011)

$$\Delta \rho_v = \frac{\rho_{v2} - \rho_{v1}}{ln((\rho_{v2} - \rho_{wb})/(\rho_{v1} - \rho_{wb}))}$$ Equation 12

2.5 Water evaporation rate

The amount of water evaporated during the evaporative cooling process can be calculated as:

$$Er = \frac{me}{\rho vw}$$ Equation 13

ρvw is density of water vapour obtained from saturated water table (International Association for the Properties of Water and Steam (IAPWS, 1995).

2.6 Pressure drop

Evaporative cooling process causes a Pressure drop across the pads which can be expressed as

$$\Delta Pv = Pv_2 - Pv_1$$ Equation 14 (Laknizi et al., 2018; Pal et al., 2006)

$$Pv_2 = Ps_2 \times RH_2 \; ; \; Pv_1 = Ps_1 \times RH_1$$

Pv_2 and Pv_1 are vapour pressure at inlet and outlet respectively, and Ps is the saturated vapour pressure obtained from air properties table (Alvarado and Klein, 1970)

2.7 Permeability of pads

The coefficient of permeability K of a pad gives an information on its capacity of retaining water for the time necessary for an optimum heat and mass transfer. From Darcy's law, the kinetics of fluid flow through a porous media can be expressed in terms of driving force and permeability of the medium (Pal et al., 2006). For an evaporative cooling pad, the permeability can be expressed as:

$$q = \frac{K}{} \frac{\Delta Pv}{\square} As \quad => \quad K = \frac{\frac{me}{\Delta \rho v} \times \square}{\Delta Pv \times As}$$ Equation 15 (Pal et al., 2006)

where Q represents volumetric flow rate, □ is dynamic viscosity obtained from air properties table and □ is thickness (Alvarado and Klein, 1970).

The greater the K value, the higher will be the rate of fluid flow through a material. K is dependent on the fluid and porous material used (Pal et al., 2006).

2.8 Coefficient of performance (COP)

As the ratio of the cooling capacity to the energy input, the coefficient of performance (COP) helps in evaluating the energy efficiency of cooling pads. The higher the COP the more efficient a cooling pad is.

$$\text{COP} = \frac{q_{pad}}{P_{fan} + P_{pump}}$$ Equation 16 (Laknizi et al., 2018)

P_{pump} = 18W given by the manufacturer.

$$P_{fan} = \frac{ma \times \Delta Pv}{\rho a \times \eta_{fan} \times \eta_{motor}}$$ Equation 17 (Laknizi et al., 2018)

Where ρa is density of air $\eta_{fan} = \eta_{motor}$ = 80% by assumptions

2.9 Cost to efficiency ratio (CER)

The ratio of cost of the pad to efficiency (saturation efficiency) (CER) allows the selection of optimum evaporative cooling pads and materials accessible to a certain class of user. It is expressed as:

$$\text{CER} = \frac{Cost}{eff}$$ Equation 18

3 RESULTS AND DISCUSSION

3.1 Overall analysis

Exposed to similar initial conditions of dry bulb temperature as shown on figure 4, Celdek pad and wood wool pad (*Hyphaene thebaica*) gave out similar outlet temperature with Celdek giving 20.92^{o}C on average against 21.83^{o}C for wood wool. Figure 5 and 6 present a plot of wet bulb temperature against running water temperature with time at different frontal velocity. We observe that the water temperature is getting close to the wet bulb temperature in an asymptotic manner. This behaviour was also observed by Jain & Hindoliya (2011).

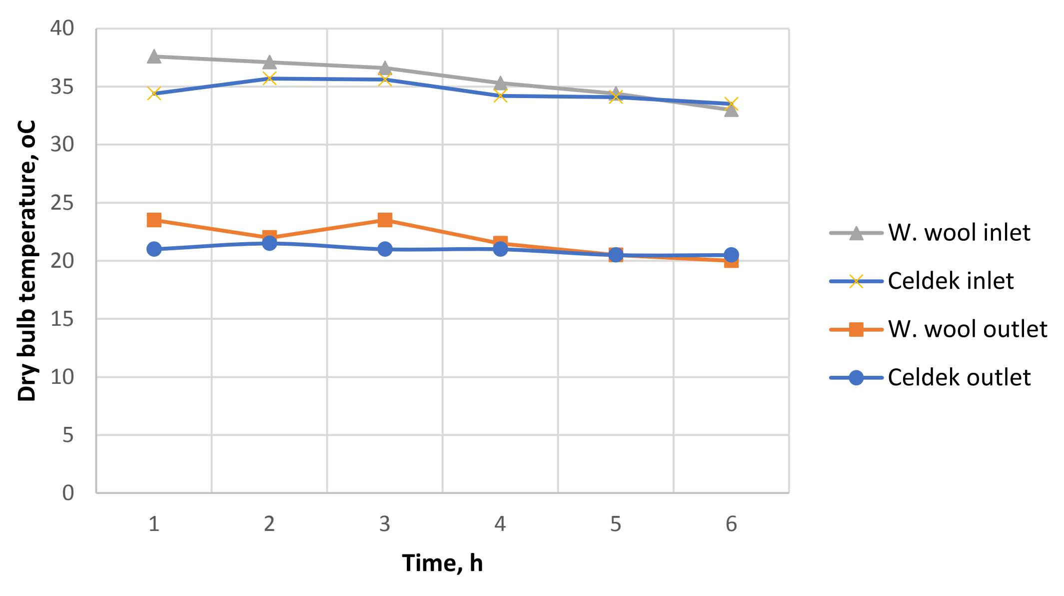

Figure 4 Dry bulb vs water temperature for Celdek pad at low frontal velocity

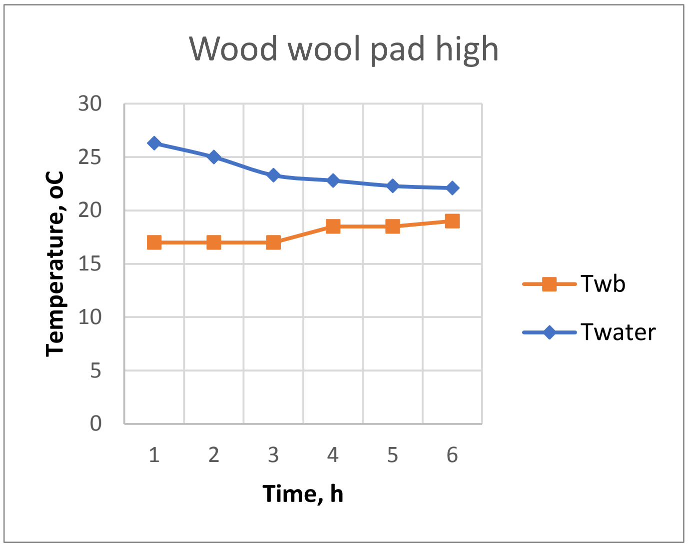

Figure 5 Wet bulb (T_{wb}) vs water temperature (T_{water}) for wood wool pad at high frontal velocity

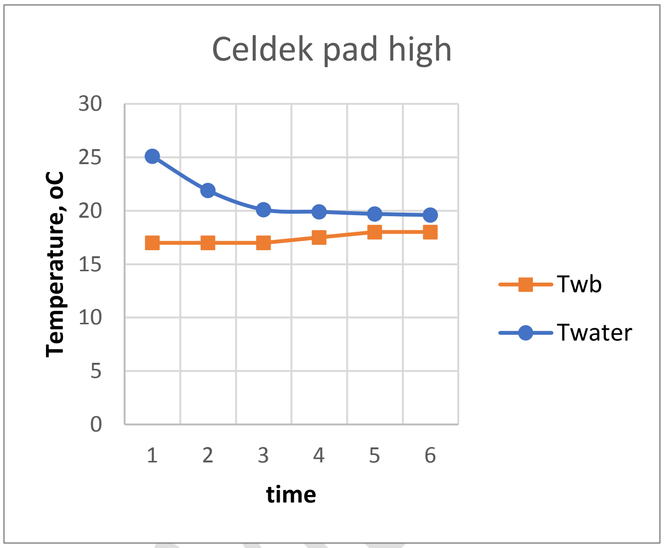

Figure 6 Wet bulb (T_{wb}) vs water temperature (T_{water}) for Celdek pad at high frontal velocity

A close analysis of the pads at a frontal velocity of 5.522 m/s was done and the detailed experimental data are given from the figure 4 to figure 10 concerning saturation efficiency, cooling capacity, pressure drop, mass and heat transfer coefficients, water evaporation rate and coefficient of performance. With increasing time, the pads become more wet and more efficient as shown in the figure 4 with saturation efficiency ranging from 68.45% to 92.86% for wood wool pad and from 77.01% to 83.87% for Celdek pad. More mass is transferred (figure 7) creating more water to evaporate (figure 8). This drops the pressure drop across the pad and allows more heat exchange (figures 6 and 9) leading to a lower outlet temperature for better comfort. However, a variation of cooling capacity is observed from 0.1867 kW (wood wool) and 0.1658 kW (Celdek) to around 0.1606 kW for both pads in a form of a decreasing oscillating curve as showed in the figure 5 causing the pads to perform less with time (figure 10). This latter phenomenon could be assigned to the fact that with time, the pads became saturated with dirt since the water was directly recycled without filtration. Indeed, the water used was becoming cooler but dirtier since not cleaned throughout the process. That is why regular changing of the water is recommended when the pad system is exposed to outside dusty environment as suggested by many researchers (Chijioke, 2017; Dhamneya et al., 2018). In certain evaporative coolers, a protective net is added to reduce the entrance of dust into the pads.

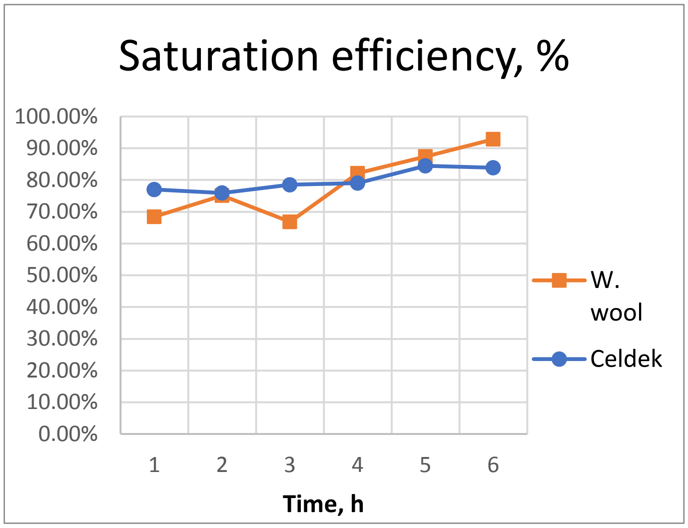

Figure 7 Saturation efficiency of Wood wool and Celdek pad

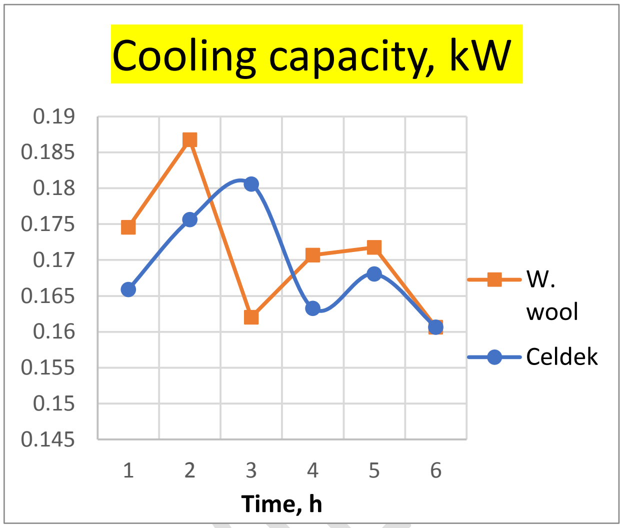

Figure 8 Cooling capacity of Wood wool and Celdek pad

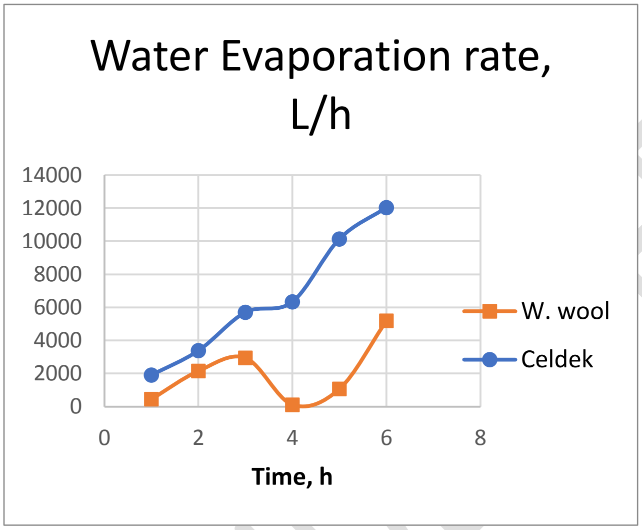

Figure 9 water evaporation rate of Wood wool and Celdek pad

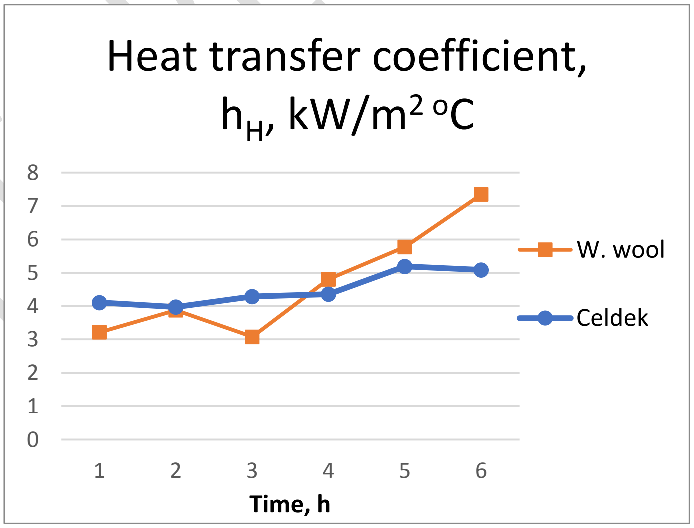

Figure 10 Heat transfer coefficient of Wood wool and Celdek pad

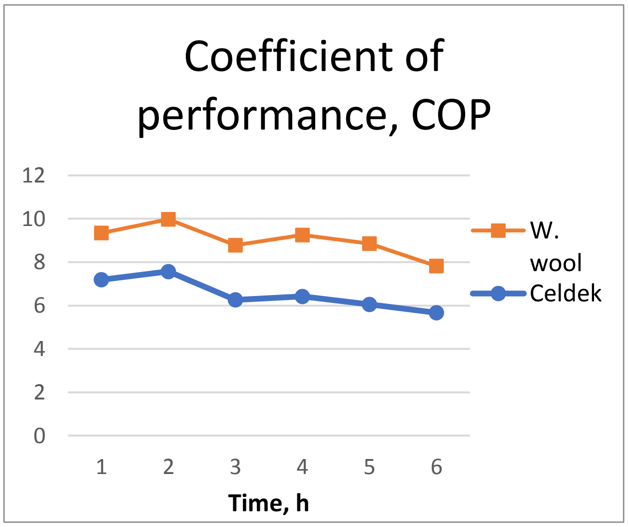

Figure 1 Coefficient of performance of Wood wool and Celdek pad

3.2 Effect of Relative humidity and physical properties on the performance of pads

Based on ASHRAE Standards-55 (2013), a comfort zone should have a relative humidity between 20% and 70% (ASHRAE, 2013). In this experiment, wood wool could provide an outlet air with 33.33% relative humidity against 50% for Celdek on average basis (see table 2). The mass transfer coefficient and the pressure drop across Celdek pad happened to be higher than that of wood wool pad. In fact, these two properties mostly are influenced by the size and the structure / arrangement of the pad. As shown in table 1, Celdek pad is more organized with optimized size to perform well. On the other hand, wood wool pad is a filling of wood wool inside a certain cubic structure which made it have a higher permeability coefficient (see table 2). Therefore, wood wool retained more water than Celdek material. Besides, individual wood wool fibers are packed in disordered and uncontrolled manner (figure 1). That is what could explain the non-smoothness of wood wool pad plots in the figure 7 (mass transfer coefficient graph) and figure 8 (water evaporation rate graph).

Table 1 Physical characteristics of Celdek and wood wool pad

Pad type	**Scientific names**	**Frontal Velocity v (m/s)**	**Mass flow rate ma (kg/s)**	**Outlet velocity v_{out}, m/s**	**Flute height / Coil thickness (mm)**	**Structure**	**Arrangement**	**Pad size, cm^3**	**Material's Mass (g)**	**Pad/packing density (g/cm^3)**
Celdek pad	'Trade name'	5.522	0.0122	1.166	1.5	Honeycomb	ordered: 1 cm between crests	9635	351	36.4297
Wood wool pad	Hyphaene thebaica (leaves stipulate)	5.522	0.0122	0.825	1	Coil	disordered: packing to filling	9635	180	18.6819

Table 2 Average temperature, efficiency and evaporation rate of Celdek and wood wool pad

Pad type	**Average inlet dry bulb temperature T_{db1} (^oC)**	**Average wet bulb temperature T_{wb} (^oC)**	**Average outlet dry bulb temperature T_{db2} (^oC)**	**Minimum outlet dry bulb temperature $T_{db2\ min}$ (^oC)**	**Average saturation efficiency (%)**	**Average RH of inlet wind**	**Average RH of outlet wind**	**Average water evaporation rate (L/h)**	**Average Permeability coefficient (mm^2)**

Celdek pad	34.58	17.42	20.92	20.50	79.80%	13.50%	50.00%	6581.736	0.000265
Wood wool pad	35.67	17.83	21.83	20.00	78.80%	13.83%	33.33%	1984.414	0.001568

3.3 Analysis based on average and maximum performances of pads

Tables 1 and 2 present some physical and thermal properties of Celdek pad and wood wool pad (*Hyphaene thebaica*). On average data basis, Celdek pad and wood wool pad have similar performances. Wood wool could provide an outlet temperature of as low as 20.0^{o}C against 20.5^{o}C for Celdek even though the latter had a higher saturation efficiency (79.80%) and could provide a more humid air (50% Relative humidity). This higher relative humidity implies a higher water evaporation rate of 6581.736 L/h for Celdek pad. However, based on maximum values observed during the experiment, wood wool pad presented the highest saturation efficiency of 92.86% (see figure 11), highest cooling capacity of 0.1867 kW (figure 12), highest heat transfer coefficient of 7.3497 kW/m^{2} ^{o}C (figure 13), highest coefficient of performance of 9.9775 (figure 13) and the best (lowest) cost to efficiency ratio of 6.68076 and pressure drop of 0.1523kPa (figure 13). To the best of our knowledge, this performance and data from wood wool of *Hyphaene thebaica* is unique and not available in the literature.

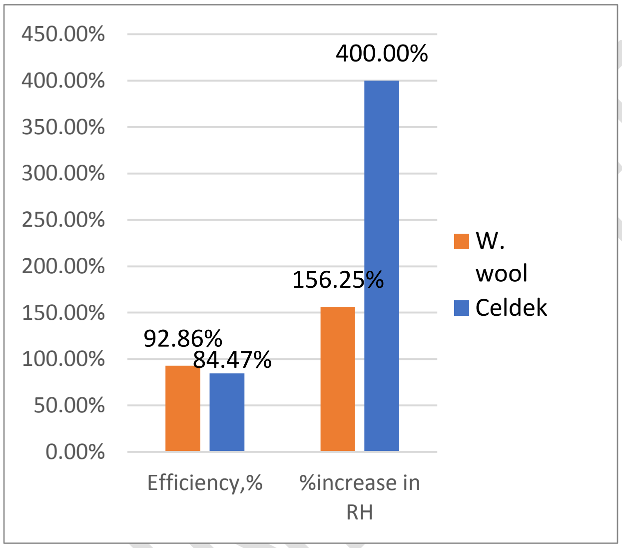

Figure 2 Maximum efficiency and relative humidity increase of Wood wool and Celdek pad

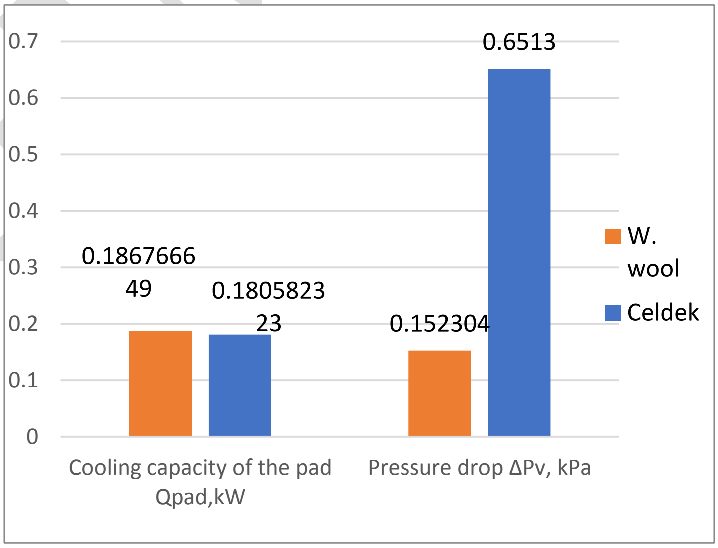

Figure 33 Maximum Cooling capacity and pressure drop of Wood wool and Celdek pad

3.4 Cost-effectiveness analysis

On the basis of USD currency (March 2021 rate) cost to efficiency ratio (CER) was plotted. The CER plot on figure 13 of wood wool is lower than that of Celdek (6.8070 against 23.9676). This shows a relatively lower initial operating cost from wood wool pad compare to commercial Celdek pad.

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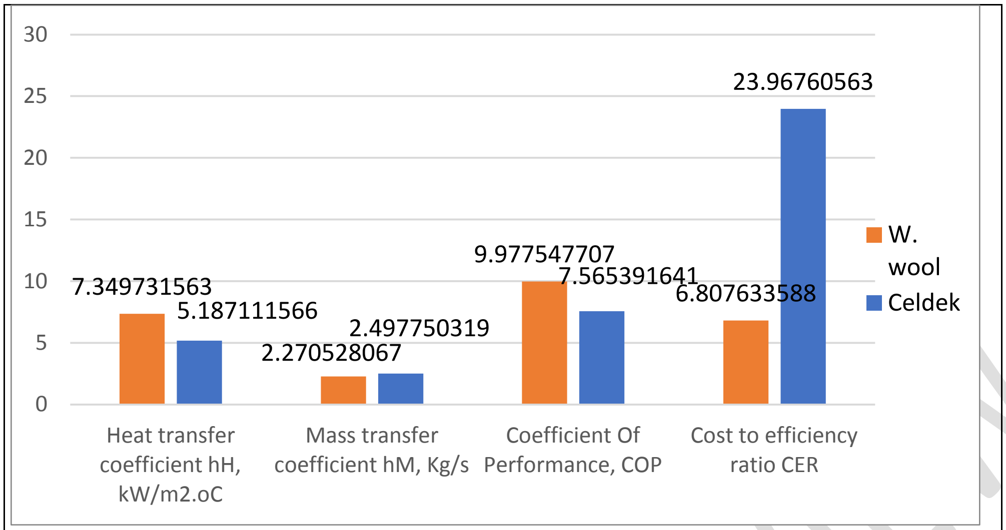

Figure 44 Maximum values of heat and mass transfer coefficients, coefficient of performance and cost to efficiency of Wood wool and Celdek pad

4 CONCLUSION

A cost-effective locally made evaporative cooling pad from the fibres of the stipulates of *Hyphaene thebaica* (wood wool pad) was characterized successfully. It presented interesting thermodynamic parameters with performances challenging those of commercially available Celdek pad and having better cost-to-efficiency ratio. Studying and improving physical characteristics could optimize the performance of wood wool pad (*Hyphaene thebaica*) and even open up ways for industrial production of such pads.

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