ADIABATIC COOLING, USE AND POTENTIALITIES IN BRASIL

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Abstract. *This work evaluates the potentiality of the use of direct type adiabatic air cooling in different regions of Brazil. In order to do that the psychometric air process was modeled considering the heat and mass transfer process, **carried out** in two separated heat and mass counterflow exchangers. Once the model was validated, it was applied to climate data from different places in Brazil, to see in which places the air conditions obtained from simulations using this air-cooling method were inside comfort conditions normally accepted in the country. Results obtained as well as comments regarding these results are included.*

Keywords: *cooling, thermal comfort, adiabatic process*

1. INTRODUCTION

Hot and dry climates normally cause health problems and low productivity in human beings (NASA- Report CR-1), because the body diminishes it capability to control internal temperature.

The “apparent temperature” (AT), indicates how air humidity and high temperature can reduce body capability to keep the normal internal temperature. Table 1 shows that for relative humidity (RH) lower than 70% and temperature between 26ºC-38ºC it is possible to increase the AT between 2.4 ºC-25.1ºC, respectively, independent of air velocity. The site “http://www.inmet.gov.br/clima/sensaçãotermica”, has a table that indicates the effects of AT on human body going from 27 ºC to 54 ºC. It is also possible to observe that the effect goes from moderate body weakness to severe brain vascular damage. The comfort levels recommended to avoid these problems go from temperatures between 20-27 ºC and RH from 60-75%, these are the comfort conditions used in this work.

Normally, the window air split type air conditioners produce a cool and dry humid air at temperature below dew point and the energy consumption for 75m³ rooms is of the order of 2.2 kW·h. In adiabatic air cooling systems water is evaporated by the same humid air being cooled, causing a dry temperature reduction and increasing the RH. The energy consumption is 70% less for the same volume rooms and the same thermal charge (*www.armec.com.br/artigotecnico*).

2. EVAPORATIVE AIR COOLERS

Direct type with micro-splitting is normally used in semi-humid climate (Roris, 2000) because the process is almost isenthalpic, see Fig.1 below.

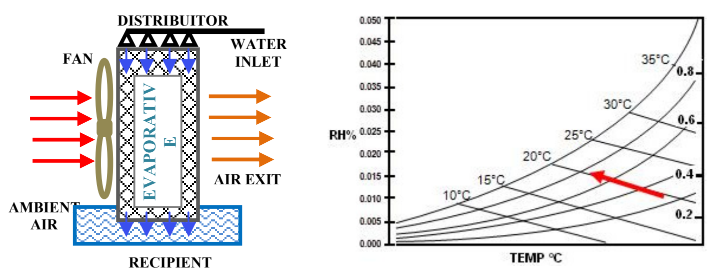


Figure 1. Direct evaporative air cooling system.(DEAC)

In indirect evaporative (adiabatic) air cooling system, normally primary dry air exchanges heat with secondary air that evaporates water located in wet surfaces as show in Fig. 2.

One of the typical advantages of the evaporative air cooling system, EAC, is the total (100%) air renewal of room being conditioned. According to the journal of water work association (AWWA, Vol. 40, No. 4, 1998), the water consumption of EAC systems goes from 2-7% of the total water consumption of a residence depending on the RH of the external air and of the desired dry temperature, as shown in Tab.1.

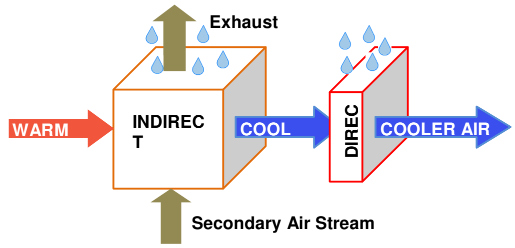


Figure 2. Indirect evaporative air cooling system (IEAC).

Table 1. Water consumption in EAC.

RELATIVE HUMIDITY	20%			35%			60%		
Drop Temperature ºC	13	15	18	10	11	13	5	5,5	6
Water Consumption (L/h)	60	70	80	45	50	60	40	40	45

3. LITERATURE ON EAC MODELS

Camargo and Ebinuma(2001) made a basic model for the direct and indirect system, EAC, using heat transfer and mass transfer differential models with several parameters to adjust the model, in order to see potentialities of EAC use as an improvement for conventional air conditioners.

Sumathy and Dai (2002) found in EAC honeycomb type, a relation between the air thickness channel and minimum EAC exit temperature in experimental work.

Antonio Cesar Silva(2002) modeled direct EAC system, using numerical techniques, and for a pre-selectioned room it was possible to find air volume flow rate, dry temperature and RH of the air supplied by the EAC to obtain a good degree of comfort.

Pimenta and Castro(2004) developed a parametric model for heat and mass transfer processes in direct EAC system, very simple and easy to be implemented, using geometric and thermal data given by the manufacturers of Brazilian EAC.This work uses the Pimenta et al (2004) model, applied to a commercial Brazilian EAC, which is described below. Figure 3 shows in schematic and simple way the system used in this work and a photo of a similar EAC used for experiments.

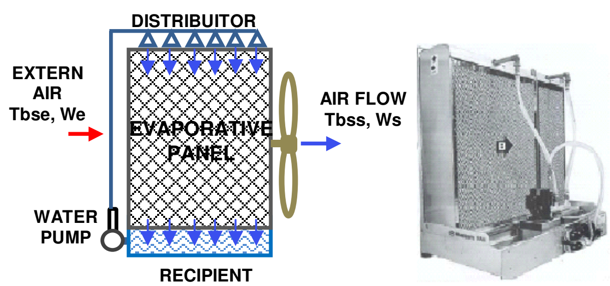


Figure 3. Evaporative direct air cooling system used in this work

The model used in this work, Pimenta and Castro (2004), gives the dry temperature and RH of exit air from the EAC. It was implemented by authors of this work the COP calculation and it was eliminated the pressure loss calculation.

Model suppositions: Humid air has psychrometric behavior, the temperature of the water inside the recipient of the EAC remains constant, the air is submitted to a adiabatic process, the water temperature in the evaporative panel is considered equal to the air wet bulb temperature.Figure 4(a) shows the temperature behavior when humid air is submitted to pure heat transfer in a EAC system.

For energy balance in an elementary portion of the EAC in Eq. (1), have:

$$h_c dA(T - T_{sm}) = -\dot{m}_a C_{pa} dt \tag{1}$$

Mathematically it can be proved that the EAC heat transfer efficiency (ε) is given by Eq.(2)

$$\varepsilon = \frac{T_{bse} - T_{bssa}}{T_{bse} - T_{sm}} = 1 - \exp\left[\frac{-h_c A}{\dot{m}_a Cpa}\right] \tag{2}$$

From Eq.(2), obtain:

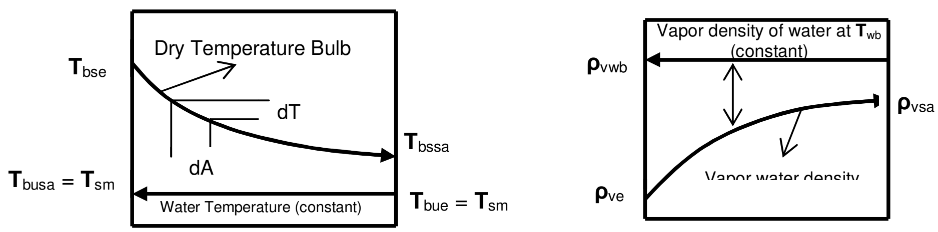
$$T_{bssa} = T_{bse} - \varepsilon\left(T_{bse} - T_{sm}\right) \tag{3}$$

The air mass flow rate can be given (that is a particular case) or calculated by Eq. (4) as follows

$$\dot{m}_a = \frac{\dot{Q}_e + \dot{Q}_{ss}}{C_{pa}\left(T_{bsr} - T_{bssa}\right)} = \frac{\dot{Q}_e + \dot{Q}_{ss}}{h_{ar} - h_{asa}} \tag{4}$$

Normally, the difference T_{bsr}-T_{bssa} is between 4.0 and 5.0 °C (Watt y Brown, 1997).

From mass balance applied to the EAC, a counterflow mass exchanger can be represented like a counterflow heat exchanger, see Fig. (4b) below.



(a) (b)

Figure 4. (a) Temperature evolution of humid air in the EAC due only to heat transfer.
(b) Specific mass behavior of the air inside the cooler

$$\dot{m}_e = h_m A \Delta\rho_{em} \tag{5}$$

Mathematically it can be proved by Eq. (6) that

$$\Delta\rho_{\ell m} = \frac{\rho_{vsa} - \rho_{ve}}{\ln\left[\dfrac{\rho_{vsa} - \rho_{vbu}}{\rho_{vse} - \rho_{vbu}}\right]} \tag{6}$$

Where: $\rho_{ve}, \rho_{vsa}, \rho_{vbu}$ are respectively, specific mass of water vapor at supply face, exhaust face of EAC and at wet bulb humid air temperature.

$$h_m = Sh\frac{D}{\ell e} \tag{7}$$

D= 2.6 x 10^5 (kg/m-s-K) as recommended by (Dowdy and Karabosh, 1987)

$$\mathrm{Sh} = 0.08\left(\frac{\ell e}{\ell}\right)^{0.12} \mathrm{Re}^{0.8}\,\mathrm{Sc}^{1/3} \tag{8}$$

$$Sc = \frac{\vartheta a}{D} \tag{9}$$

It is possible to calculate the room specific humidity (Wr) if know Tbssa and by using the wet bulb temperature of air supply to the EAC as panel temperature, as Jodi (2000) recommends.

$$W_r = W_s + \frac{\dot{Q}_e}{\dot{m}_a\, h_{\ell v}} \qquad (\text{ kgw/kgas}) \tag{10}$$

In this work is defined COP of de EAC as

$$COP = \frac{\dot{Q}}{\dot{W}_t} \tag{11}$$

where:

$$\dot{Q} = \dot{m}\, C_{pa}\left(T_{bse} - T_{bssa}\right) \tag{12}$$

$$\dot{W}_{t} = \dot{W}_{bb} + \dot{W}_{vent} \tag{13}$$

Obs: because of this COP definition, the COP seems to be lower than in conventional window air conditioners, but can not be forget that most of the cooling capability is caused by water evaporation at almost no cost with 100% air room renovation, and air volume flow rates are high, in relation with conventional air conditioners.

Finally combining the equations above, have:

$$\dot{Q} = \dot{m}_a\left[C_{pa}\left(T_{bse} - T_{bssa}\right) + W_e\left(h_{ge} - h_{gbu}\right) - W_e\left(h_{gsa} - h_{gbu}\right)\right] \tag{14}$$

With Eq. (14**);** data of humid air outside the room and EAC specifications known, dry air temperature and RH of humid air at EAC exit can be calculate.

4. MODEL VALIDATION

It was used a commercial EAC manufactured in Brazil and appropriated for rooms of 20-50 m³. It has five (5) fan velocities from which used only three (3) velocities in the test, each test took 8 hours and data was taken at each 30 min. Climate conditions as well as room conditions were registered and all data was recorded in stable conditions.

There were used two (2) thermo-hygrometers, installed 10 cm apart from the EAC, located in front of the supply and exhaust faces of the EAC. Fig. 6 shows a picture of the test bench used showing the position of one of the hygrometers. Table 2 shows the EAC specifications given by the manufacturer.

It was used a mercury type thermometer to determinate ambient temperature installed 5 meters apart from the EAC.

To measure air velocity it was used an anemometer with scale 0.5 - 30 m/s and a piezo-resistive pressure transducer of maximum 1 bar full scale, which was properly calibrated to measure the water volume being consumed by the EAC. The EAC used has a constant volume recipient controlled by a flotation valve, which was fed by another recipient where it was measured all the time the static pressure (pressure transducer) caused by water column, as shown in right upper part of Fig.5.

Air dry temperatures at supply and exhaust faces as well as water temperature inside of EAC were measured by T type thermocouples.

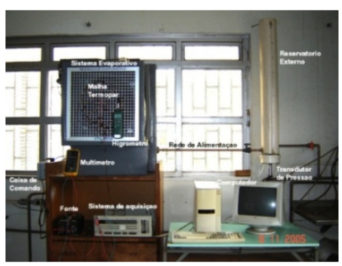


Figure 5. Test bench.

The air mass from rate was calculated as follows:

$$\dot{m}_e = \sum_{i=1}^{16} \overline{V}i \cdot Ai \cdot \overline{\rho} \qquad 15)$$

Table 2. Technical information of ECOBRISA model EB-50 used as EAC in the test bench.

Item	Unit	Description	simbol	value
01	m	panel thickness	**I**	**0.1524**
02	m^2/m^3	humid area of surface per unity of volume	$\mathbf{A_{sv}}$	**400**
03	m	Characteristic length de flujo in panel	$\mathbf{I_e}$	$\mathbf{1 / A_{sv}}$
04	m	height and width of panel	**H**	**0,06**
05	m^2	straight Section area of panel	$\mathbf{A_{sr}}$	**H . H**
06	m^2	humid area per plate of panel	$\mathbf{A_{up}}$	$\mathbf{2 . A_{sr}}$
07	m^2	humid area in all panels	$\mathbf{A_{su}}$	$\mathbf{A_{sv} . I . A_{sr}}$
08	un	Numbers of plates inside the panel	**N**	$\mathbf{A_{su} / A_{up}}$
09	m^3/s	mass flow rate air across the panel	**Q**	$\mathbf{U . A_{sr}}$
10	m	thickness of plates	**δ**	**0,0004**
11	m	Distance between two plates	$\mathbf{I_c}$	**((I- δ)/(N-1)) - δ**

The panel area was divided in 16 (0.44 x 0.44 m²) square areas as show in Fig. 6.

Figure 6. Thermocouple installation at the supply tested and the exhaust face of EAC showing thermohygrometer used.

5. RESULTS

Figures 7 and 8 show temperatures and RH for 2680 m³/hr air volumetric flow (maximum). The errors were calculated as follows:

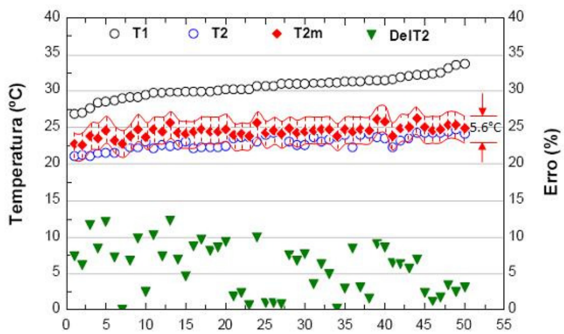


Figure 7. Temperature evolution in EAC for 2680 m³/hr.

$$\Delta T_2 = 100\frac{|T_{2m} - T_2|}{T_{2m}} \tag{16}$$

$$\Delta \phi_2 = 100\frac{|\phi_{2m} - \phi_2|}{\phi_{2m}} \tag{17}$$

$T_{2m}; T_2; and \emptyset_{2m}; \emptyset_2$, are the temperatures and RH measured (m) and calculated at EAC exit. The differences observed are of the order of 15% or maximum 3,7ºC. In this case for temperatures up to 25ºC, the incertitude of the measurements is of the order of ±2.8 ºC or 5.6 ºC; can to see that calculated values are inside the measurement incertitude.

In the case of RH, the differences are of the order of 20%, which represents maximum ±7.5% in terms of uncertainty in relative humidity measurements (RH measured was maximum 75%) .The uncertainty calculated due to instruments used is of order of ±11.9%.of RH

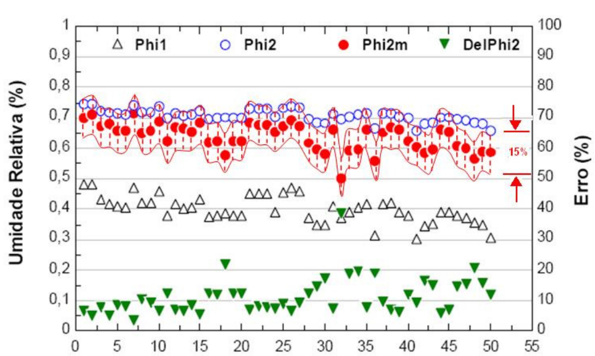


Figure 8. Relative humidity evolution in EAC for 2680 m³/hr

The water consumption is of order of 4.8 lts/hr for 2680 m³/hr air volumetric flow; the water temperature in EAC water recipient oscillated between 18-22ºC for the three test air velocities used to validate the model, being almost constant for each one of fan velocities used. The maximum COP obtained for the EAC used was 1.0 for the maximum air velocity and 0.45 for the minimum air velocity.

6. POTENTIALITIES OF EAC USE IN BRAZIL

Consulting the "www.inmet.gov.br/climatologia/mapas" given by the Brazilian meteorological institute (INMET), can be found monthly averaged data for temperature and RH for all Brazilian territory. In order to evaluate the potential use of EAC, it was considered as comfortable conditions when dry temperature goes from 20 to 25ºC to and from 40 to 75% RH.

For interpretation of data shown in Tab. 3, each location is identified with one color as show at the bottom of the table (Ex: NE: north-east, NO: north-west, SE: south-east, SO: south-west, CE: center-east, N: north, S: south, O: west, L: east, TD: all territory).

It is analyzed only one "case" as example. From Tab. 3, for the Tocantins Brazilian State (TO), on May, at central-east and south, the climate conditions are 28 ºC and the RH is between 40-50%. If enter with these data in the model, can see in Tab. 4 the results obtained using EAC similar to the one tested. For this case when RH is 40% can be obtained 20.8 ºC of dry temperature and 45% of RH.

Table 3. Indicative of potential use of EAC in Tocantins, Brazil. The complete table can be found in www.fapemig.br

	RH%	JAN	FEV	MAR	ABR	MAI	JUN	JUL	AGO	SET	OUT	NOV	DEZ
TO	20-30								32	34			
	30-40							30	32		30		
	40-50					28	32					30	30
	50-60											28	28

Table 4. Potential use of EAC

TEMP °C	26		28		30		32		34			
HR %	ºC	%	ºC	%	ºC		ºC	%	ºC	%		
10									19,6	49,8		
15									21,0	54,0		
20							20,6	57,8	22,1	57,8		
25							21,5	61,1	23,1	61,1		
30			19,3	64,0	20,9	64,1	22,5	64,1	24,1	63,5		
35			20,1	66,8	21,7	66,8	23,3	66,7				
40			20,8	69,3	22,5	69,2	24,2	69,1				
45			21,5	71,6	23,3	71,4	24,9	71,1				
50	20,5	73,7	22,2	73,6	23,9	73,4	25,7	73,0				Use without reserves
55	21,1	75,7	22,9	75,5	24,7	75,2	26,5	74,7				Use with reserves
60	21,7	77,5	23,5	77,2	25,3	76,8	27,2	76,1				Not use

For the same air temperature and 45% RH, can be obtained at EAC exit 21.5 ºC/71.6%, and for the case in which RH is 50% obtained 22.2 ºC/73.6%. If is considered that thermal charge in room being conditioned cause an increase of EAC exit air temperature of 4ºC (see "Manual Técnico Basenge", page 6), we can get room temperatures of 24.8ºC /25.5ºC /26.2ºC considering 100% air renovation.

Analyzing the data shown in Tab. 3 for all the Brazilian regions, the EAC has potential of use in following locations: central-south (CS) on May, in west/south-west/central/east, on November and in the whole country on June/July/August/October and December.

7. CONCLUSIONS

This work showed that the analysis of thermal and mass transfer, considering these transfer phenomena both acting independently behaves well in the case of adiabatic evaporative process.

The model developed can be used in any type of direct evaporative air adiabatic cooling equipment with enough precision (±7.5% error), allowing the use of this model for studies related to applications, and even to give more confidence to costumers of these equipments, because it is possible to extrapolate data and see clearly the economy made when using this type of air cooling.

It is observed in this work that in Brazilian States: Bahia, Ceará, Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Paraíba, Pernambuco, Piauí, São Paulo, Tocantins and Triangulo Mineiro (MG) there is a great potential of use (75%) of these equipments. For the States of: Sergipe, Santa Catarina, Roraima, Rio Grande Do Sul, Espírito Santo, Amazonas, Amapá, Alagoas and Acre, the potential of use goes down to 25% for week-days in a year period, because most of these regions have hot climate and high relative humidity .

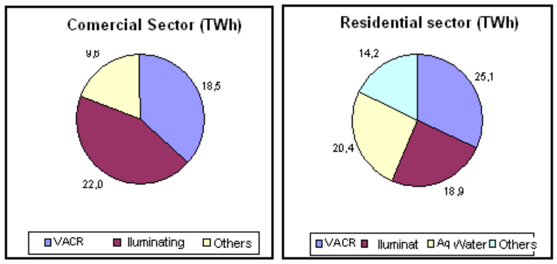


Figure 9. Energy consumption in commercial and residential sector indicating VACR consumption

In figure 9, obtained from Brazilian Mines and Energy Ministry (MME), a report given by the conservation program (PROCEL) in 2002 says that the VACR (VCAR= ventilation, heating, air conditioning) sector in commercial and residential sectors consumed more than 18 % of total electric energy.

If we consider the study made by Brown (1991), in which it is proved that direct EAC gives a economy of 15% in electrical energy consumption and indirect EAC gives 38%, it seems a good and simple air conditioning equipment to be used in dry and hot climates. Is recommended a comparative study of direct and indirect EAC equipments and the study of EAC using dry air (obtained by solid dryers), at the inlet of EAC equipments when these equipments are used in hot and humid regions.

If we analyze a psychometric chart, it is possible to see that conventional air conditioners normally decrease humid air temperature, and go down to the wet bulb temperature and this is accomplished with a decrease of 3-5°C in dry temperature. For this reason, we adopted 4°C as a good decrease of temperature for potential analysis of EAC use.

NOMENCLATURE

An	Evaporative panel area (m²)
D	mass diffusion coefficient of water in air (kg/m-s-K
C_{pa}	Constant pressure air specific heat. (kJ/kgK)
h_{ar}	Dry air enthalpy inside the room (kJ/kg)
h_{asa}	dry air enthalpy supply to the EAC (kJ/kg)
h_c	Convection heat transfer coefficient (kJ/m²sK)
h_c	Nus$\cdot$(Ra/le)
$hgbu$	satured water vapor enthalpy at wet bulb temperature (kJ/kgw).
hge	enthalpy of water in humid air at EAC supply (kJ/kgw)
$hgsa$	enthalpy of water vapor in humid air at EAC exit (kJ/kgw)
h_{lv}	latent heat of vaporization (kJ/kg) at room atmospheric pressure
h_m	Mass transfer coefficient (Kg/m²-s-K).
$kgas$	dry air mass (Kg)
kgw	water vapor mass in humid air (kg)
ℓ_e	Panel characteristic length
m_a	Air mass flow rate(kg/sec).
m_e	water mass flow rate evaporated (kg/sec).
m_w	water consumption (kg/sec)
Q_{ev}	mw$\cdot$hlv
Q_{ss}	air sensible heat (KJ).
T_{bse}	inlet dry air temperature (K).
T_{bsr}	Room air temperature (K)
T_{bssa}	outlet dry air temperature (K).
T_{sm}	Panel surface temperature (K).
U	Air velocity inside the panel (m/s)
$\overline{\mathrm{V}}\mathrm{i}$	: mean air velocity in each (m/sec)
W_{bb}	Water pump power (kW).
We	specific humidity of humid air at EAC supply (kgw/kgas)
W_s	humid air specific humidity of air supply to the EAC (kgw/kgas)
W_{vent}	Air fan power (kW).

Greek symbols

γ_a	Cinematic viscosity (μ / ρ_a)
$\Delta\rho_{em}$	Logarithm mean specific mass (density)of water in the humid air (kg/m^3).
ρ_a	air specific mass (Kg/m³)

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