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THE USE OF FIBER WOOD AS EVAPORATIVE PAD PACKAGING MATERIAL

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***Abstract**: Currently, the most used refrigeration system applied to air conditioning for human thermal comfort is the vapor compression system. However, other thermal systems such as the evaporative cooling system can be an economical alternative in many cases. This paper presents the basic principles of the direct evaporative cooling process, the mathematical development of the equations of thermal exchanges and the results of experimental tests performed in the Air Conditioning Laboratory at the University of Taubate Mechanical Engineering Department .The main objective of this paper is to analyze the technical and economic viability of use of natural fibers as evaporative cooling package material and new configurations aimed to energy saving and use of natural resources. Currently, the cellulose is the material commercially used and this research studies the use of fiber wood as replacement material. It will be constructed a several range of panel thicknesses, with different densities and conducted laboratory tests with the purpose of obtaining graphs that represent the coefficient of performance (COP) as a function of flow rate and compare the results with those of the panels commercially available. It concludes that the use of fiber wood as evaporative pad material have a large potential to propitiate thermal comfort and can still be used as an alternative to the evaporative pads actually available, when compatible cost-benefit is presenting good thermal performance and a relation to an expected one.*

***Keywords**: evaporative cooling, natural fibers, thermal comfort, evaporative panel*

1. INTRODUCTION

Evaporative cooling operates using induced processes of heat and mass transfer, where water and air are the working fluids. It consists, specifically, in water evaporation, induced by the passage of an air flow, thus decreasing the air temperature. When water evaporates into the air to be cooled, simultaneously humidifying it, that is called direct evaporative cooling (DEC) and the thermal process is the adiabatic saturation. The main characteristic of this process is the fact that it is more efficient when the temperatures are higher, that means, when more cooling is necessary for thermal comfort. It has the additional attractiveness of low energy consumption and easy maintenance. Due to use total airflow renewal, it eliminates the recirculation flow and proliferation of fungi and bacteria, a constant problem in conventional air conditioning systems. Due to its characteristics the evaporative cooling system is more efficient in places where the climate is hot and dry but it can also be used under other climatic conditions.

Several authors dedicated their researches to the development of direct and indirect evaporative cooling systems. Watt (1963) developed the first serious analyses of direct and indirect evaporative systems; Leung (1995) presents an experimental research of the forced convection between an air flow and an inner surface of a horizontal isosceles triangular duct; Halasz (1998) presented a general dimensionless mathematical model to describe all evaporative cooling devices used today; Camargo, Cardoso and Travelho (2000) developed a research where a thermal balance study for direct and indirect cooling systems was developed; Camargo and Ebinuma (2002) presented the principles of operation for direct and indirect evaporative cooling systems and the mathematical development of the equations of thermal exchanges, allowing for the determination of heat transfer convection coefficients for primary and secondary air flow; Dai and Sumathy (2002) investigated a cross-flow direct evaporative cooler, in which the wet honeycomb paper constitutes the packing material and the results indicate that there exists an optimum length of the air channel and the performance can be improved by optimizing some operation parameters; Liao and Chiu (2002) developed a compact wind tunnel to simulate evaporative cooling pad-fan systems and tested two alternative materials; Al-Sulaiman (2002) evaluated the performance of three natural fibers (palm fiber, jute and luffa) to be used as wetted pads in evaporative cooling; Camargo, Ebinuma and Silveira (2003) presents a thermoeconomic analysis method based on the first and second law of thermodynamics and applied to an evaporative cooling system coupled to an adsorption dehumidifier; Hasan and Sirén (2003) investigated the performance of two evaporatively heat exchangers operating under similar conditions of air flow and inlet water temperatures; Camargo, Ebinuma and Cardoso (2003) presents the basic principles of the evaporative cooling processes for human thermal comfort and presents the mathematical development of the thermal exchanges equations, allowing the determination of the effectiveness of saturation.

This paper develops a mathematical model for direct evaporative cooling system and presents the experimental results of the tests performed in a direct evaporative cooler that took place in the Air Conditioning Laboratory at the University of Taubate, placed in the city of Taubate, State of Sao Paulo, Brazil.

2. DIRECT EVAPORATIVE COOLING

The principle underlying direct evaporative cooling is the conversion of sensible heat to latent heat. Non-saturated air is cooled by heat and mass transfer increases by forcing the movement of air through an enlarged liquid water surface area for evaporation by utilizing blowers or fans. Some of the sensible heat of the air is transferred to the water and becomes latent heat by evaporating some of the water. The latent heat follows the water vapor and diffuses into the air (Watt and Brown, 1997).

Figure (1) shows a schematic direct evaporative cooling system, where water is running in a loop and the makeup water entering the sump to replace evaporated water must be at the same adiabatic saturation temperature of the incoming air. In a DEC, the heat and mass transferred between air and water decreases the air dry bulb temperature (DBT) and increases its humidity, keeping the enthalpy constant (adiabatic cooling) in an ideal process. The minimum temperature that can be reached is the thermodynamic wet bulb temperature (TWBT) of the incoming air. The effectiveness of this system is defined as the rate between the real decrease of the DBT and the maximum theoretical decrease that the DBT could have if the cooling were 100% efficient and the outlet air were saturated. Practically, wet porous materials or pads provide a large water surface in which the air moisture contact is achieved and the pad is wetted by dripping water onto the upper edge of vertically mounted pads.

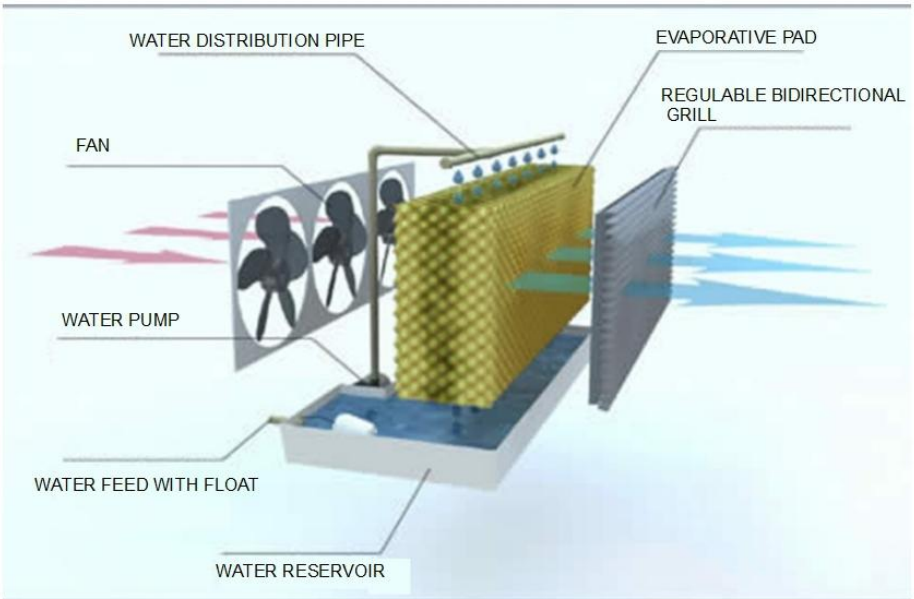


Figure 1. Schematic of evaporative pad for comfort

3. MATHEMATICAL MODEL

In the study of the psychometric process dry air is considered as a single gas characterized by an average molecular mass equal to 28.9645. In this work the humid air is considered as a mixture of two gases: the dry air and water vapour.

Considering the humid air flow close to a wet surface, according to Fig. (2), the heat transfer will occur if the surface temperature T_s is different from the draft temperature T. If the absolute humidity (concentration) of the air close the surface w_s is different from the humidity of the draft w a mass transfer will also occur. The elementary sensible heat is

$$\delta Q_s = h_c \, dA \, (T_s - T) \tag{1}$$

The h_c coefficient is determined from the Nusselt number (Nu) expressed as a function of the Reynolds number (Re) and Prandtl number (Pr). In a similar way the rate of water vapour transfer dm_V between the draft and the air close to the surface will be

$$dm_v = h_m dA\,(w_s - w) \tag{2}$$

By analysis of the interface air-liquid, the latent heat δQ_L is determined by the energy conservation law.

$$\delta Q_L = \delta Q - \delta Q_s = h_{Lvs}\; dm_v \tag{3}$$

Rearranging Eqs. (1), (2) and (3), the total differential heat flow is

$$\delta Q = [h_c\,(T_s - T) + \rho_w\, h_{Lvs}\, h_m\,(w_s - w)]\,dA \tag{4}$$

Equation (4) indicates that the total heat transfer is the result of a combination of a portion originating from temperature difference and other portion originating from the difference of the absolute humidities. These two potentials can be combined by the Lewis relationship so that the total heat flow will be expressed by a single potential that is the enthalpy difference between the air close to the wet surface and the air free current.

Using the specific enthalpy of the mixture as the sum of the individual enthalpies (Moreira, 1999) gives

$$h_s - h = (h_{sa} - h_a) + (w_s h_{vs} - w\, h_v) \tag{5}$$

With the hypothesis that air and vapor are perfect gases it follows that

$$h_s - h = c_{pu}\,(T_s - T) + h_{vs}\,(w_s - w) \tag{6}$$

where the humid specific heat is

$$c_{pu} = c_{pa} + w\, c_{pv} \tag{7}$$

In the standard environmental conditions C_{pa} = 1006 J/kg.K and C_{pv} = 1805 J/kg.K.
Therefore

$$T_s - T = \frac{(h_s - h) - h_{vs}(w_s - w)}{c_{pu}} \tag{8}$$

Combining Eq. (4) and Eq. (8) gives

$$\delta Q = \frac{h_c\, dA}{c_{pu}} \left[(h_s - h) + \frac{(w_s - w)}{R_{Le}}\,(h_{Lvs} - R_{Le}\, h_{vs}) \right] \tag{9}$$

where R_{Le} is the Lewis relationship, a dimensionless number expressed as

$$R_{Le} = \frac{h_c}{h_m\, C_{pu}\, \rho} \tag{10}$$

In the above deduction the density of the humid air was approximated by the density of the dry air. Taking the Lewis relationship as being unitary, gives $(h_{Lvs} - h_{vs}) \approx h_{Ls}$. It is also verified that the term $(w - w_s)h_{Ls}$ is usually negligible in the presence of difference of the specific enthalpies $(h_s - h)$, so that only the first term inside brackets is significant. In the same way, the total heat flow is caused by the difference of specific enthalpies of the air and of the saturated air close to the wet surface and is given by

$$\delta Q = \frac{h_c\, dA}{c_{pu}}(h_s - h) \tag{11}$$

The sensible heat transferred is

$$\delta Q_s = m_a \, c_{pu} \, dT \tag{12}$$

Therefore by combining Eq. (12) with Eq. (1) gives

$$h_c \, dA \, (T_s - T) = m_a \, c_{pu} \, dT \tag{13}$$

which can be integrated, resulting in

$$1 - \frac{T_1 - T_2}{T_1 - T_s} = \exp\left(- \frac{h_c \, A}{m_a \, c_{pu}} \right) \tag{14}$$

The *effectiveness* of a direct evaporative cooling equipment is defined as

$$\varepsilon = \frac{T_1 - T_2}{T_1 - T_s} \tag{15}$$

then

$$\varepsilon = 1 - \exp\left(- \frac{h_C \, A}{m_a \, c_{pu}} \right) \tag{16}$$

Analyzing Eq. (15) it is verified that an effectiveness of 100% corresponds to air leaving the equipment at the wet bulb temperature of entrance. This requires a combination of large area of heat transfer and a high heat transfer coefficient and low mass flow. It is also observed that the effectiveness is constant if the mass flow is constant since it controls directly and indirectly the value of the parameters on the Eq. (16).

4. EXPERIMENTAL WORK

Experiments were developed during the months from May/2009 to September/2009 in the Air Conditioning Laboratory at the University of Taubate Mechanical Engineering Department, located in the city of Taubate (latitude S23º01´30”, longitude E45º33´30” and altitude 580 m), State of São Paulo, Brazil. Performance tests were carried on an air conditioning device by direct evaporative cooling. The evaporative device was installed in a room of 6.50m x 5.30m x 2.90m and the following parameters were monitored: outdoor air humidity and temperature, evaporative cooler inlet air humidity and temperature, evaporative cooler outlet air humidity and temperature, water temperature inside the supplying tubes, water temperature at the evaporative cooling reservoir, evaporative pad surface temperature, evaporative cooler outlet air speed and the temperature and humidity inside the conditioned room.

The air flow fan is controlled by a variable voltage transformer “Varikeld 220V”. The air temperature and humidity are measured with thermo-hygrometers model “Instrutherm HT-210”. It is also monitored the current and voltage in the electric motor with multimeters. The air flow speed is measured with digital hot wire thermo-anemometers model “Instrutherm TAFR-180”.

The accuracy characteristics of the measurement instruments are presented in Table 1.

Table 1. Characteristics of the measurement instruments

INSTRUMENT	MANUFACTURER/MODEL	RESOLUTION/ACCURACY
Variable voltage transformer	Varikeld 220V	± 2,5 V
Thermo-higrometer	Instrutherm/HT-210	1^oC / ± 0,05 %
Multimeter	Minipa/ET 2052	0,0005V / ± 0,5%
Multimeter	Minipa/ET 1552	0,005A / ± 0,5%
Hot wire thermo-anemometer	Instrutherm/TAFR 180	0,1 m/s / ± 5%

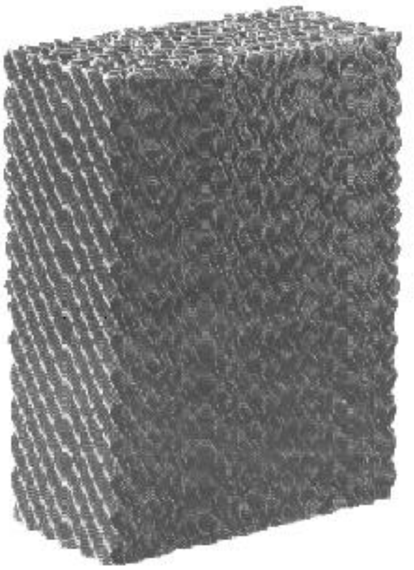
The material (straw, wood) was placed inside a panel made with wire mesh with the following dimensions: 0.25 x 0.25 x 0.10 m. Trials were carried out with filling densities of 12.8 kg/m³, 19.2 kg/m³, 25.6 kg/m³, 32.0 kg/m³, and 38.4

kg/m³. During the tests, the air flow velocity was varied between 0.5 m/s and 2.0 m/s for each density. Table (2) present the results obtained.

Table 2. Cooling effectiveness.

Velocity (m/s)	Filling density (kg/m^3)				
	12.8	**19.2**	**25.6**	**32.0**	**38.4**
0.5	0.698	0.730	0.740	0.760	0.847
1.0	0.670	0.680	0.688	0.732	0.834
1.5	0.649	0.655	0.680	0.702	0.825
2.0	0.638	0.645	0.667	0.680	0.816

Figure 2 shows the experimental evaporative pad with the fiber wood as alternative for conventional cellulosic.



(a)

(b)

Figure 2. Evaporative pad used: (a) conventional (cellulose); (b) experimental (fiber wood).

Figure (3) shows the graph of the performance of the straw used as wood filler pad evaporative function of air speed at which it was submitted.

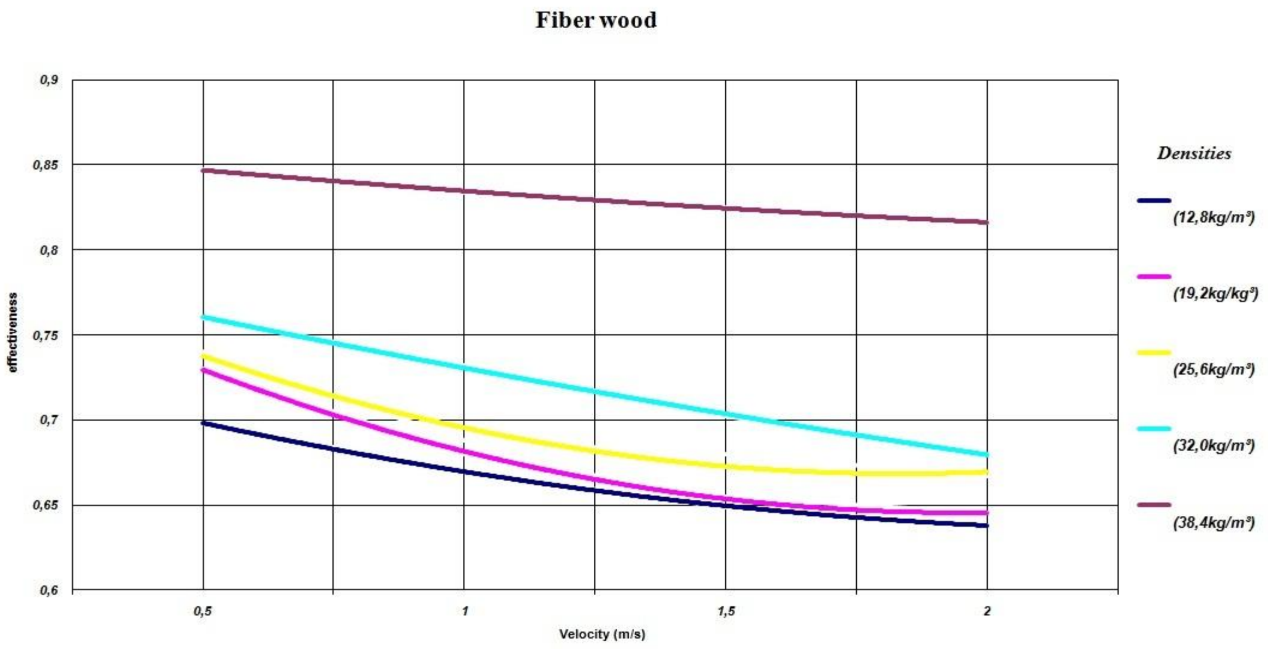


Figure 3. Effectiveness of straw wood in function of the air velocity

5. CONCLUSIONS

The results obtained, it can be said that the straw wood have great potential to be used as an alternative to fill the evaporative pad. Analyzing graphically their performance through the effective velocity. Note that the higher the density of the filling (kg/m³), the better effectiveness of cooling. It appears that while the pad at a velocity between 0.5 and 2.0 m/s the effectiveness ranges from 0.847 to 0.816, which shows that the use of straw and wood filler pad is feasible evaporative.

6. ACKNOWLEDGEMENTS

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