Theoretical Performance Analysis Of Coconut Coir As Media In Evaporative Coolers

Lateef L. Akintunji, Ibrahim U. Haruna, Bello S. Momoh

Abstract: Coconut coir is an agricultural waste that is produced in reasonable quantities in some developing countries of the world like Nigeria. This waste is used in some evaporative cooling systems as cooling media. This paper therefore attempts to analyze the performance of coconut coir pad as a media in direct evaporative coolers. In this study, the average condition of 39.9 ^{0}C dry bulb temperature and 8.1% relative humidity of Kano is selected for the analysis. The primary air mass flow rate considered varies between 0.16 kg/s to 0.54kg/s and the performance of the coconut coir pad is analyzed based on the saturation efficiency, leaving air temperature, relative humidity, cooling capacity and water consumption. The results of the analysis of the coconut coir based on the air flow rates considered reveal that the saturation efficiency decreases from 64.7% to 55.9%, the leaving air temperature increases from 25.2^{0}C to 27.1^{0}C, relative humidity decreases from 46.4% to 38.2%, the cooling capacity increases from 8230kJ/h to 24055.kJ/h and the water consumption increases from 3.57kg/h to 9.72kg/h. These results show that the coconut coir pad performed better at lower air mass flow rates where lower leaving air temperature and relatively higher relative humidities are obtained.

Index terms: Temperature, Relative humidity, Water consumption, Coconut coir, Cooling capacity

Nomenclature

C_p = Specific heat of air, J/kg K
T_1, T_3 = Dry and wet bulb temperatures of ambient air, ^{0}C
T_2 = Leaving air temperature, ^{0}C
A_f = Frontal area of the pad, m^2
A_{fi}, A_{fo} = Inlet and exit areas of the pad respectively, m^2
A_w = Wetted surface area of the pad, m^2
A_s = Wetted surface area per unit volume of pad, m^2/m^3
ω_1, ω_2 = Ambient and indoor humidity ratio respectively, kg/kg of dry air
H, W, l = Height, width and length of the cooler, m
V_i, V_o = Inlet and outlet velocities of the cooler, m/s
V_p = Volume of the pad, m^3
V_a = Average velocity of air through the pad, m/s
υ, ρ = Kinematic viscosity (m^2/s) and density (kg/m^3) of air
k = Thermal conductivity of air, W/m. K
RH_o, RH_i = Ambient and indoor relative humidities respectively, %
m_a, V_f = Air and volume flow rate of air in kg/s and m^3/s respectively
l_c = Charateristic dimension of the pad, m
NU, Re, Pr = Nusselt, Reynold and Prandtl numbers respectively
h = Heat transfer coefficient
Q_c, Q_{co} = Cooling capacity (kJ/h)and water consumption rate (kg/h)
η_{sat} = Saturation efficiency of the cooling pad

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1.0 Introduction

There is growing demand for space cooling in hot climates as people spend most of their days indoors. To a very large extent, the quality of lives of human beings depends on the quality of their indoor environment. Thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment [1]. Therefore, the provision of thermal comfort for the user of buildings is fundamental. The conventional refrigerated-based air conditioning systems are the systems commonly used for providing thermal comfort for occupants of a living space. But in most developing countries of the world, the use of these systems is impeded by the epileptic power supply and the high cost of the systems. Other problems associated with the use of such systems include: They are relatively expensive for the common man They are not fully utilized in areas where the power supply is epileptic and constantly interrupted They are characterized by poor indoor air quality because of the use of recirculated air Their maintenance require the service of a skilled personnel They are detrimental to the ozone layer because of the release of CFC and HCFC Their high electric power consumptions translate to high operational cost. Evaporative coolers are suitable alternative to refrigerated-based air conditioning systems. In this system, the natural effect of evaporation is used to remove the heat from the air of the living space. Unlike the refrigerated-based air conditioning systems, the evaporative coolers have the following advantages: Unlike most refrigerated cooling systems that rely on recycled cooled air with partial fresh air replacement, the evaporative cooler enjoys popularity in the introduction of a continuous supply of freshly cooled outdoor air. These creations of healthy invigorating conditions generate a feeling of relaxed enthusiasm, conducive to improve people concentration and work output. This is due to the naturally cooled, humidified, negatively ionized air which does not dry up nasal passages, eyes or skin, unlike the positively ionized, artificially cooled air from a refrigerated based air conditioning Helps maintain natural humidity levels, which benefits both people and furniture and cut static electricity Does not need an air-tight structure for maximum efficiency, so occupants can open doors and windows The working fluid, water, does not have negative impacts on the environment and it is relatively available and cheap The technology of evaporative cooler is simpler, the cooler costs about 80 per cent less than refrigerated based air conditioner that will cool the same area. The installation costs of evaporative coolers are comparable to conventional air conditioning. Evaporative coolers can be direct, indirect or direct-indirect systems. Apart from the climatic region where the evaporative cooler is to be used, one significant factor that determines the performance of an evaporative cooler is the type of the evaporative cooling pad used [2]. Different evaporative cooling pads have a different water retention capacity which is attributable to the different structural features of the pad. Therefore, the performance of evaporative coolers to a reasonable degree is hinged on the saturation effectiveness of the evaporative cooling pad material. This paper attempts to analyze the performance of coconut coir as media in direct evaporative cooler.

1.1 Recent work on evaporative coolers

In the context of evaporative cooling, several authors dedicated their researches to the development of direct, indirect and combined indirect-direct evaporative cooling systems. Qun et al [3] worked on the new approach to analyse and optimize evaporative cooling systems, Kulkarni et al [4] theoretically analysed the performance of jute fiber rope bank as media in evaporative coolers, Metin et al [5] determined the relationship among air velocity, cooling efficiency and temperature decrease at cellulose based evaporative cooling pad, Valesco et al [6] discussed the phenomenon of evaporative cooling from a humid surface as an alternative method for air-conditioning, Kulkarni et al [7] theoretically analysed the performance of indirect-direct evaporative coolers in hot and dry climates, Vivek [2] experimentally investigated the performance of evaporative desert cooler using four different cooling pad materials, Metin et al [8] studied the effects of air velocity on the performance of pad evaporative cooling, Kulkarni et al [9] compared the performance of evaporative cooling pads of alternative materials.

1.2 Description of direct evaporative cooler

In direct evaporative coolers, non-saturated air comes into contact with water-saturated cooling pad, and evaporation occurs. The necessary latent heat is provided by the air, which cools down. In addition, the moisture content of the air rises. Direct evaporative cooling is represented on psychrometric chart by a displacement along a constant wet-bulb temperature line as shown in figure 1 [10].

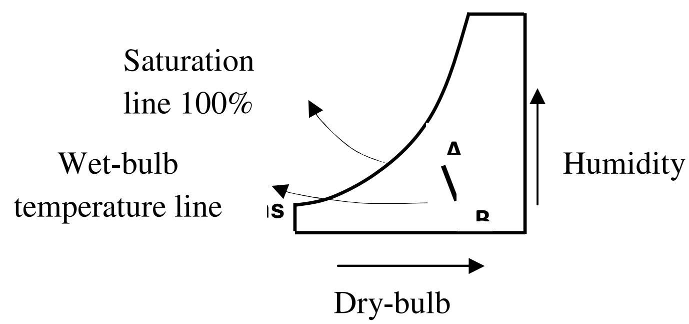

Figure 1.0 Psychrometric Chart of Direct

The weather data of Kano on the basis of usually prevalent conditions in the months of March, April and May were classified into five groups of average maximum dry bulb temperature (T_1), relative humidity (RH_0), wet bulb temperature (T_3) and humidity ratio (w_1) as shown in Table 1. The most frequent occurring conditions of $T_1 = 39.9$ 0C,$RH_0 = 8.1\%$, $T_3 = 17.40$C and $w_1 = 0.0032$ kg/kg of dry air, are selected for the analysis.

Table1. Average weather data of Kano, Nigeria

Ambient Condition	DBT_{max} (^0C)	Total days	T_1(^0C)	RH_0 (%)	T_3(^0C)	W_1 (kg/kg)
A	Less than 34	3	32.4	9.4	13.7	0.0028
B	$34 \leq DBT < 37$	7	36.1	6.8	14.2	0.0020
C	$37 \leq DBT < 40$	23	39.4	8.1	17.4	0.0032
D	$40 \leq DBT < 42$	12	41.4	12.2	19.8	0.0058
E	42 & Above	–	–	–	–	-

$\rho = 1.12\ kg/m^3$ $K = 0.027\ W/m.^0C$ $C_{pa} = 1006\ J/kg.^0C$ $v = 1.69 \times 10^{-5} m^2/s$ $Pr = 0.711$

The humid specific heat, C_{pu}, is determined from equation 1.

$$C_{pu} = C_{pa} + w_1 C_{pv} \quad \ldots (1)$$

Where $C_{pv} = 1868$ J/kg K and $w_1 = 0.0032$ kg/kg of dry air. All these properties were evaluated at the ambient air temperature considered.

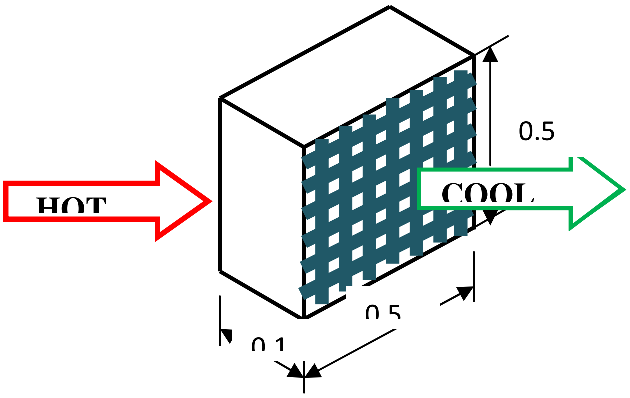

Figure 2.0 Cooling Pad

2.2 The Cooling Pad Geometrical Parameters

The coconut coir pad considered in this study is assumed positioned in such a way that air traverses horizontally across the pad entering on one side and leaving the other as shown in figure 2. The lateral sides of the cooler are assumed to be closed. This means that there is one dimensional flow of air across the pad. The wetted surface area per unit volume of the coconut coir pad is taken to be 320m^2/m^3. The frontal area is the area of the pad through which hot air enters the pad and and is calculated using equation 2.

$$A_f = H \times W \quad \ldots (2)$$

The volume of the pad is computed from equation 3.

$$V_P = H \times W \times l \quad \ldots (3)$$

Since the wetted surface area per unit volume of the cooling pad is assumed to be 320m2/m3, therefore, the total wetted surface area of the pad is computed using equation 4.

$$A_w = V_P \times A_S \quad \ldots (4)$$

2.3 Mass flow rates of air

The mass flow rate of air through the cooling pad is a function of the air velocity and is calculated on the basis of the frontal area of the pad, the density of the coconut coir pad and the velocity of air at the entry. The mass flow rates of air considered in this study are 0.16, 0.23, 0.31, 0.39 and 0.54 kg/s. The volume flow rate of air is calculated from equation 4a

$$V_f = \frac{m_a}{\rho} \quad \ldots (4a)$$

The inlet and the outlet velocities of air calculated based on equation 5 and 6 [9].

$$V_i = \frac{V_f}{A_{fi}} \quad \ldots (5)$$

$$V_o = \frac{V_f}{A_{fo}} \quad \ldots (6)$$

The characteristic dimension of the pad is given by:

$$l_c = \frac{V_P}{A_w} \quad \ldots (7)$$

The characteristic dimension is used to determine the Reynolds number. The pertinent parameters for the pad are shown in Table 2.

Table 2. The cooling pad geometry parameters

l (m)	0.10				
l_c (m)	0.003125				
A_{fi} (m^2)	0.25				
V_p (m^3)	0.025				
A_w (m^2)	8.0				
m_a(kg/s)	**0.16**	**0.23**	**0.31**	**0.39**	**0.54**
V_f (m^3/s)	0.14	0.21	0.28	0.34	0.48
V_i (m/s)	0.57	0.82	1.10	1.39	1.92
A_{fo} (m^2)	0.25				
V_o (m/s)	0.57	0.82	1.10	1.39	1.92
V_a (m/s)	0.57	0.82	1.10	1.39	1.92

The characteristic dimension is used to determine the Reynolds number. The pertinent parameters for the pad are shown in Table 2. The Nusselt number correlation is expressed in equation 8 [9].

$$Nu = 0.1\left(\frac{l_c}{l}\right)^{0.12} (Re)^{0.8} (Pr)^{0.33} \quad \ldots (8)$$

The heat transfer coefficient is determined from equation 9.

$$h = \frac{Nu \times K}{l_c} \quad \ldots (9)$$

From equation 8, the Reynolds number is then determined and expressed based on the average velocity of air through the cooling pad and the characteristic dimension.

$$Re = \frac{V_a \times l_c}{v} \qquad \ldots (10)$$

In this study, the air properties are evaluated based on the selected ambient conditions.

2.5 Determination of the performance parameters of the cooling pad

The saturation efficiency of the cooling pad is calculated based on equation 11 [11].

$$\eta = 1 - \exp\left[-\frac{h \times A_w}{m_a \times C_{pu}}\right] \qquad \ldots (11)$$

The leaving air temperature is calculated based on equation 12.

$$T_2 = T_1 - \eta \times (T_1 - T_3) \qquad \ldots (12)$$

Since the process in the evaporative cooler is adiabatic, it means that the wet bulb temperature of the inlet and outlet of the cooler are the same. Therefore, the humidity ratio and the relative humidity of the leaving air are determined using the psychrometric chart. The cooling capacity of the evaporative cooling pad is calculated from equation 13.

$$Q_c = m_a(T_1 - T_2) \times 3.6 \quad kJ/h \quad \ldots (13)$$

The water consumption rate which is a function of the specific humidity and the mass flow rate of air is determined from equation 14.

$$Q_{co} = m_a(w_2 - w_1) \qquad \ldots (14)$$

4.0 Results and Discussion

Table 3. Performance parameters of the coconut coir

m_a (kg/s)	0.16	0.23	0.31	0.39	0.54
Re	105	152	204	257	356
Nu	2.44	3.28	4.15	4.99	6.48
h	21.08	28.34	35.86	43.11	55.98
η (%)	64.7	62.2	59.9	58.2	55.9
T_2 (0C)	25.2	25.7	26.2	26.6	27.1
$w_2(kg/kg)$	0.0094	0.0090	0.0088	0.0085	0.0082
$(RH)_i(\%)$	46.4	45.0	41.3	40.0	38.2
$Q_c(kJ/h)$	8230	11412	14818	18079	24055
$Q_{co}(kg/h)$	3.57	4.96	6.24	7.44	9.72

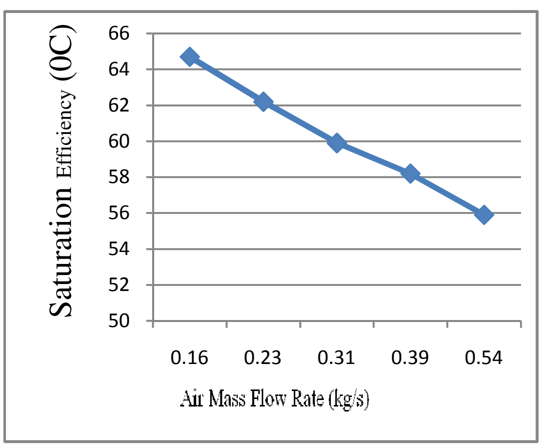

Figure 3. Saturation efficiency versus air mass flow rate

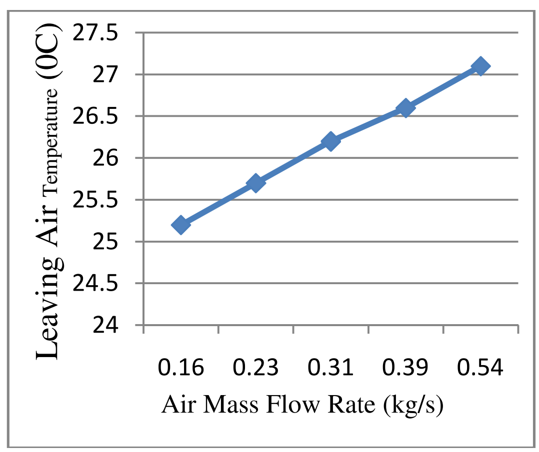

Figure 4. Leaving air temperature versus Air mass flow rate

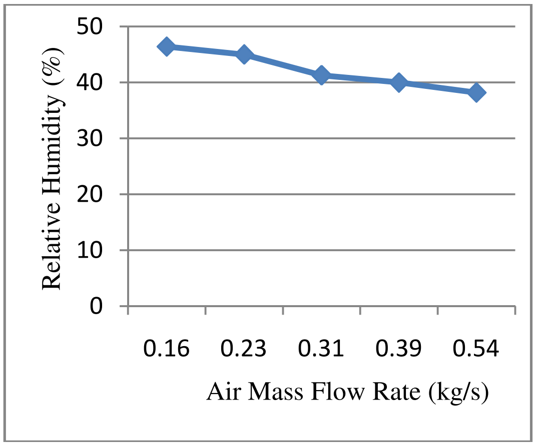

Figure 5. Relative Humidity versus Air Mass Flow rate

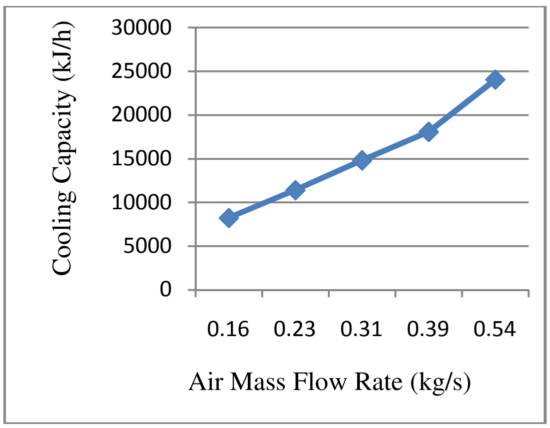

Figure 6. Cooling capacity versus air mass flow rate

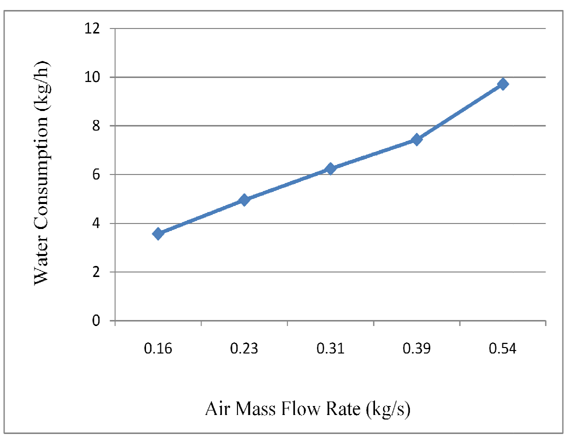

Figure 7. Water consumption versus air mass flow rate

The variation of saturation efficiency with air mass flow rate through the coconut coir pad is shown in figure 3.. This shows that there is an inverse relation between the saturation efficiency of the cooling pad and the air mass flow rate. This however can be attributed to the fact that the higher the air mass flow rate through the cooling pad, the shorter the period the air stream stays in contact with the wetted pad. Therefore, the lesser the quantity of water that would be evaporated from the pad which will consequently affect the relative humidity and the temperature of the space conditioned by the cooler that uses the coconut coir pad. This agrees with the work of [4] that saturation effectiveness is a function of air velocity. Figure 4 shows that the leaving air temperature increases with increase in the air mass flow rate while figure 5.0 shows that the relative humidity in the downstream of the coconut coir pad decreases with the increase in the air mass flow rate. As stated above, these conditions can be attributed to the shorter period of contact between the air stream and the wetted pad. This means that there is no enough time to ensure maximum conversion of the sensible heat in the incoming air stream to the latent heat of evaporation of the water soaked coconut coir pad. Therefore, less water evaporates into the air stream with a consequent lower temperature reduction. According to [5], there is negative relationship between velocity of air passing through a pad and temperature decrease of air passing through a pad in evaporative pad cooling systems. The variation of the cooling capacity of the coconut coir pad with air mass flow rate is shown in figure 6. It can be seen that the cooling capacity varies linearly with the air mass flow rate. This can be attributed to the fact that the cooling capacity of cooling pads in an evaporative cooling system is a function of the air velocity through it. Figure 7 show that there is positive relationship between the water consumption of the cooling pad and the air mass flow rate. This can be attributed to the condition that the higher the air velocity through the cooling pad the higher would be the rate of evaporation of water from the water soaked pad. This scenario shortens the contact period of air and the cooling pad which invariably affect the desired relative humidity and the leaving air temperature in the conditioned space.

References

[1]. ASHRE, 2005. Handbook of Fundamentals

[2]. Vivek, W.K, 2011. “Experimental Investigation of Desert Cooler Performance Using Four Different Cooling Pad Materials”. American Journal of Scientific and Industrial Research 2(3): 418-421. 2011, science Huβ, http://www.scihub.org/AJSIR , doi: 10.5251/ajsir. 2011.2.3.418.421

[3]. Qun, C., Kangding, Y., Moran, W., Ning, P. and Zen-Yuan, G, 2010. A new approach to 1-7. analysis and optimization of evaporative cooling system 1: Article in Press, Energy xxx, pp.doi: 10.1016/j.energy.2010.02.037

[4]. Kulkarni, R.K. and Rajput, S.P.S, 2010. “Theoretical Performance Analysis of Jute Fiber Rope Bank as Media in Evaporative Coolers”. Indian Journal of Science and Technology. Vol. 3, No. 10, pp. 1075-1080. Jute for air conditioning http://www.indjst.org

[5]. Metin, D., Cengiz, K., Levent, S. and Yilmaz, Y, 2010. “Determination of the Relationship Among Air Velocity, Cooling Efficiency and

Temperature Decrease at Cellulose based Evaporative Cooling Pad". African Journal of Agricultural Research, Vol. 5 (24), Pp3477-3482. http://www.academicjournals.org/AJAR

[6]. Valesco,E., Rey, M.A. and Tejoro, G.A, 2010. "The phenomenon of evaporative Cooling from a Humid surface as an alternative method for air-conditioning" International Journal of Energy and Environment, Volume 1, Issue 1, Pp 69-96.http://www.IJEE.IEEFoundation.org

[7]. Kulkarni, R.K. and Rajput, S.P.S, 2011. "Theoretical Performance Analysis of Indirect-Direct Evaporative Cooler in Hot and Dry Climates". International Journal of Engineering Science Technology (IJEST), Vol. 3, No. 2, pp. 1239-1251. http://www.ipublishing.co.in/jarvol1no1210/EIJAER2046.pdf

[8]. Metin, D., Cengiz, K., Levent, S. and Yilmaz, Y., Ali, B. and Omer, P, 2011. The Effect of Air Velocity on the Performance of Pad Evaporative Cooling Systems. African Journal of Agricultural Research, Vol.6 (7), pp. 1813-1822. http://www.academicjournals.org/AJAR

[9]. Kulkarni, R.K. and Rajput, S.P.S, 2011. Comparative performance of evaporative cooling pads of , Alternative materials, International Journal of Advanced Engineering and Technologies vol. 10, issue No. 2, pp. 239-244. 2011 http://ijaest.iserp.org

[10]. www.docstoc.com/.../Energy-Efficient Space Cooling-A case for evaporative cooling

[11]. Camrago, J.R., Ebinuma, C.D., and Siveria, J.L, 2005. "Experimental Performance of Direct Evaporative Cooler operating during summer in Brazilian City", International Journal of Refrigeration, Vol. 28 pp1124-1136. http://www.academicjournals.org/AJSIR