EVAPORATIVE AIR COOLER THERMAL PERFORMANCE FOR RESIDENTIAL USE

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ABSTRACT

This paper investigates an Evaporative Air Cooler (EAC) thermal performance and energy efficiency, when reducing the air temperature. EAC equipment typically consists of fan, small hydraulic pump and cooling pads. That device is able to provide ventilation only or air cooling trough water evaporative process that increases the air humidity (absolute and relative) and, as consequence, air temperature decreases (dry and wet bulb). The methodology adapts some aspects from ABNT - Brazilian Technical Standards Normative, for air conditioning devices. During tests, the fan rotor operates in 3 (three) angular speeds (RPM) in different ambient conditions for inlet air. Appropriate instrumentation and measurements registration allow to register the behavior of thermal parameters as: dry and wet bulb temperatures (Tdb and Twb, °C), air relative humidity (RH, %), enthalpy ($kJ.kg^{-1}$), and water mass flow ($kg.s^{-1}$). Thus, main results are for overall efficiency (η, %) considering the energy conversion from electricity to air flow hydraulic power, and cooling effectiveness (ε, %) is based on heat exchange between water evaporation and airflow rate. As main conclusions, we point out that: a) ↓Tdb for ↓mAir, reaching ΔT~5.0°C and corresponding ΔΦ~20%, when comparing outlet and inlet airflow parameters; b) EAC efectiveness reaches maximum values for lower rotor angular speeds (εEAC ~90%@1300 RPM), in comparison to higher ones; c) For a constant rotor angular speed, EAC performance (CP, εEAC and others) is strongly dependent on air ambient conditions; mAir increases from ~13.8 $kg.s^{-1}$ up to ~16.5 $kg.s^{-1}$ when rotor angular speeds goes from 1300 RPM to 1500 RPM.

Keywords: energy label; cooling systems; thermal machines; turbomachinery; energy conversion.

NOMENCLATURE

A	surface area, m^2
c_p	specific heat at constant pressure, $kJ.kg^{-1}.K^{-1}$
h	specific enthalpy, $kJ.kg^{-1}.K^{-1}$
h_C	convection heat transfer coefficient, $kJ.kg^{-1}.K^{-1}$
p	pressure, kPa
m	mass flow, $kg.s^{-1}$
T	temperature, ºC or K
U	overall heat transfer coefficient, ___
Q	heat transferred or received, $J.kg^{-1}$
RH	relative humidity, %
u	uncertainty

Greek symbols

ρ	density, $kg.m^{-3}$
Δ	differences (temperature, mass, time, etc)
η	overall efficiency in energy conversion, %
ε	Effectiveness in cooling, %
ϕ	air relative humidity, %

Subscripts

air	air as working fluid
v	water in vapor phase
l	water in liquid phase
w	water in the reservoir (liquid phase)
lab	laboratory ambient conditions
db	dry bulb
wb	web bulb
i	inlet
2	oulet
3	outlet, wet bulb temperature
C	chronometer uncertainty
T	thermometer uncertainty
Thermal	thermal energy
p	constant pressure condition

Acronyms

COP	Coefficient of Performance
EAC	Evaporative Air Cooler
ECS	Ejector Cooling System
EC	Evaporative Cooler
EE	Energy Efficiency
EER	Energy Efficiency Ratio
EES	Engineering Equation Solver

INMETRO	Brazilian National Institute of Metrology Standardization and Industrial Quality
ISO	International Organization for Standardization
NBR	Brazilian Technical Standards Normatives

INTRODUCTION

Air cooling systems have plenty of engineering applications worldwide. Evaporative cooling – EC, is its simplest form is one of the oldest ways of keeping things cool (Eastop and Croft, 1990). The most obvious example of that phenomena if given by the cooling of the human body by sweating. Thus, EC process is based on a physical phenomenon in which evaporation of a liquid (usually water) into the surrounding air cools down an object or a liquid in contact with it, i.e. ↓ temperature. When the liquid changes to gas/vapor phase, it absorbs heat. Technically, this is called the "latent heat of evaporation". Water is an excellent coolant: it is plentiful, non-toxic, and evaporates easily in most climates.

Typically, there are three types of systems able to cool down the ambient air temperature (Eastop and Croft, 1990): a) Evaporative cooling - EC; b) Cooling by vapor compression cycles - VCP, that usually requires a great amount of energy, due to the compression process; c) Absorption refrigeration cycles - ARC, typically for applications < 0°C. Other options are, for instance, solar cooling by VCP (Wang et al., 2009) with investigation for COP improvements when replacing the working fluid for an EC that presents a simple design and low cost.

Equipment based on EC processes have lower energy consumption when compared to other air conditioning systems. It is also an interesting option in industry, commerce, and domestic applications. Industry already uses equipment that provides EC but for water cooling purposes, instead of air cooling, the cooling towers. The most common design of a cooling tower sprays the water from the top and it flows down by gravity forces, through a fill of material, in counter-flow to air in ambient conditions driven by medium and large fans - axial or radial turbomachines.

In Brazil, EAC for residential appliances is know as air coolers (*"climatizadores"*, in Portuguese), although they are able only to cool down the air temperature and unable to perform air heating. Those equipment, named as Evaporative Air Coolers (EAC), are easily found in Tropical Climate countries - better when hot and dry air is predominant, for residential and commercial use. When evaporating water, 22.7 L (or 6 gallons) have the same cooling effect as a typical home central air conditioning system - 3.5 ton.h^{-1} (AWE, 2016).

Literature have plenty of investigations on performance of EAC processes and devices. For wet cooling towers, its performance can be predicted using simplified models of accurate and simple implementation by specifying the mass evaporation rate equation (Asvapoositkul and Treeutok, 2012). In this type of equipment, its thermal performance capacity is dominated by ambient air conditions, mainly wet-bulb temperature. For counter-flow film cooling towers, cooling efficiency and effectiveness can be predicted by a mathematical model based on the evaporation and heat and mass transport mechanism for film type cooling combined with on-site experimental measurements to obtain COP and chiller load (Yingjian et al., 2011). In that work, evaporative cooling efficiency (η, %) and the effectiveness (ε, %) have the same numerical values, thus concluding that both are equal characteristic parameters for cooling tower thermal performance.

This paper aims to evaluate the thermal performance for an evaporative air cooler - small size for residential use. Motivation is that, those devices do not have energy efficiency labels at the present – in Brazil, when operating only in ventilation mode or in air cooling mode - increasing the relative humidity and reducing the air temperature. Experimental results and tests are for ventilation and air cooling operating modes, in 3 (three) fan angular speeds. Results and analysis for thermal performance and characteristic behavior of thermal parameters (temperature, RH and entalphy) until the airflow reach steady-state conditions for temperature and RH parameters. Authors evaluate the ability to the ambient air – non-controled conditions, to reach thermal comfort range (temperature and RH) in the airflow at the fan outlet position.

Motivation

Energy efficiency levels in Brazil for air conditioning were last updated on December 2014 (BRASIL, 2011) establishing as the minimum value for EER (or efficacy) of 2.60 W/W for vapor compression systems (window type, < 9495 kJ/h or < 9000 BTU/h), and the mean values for the systems evaluated up to that time by INMETRO (2014) was 2.86 W/W; Pessoa and Ghisi (2015). Their estimates indicate that Brazilian levels could reach 5.67 W/W. Nevertheless, for evaporative cooling systems, there are no legal standards to be respected for the products manufactured or imported and available in the national market.

METHODOLOGY

Equipment Specification and Experimental Set-up

Tests are in a Evaporative Air Cooler (EAC) for residential use, with the following technical data (Manufacturer/model – ECOBRISA / EB 8 "Diet Portatil"), see Fig. 1: nominal volume airflow equal to 600 m³.h, water consumption of 1.5 L.h^{-1}, 12 m² of cooling area, electrical power 125 W (110 V, 60 Hz), small size water pump (7 W, nominal value), weight 7.3 kg and size dimensions given by 0.76m x 0.35m x 0.34m. The EAC has one fan (Centrifugal type) that provides the airflow in 3 (three) different rotor angular speeds: 1300 RPM, 1400 RPM and 1500 RPM.

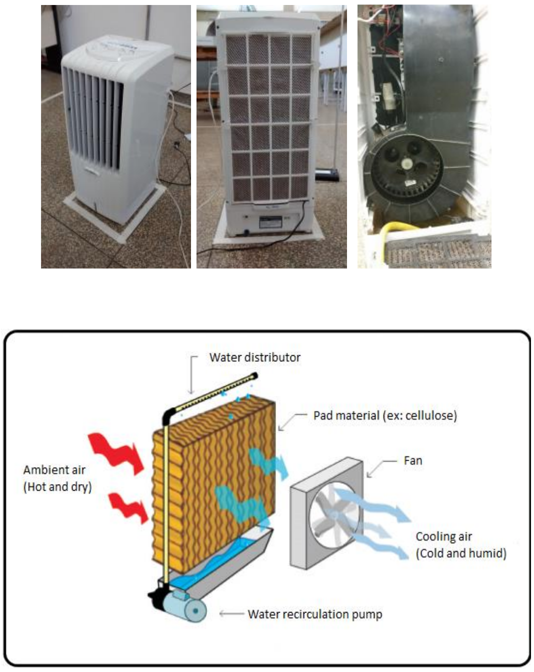


Figure 1. EAC at UFGD laboratories and operating sketch from manufacturer.

There are no INMETRO classifications for energy efficiency in that type of equipment. This work is a first step towards proposing a methodology to their classification from "A" up to "E" categories. Nevertheless, other types of cooling systems already have its INMETRO classifications available; thus these standards were considered as reference to the tests in this work: 1) Temperature measurements in air conditioning (ABNT, 1987); 2) COP determination in individual air conditioning units (ABNT, 1990); 3) Air coolers for refrigeration – Methods of test (ABNT, 2006); 4) Open area around the equipment, 0.90m at rear and lateral positions and 1.8m in front of it, adapted from NBR 11.215 (ABNT, 1990).

Instrumentation for Measurements

Table 1 indicates requirements for temperature measurements (ABNT, 1987). Table 2 shows the test instruments and its uncertainties, for experimental measurements in this work. Uncertainty analysis was performed for each one of the parameters obtained in tests, whenever feasible (Balbinot and Brusamarello, 2010).

Table 1. Instruments requirements for temperature measurement in air conditioning (ABNT, 1987)

Parameter	Measurement accuracy	Measurement precision	Tolerance recommendation: Full Range & Mean values	Usual Measurement Range
T_{db}	±0.10°C	±0.05°C	±0.50°C & ±0.30°C	-30°C up to +60°C
T_{wb}	±0.10°C	± 0.05°C	± 0.30°C & ± 0.15°C	-20°C up to +35°C
T_{Water}	±0.20°C	± 0.05°C	± 0.30°C & ± 0.10°C	-1°C up to +45°C

Table 2. Instrumentation technical specification

Instrument	Measurement quantity	Operational Range	Instrument Resolution	Instrument Uncertainty
Thermo-Hygrometer (Instrutherm, model: HT-200).	Temperature & Humidity	-20°C up to +70°C; 20% up to 99% RH	0.1°C; 1% RH	±1°C; ±5% RH
Thermo-Hygrometer (Precision Gold, model: N18FR).	Temperature & Humidity	-20°C up to +60°C; 0% up to 100% RH	0.1% RH; 0.1°C	-
Hot-wire anemometer (Instrutemp, model: ITAN-740)	Airflow velocity & Temperature	0.1 up to 25.0 m/s; 0°C up to 50°C	0.1 m/s; 0.1°C	±5%; ±0.1 m/s; ±1°C
Thermo-Hygro-Anemometer-Barometer (Instrutherm, model: THAB-500)	Barometric pressure	10 up to 999.9hPa	0.1 hPa	±(1.5hPa)
Scale - Weigh device (GEHAKA, model: BK8000 Class "II"/2011)	Mass	5 up to 8100 g (at 15–35 °C)	0.1 g	±0.1 g
Watt-meter (Instrutherm, model: WD-950)	Active Power	0.05 W-9999 kW	0.001 W ~1 kW	± 2% VA ± 5

Laboratory and Test Standard Conditions

Tests were carried out under laboratory conditions for data acquisition as indicated by NBR 13.723-1 and NBR 13.723-2 (ABNT, 2003; 1999), as T_{lab} = (25±5)ºC. Eventually, a single run could be slightly different – as $T_{lab} \geq 30$ºC, but it does not interfere in the overall behavior of the results, discussions, and conclusions presented herein. Thus, the results for experimental tests were obtained under ambient conditions in Table 3.

Table 3. Air ambient conditions during test run

	P (kPa)			T_{db} (°C)		
	Start	**End**	**Mean**	**Start**	**End**	**Mean**
12/set/15	96.09	95.98	96.04	30.9	31.9	31.4
18/set/15	95.66	95.68	95.67	33.8	32.8	33.3
21/set/15	95.47	95.50	95.49	35.7	34.7	35.2
28/set/15	95.63	95.60	95.62	25.9	26.1	26.0
29/set/15	95.78	95.70	95.74	26.2	26.9	26.6
06/out/15	96.38	96.19	96.29	23.9	25.1	24.5
12/abr/16	96.09	95.98	96.04	30.9	31.9	31.4
	T_{wb} (°C)			**Φ (%)**		
	Start	**End**	**Mean**	**Start**	**End**	**Mean**
12/set/15	22.82	23.05	22.94	51.0	48.0	49.5
18/set/15	20.69	20.92	20.81	31.0	35.0	33.0
21/set/15	16.86	17.50	17.18	13.0	17.0	15.0
28/set/15	18.49	18.48	18.49	50.0	49.0	49.5
29/set/15	20.58	20.86	20.72	61.0	59.0	60.0
06/out/15	18.43	19.15	18.79	60.0	58.0	59.0
12/abr/16	22.84	23.05	22.95	51.0	48.0	49.5

Experimental procedure

In Brazil, INMETRO standards point out two methodologies for test procedures (BRASIL, 2011): (i) Calorimeter based; (ii) indoor air enthalpy ($kJ.kg^{-1}$). Both are in accordance to International standards for performance measurements in air conditioning systems (ISO 5151, 2010; ISO 13253, 2011).

This work determines indoor air enthalpy by using EES – Engineering Equation Solver. Then providing a results comparison for exit air condition at the EAC exit: experimental (from test measurements) and theoretical (EES psychometric process).

Performance Determination

Electrical power has its direct measurement from Watt-meter. Eq. (1) determines the EAC performance, considering "ε" as the effectiveness in heat transfer able to provide air cooling (Camargo, 2009). If "ε" is 100%, it means that the exit air reaches the wet bulb temperature.

$$\varepsilon=\frac{T_1-T_2}{T_1-T_w}=1-e^{-\frac{h_c.A}{m_{ar}.C_{Pu}}} \qquad (2)$$

Where: A (m^2) is the heat transfer area; h_C ($W.m^{-2}.K^{-1}$) is convection heat transfer coefficient; m_{Air} ($kg.s^{-1}$) is the mass airflow. Still, according to Camargo (2009), ε = constant, if mass flow is also constant, once that parameter controls directly or indirectly the right-hand side of Eq. (1).

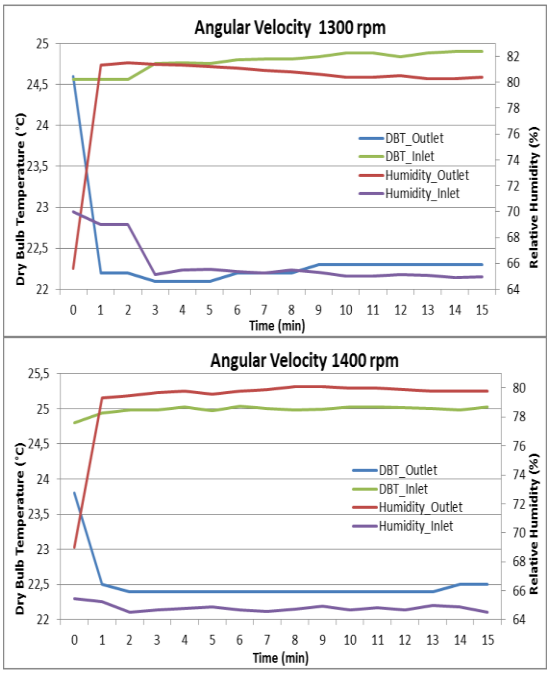
The energy balance for the EAC is given by Eq. (2), as pointed out by Moran and Shapiro (2008); or for transient conditions (Braga et al., 2013).

$$\left(m_{ar}.cp_{ar}+m_{v,i}.cp_v\right).T_1-m_{a,l}.h=\left(m_{ar}.cp_{ar}+m_{v,o}.cp_v\right).T_2 \qquad (3)$$

RESULTS AND DISCUSSION

Transient state conditions

Figure 2 indicates the behavior for T_{db} (°C) and Φ (%) parameters, from test start until the EAC reach steady state conditions after running 10-15 minutes. As the fan angular speed increases from 1300 RPM up to 1500 RPM, the T_{db} shows small increases but remains ~22.0-23.0°C and ~24.5-26.0°C, at the inlet and outlet EAC positions respectively; it is consistent once the fan airflow is typically higher for angular speeds increases in fan characteristic curves for fans of all designs (Henn, 2019) – thus for the same amount of heat exchange, ↑ airflow implies in ↓ΔT. As for humidity, Φ follows the opposite trend in comparison to T_{db}, once the waterflow dilutes for a ↑ airflow; then Φ goes from ~80% (outlet) and ~66% (inlet) at 1300 RPM, to ~78% (outlet) and ~62% (inlet) at 1500 RPM, after reaching EAC steady state. Notice that there is a bump between 8-12 minutes, due to raw data acquisition failure for the 1500 RPM test; although that data acquisition failure, data from 12-15 min confirms the steady state.



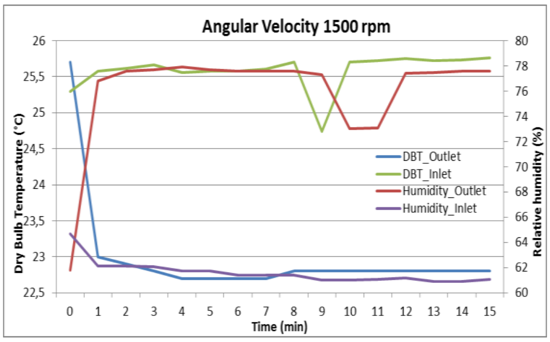
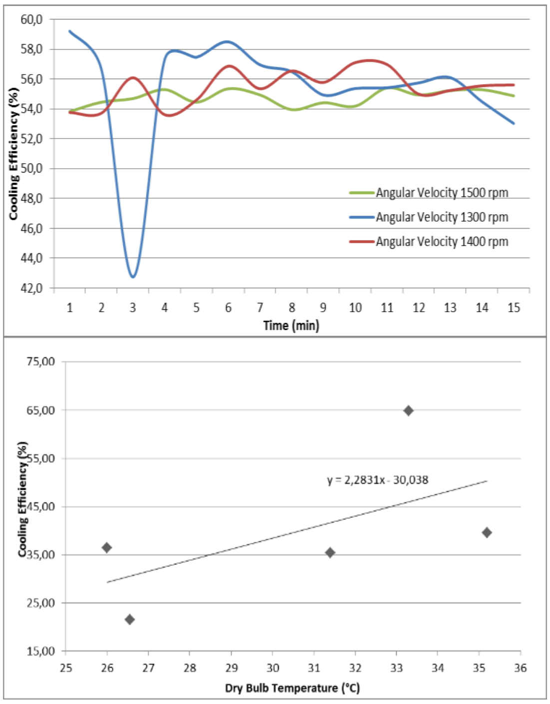


Figure 2. T_{db} and Φ behavior in transient state.

It is important to register that Φ does not surpass ~80%@1300 RPM or ~78%@1500 RPM, due to minimum values for T_{wb} – according to limits given by the theoretical psychometric process. Relative humidity reaches its limits ~80%, and when it happens the air temperature cannot be lowered, but the equipment keeps on cooling the while the inlet relative humidity is lower than that limit.



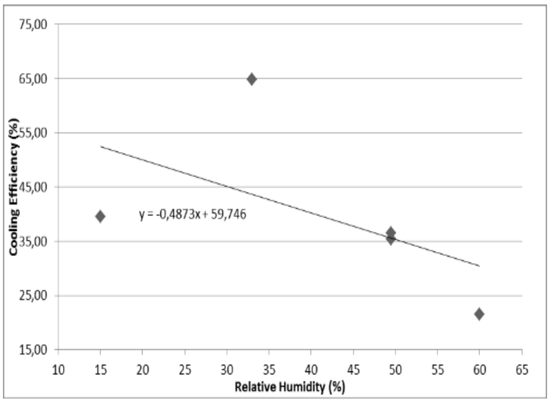


Figure 3. Effectiveness (εEAC): time behavior in transient state, and according to Tdb and Φ.

As for ε_{EAC}, Figure 3 indicates the behavior from test start until steady state; also shows the maximum and minimum values according to conditions for T_{db} and Φ. As a whole, after reaching steady state ε_{EAC}~55%; and the slightly lower or higher values at 1300 RPM and 1500 RPM can be easily attached to the inlet values for Φ – as low it is, higher will be ε_{EAC}, and vice-versa. The overall air cooling is ΔT~5°C, for the test conditions in this work. From theoretical psychometric process - and also the equipment manufacturer, EAC can reach ΔT~10-12°C is proper inlet conditions for T_{db} and Φ.

Steady state conditions

In Figure 4, there is available the evaporative cooling process and its visualization in the psycrometric chart. It corresponds to test conditions for rotor angular speeds 1300 RPM, 1400 RPM and 1500 RPM, respectively. Points identified in the processes are mean values from experimental results: P1 and P2 represent T_{db} at inlet and outlet positions, respectively from experiments; while P3 corresponds to T_{wb} and h (kJ.kg^{-1}) – EES results for Φ =100%.

It is possible to notice that experimental results approach to h~constant (straight line P1-P2), that is the theoretical behavior for the evaporative cooling process; all heat that promotes water evaporation (ΔT = constant during phase change) cames from the air heat removal (↓ΔT). As for EES results for Φ =100%, it corresponds to the maximum theoretical cooling - minimum values for T_{wb}.

Air cooling corresponds to the straight line P1-P2, respectively for 1300, 1400 and 1500 RPM: ΔT_{db}~4.5°C (~31.5-27.0); ΔT_{db}~5.0°C (~32.0-27.0); ΔT_{db}~5.0°C (~32.0-27.0). And the corresponding increases for relative humidity are: ΔΦ~20% (~75-55); ΔΦ~20% (~72-52); ΔΦ~20% (~73-53). Thus, occurs as overall air cooling of ~5.0°C and increases ΔΦ~20%; at maximum Φ=100% could reach ΔT_{db}~10.0°C, as EES simulation indicates.

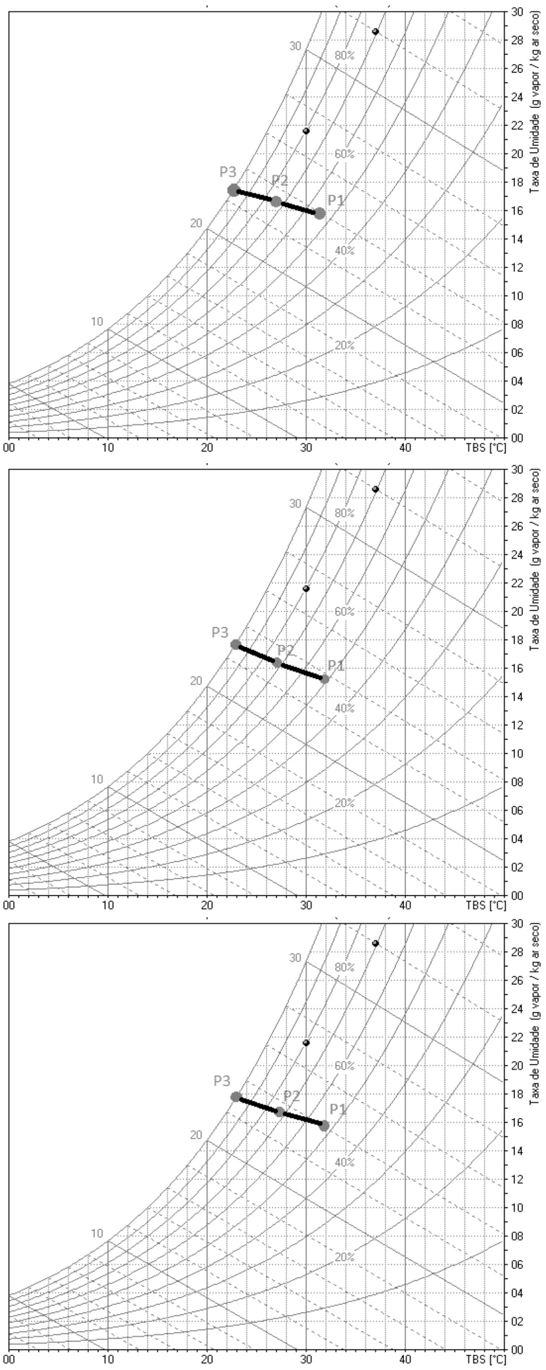


Figure 4. Psycrometric chart - Steady state conditions: T_{db} (°C), T_{wb} (°C) and h (kJ.kg^{-1}).

Temperature and enthalpy comparison for experimental and EES simulation results are in Figure 5. Different values for T_{db} and T_{wb} correspond to different ambient conditions during experimental test runs. In general, EES provides higher values for enthalpy at outlet position or P2 (h_2, kJ.kg^{-1}), in comparison to experimental results – mean values. Air with higher h_2 need better undestanding, once they are theoretical ones from EES simulation, and $\uparrow h_2$ typically corresponds to $\uparrow T_{db}$ and $\uparrow T_{wb}$; one possible explanation relates to heat/cold release to ambient (air outside the airflow or equipment solid parts) and not only between airflow and water heat exchange.

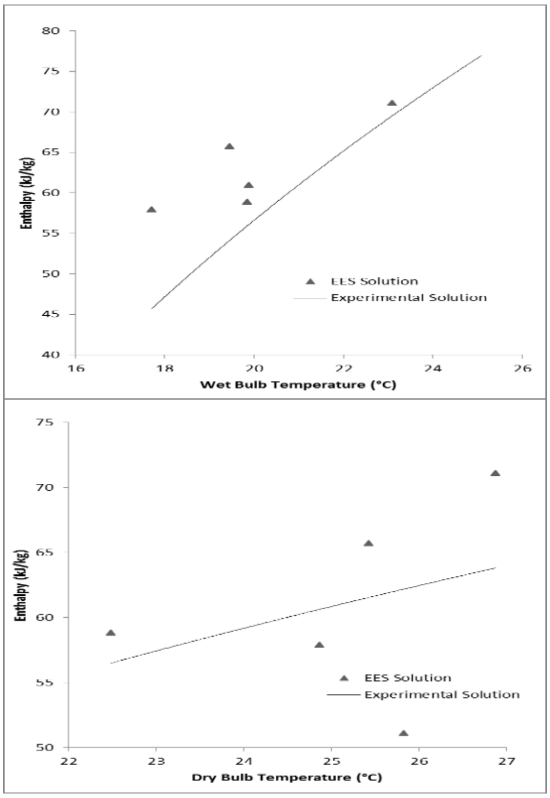
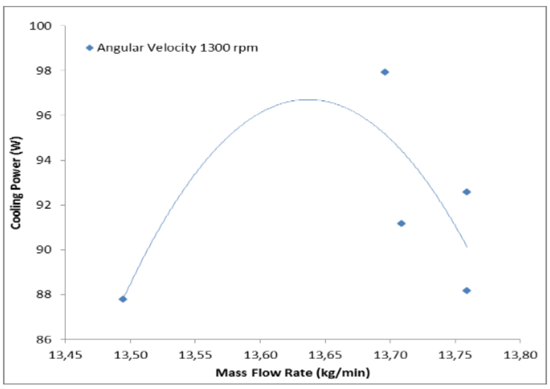


Figure 5. Experimental versus EES simulation: T_{db} (°C), T_{wb} (°C) and h (kJ.kg^{-1}).

Performance for Air cooling

Figure 6 and 7 show the EAC performance, respectively for rotor angular speeds 1300 RPM, 1400 RPM and 1500 RPM: Electrical or Cooling Power (CP, W) and effectiveness (ε_{EAC}, %) according to mass airflow (m_{Air}, kg.s^{-1} or kg.min^{-1}).

For each individual rotor angular speed, as m_{Air} increases it typically increases CP – with a non-linear behavior, first increasing and then descreasing and reaching same order of magnitude for higher m_{Air} values. Maximum power during tests is close to 114 W and hardly surpass 100 W in overall; it is consistent to EAC nominal values (FAN = 125 W; Water pump = 7W).



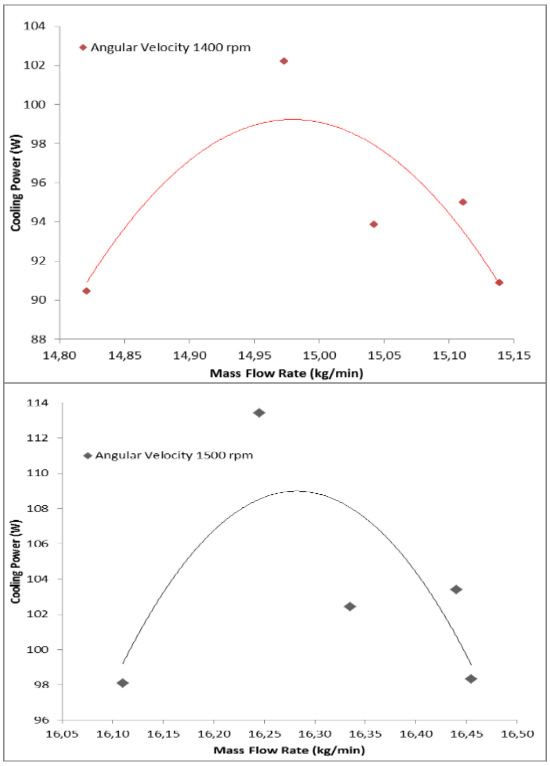


Figure 6. P (W) and m_{Air} (kg.min^{-1}): Performance behavior for different ambient conditions and steady state.

In each individual rotor angular speed, ε_{EAC} also has a non-linear behavior; but overall tendency to higher values a m_{Air} increases. If considering the rotor angular speed as main responsible for m_{Air}, increases in the first one imply in the second one also to increase. Thus, m_{Air} ranges are higher for 1500 RPM and lower for 1300 RPM. Furthermore, for $\uparrow m_{Air}$ passing through the fan´s rotor and the ΔEnergy (or Δheat) ~constant (from cooling process in steady state conditions), it may result in $\downarrow \Delta T$ and $\downarrow \varepsilon_{EAC}$.

The cooling device equipment reaches the highest ε_{EAC}~90%@1300 RPM, while in other two rotor angular speeds is ~85%@1400 RPM and ~80%@1500 RPM. Notice that 5 (five) ambient conditions - quite different from the others (T_{Lab} ~34-35ºC), one at 1300 RPM, two at 1400 RPM, and another two at 1500 RPM; when $\downarrow \varepsilon_{EAC}$ in comparison to lower values for m_{Air}; as mass airflow computes air density which depends on T_{db}.

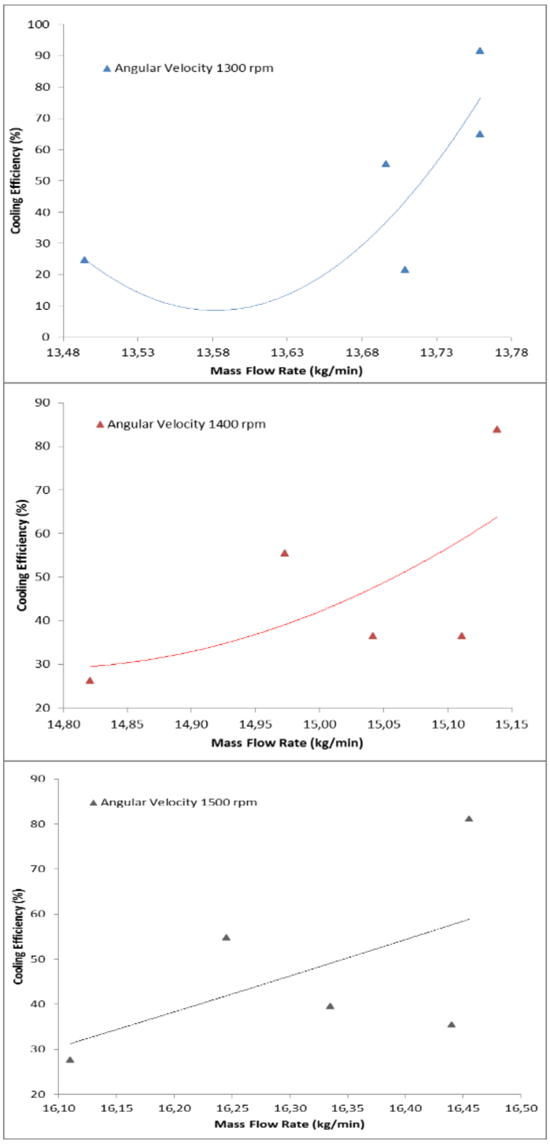


Figure 7. ε_{EAC} (%) and m_{Air} (kg.min^{-1}): Performance behavior for different ambient conditions and steady state.

CONCLUSIONS

In this work, a cooling device equipment performance is investigated for transient and steady state conditions. Experimental tests data acquisition considers Brazilian standards as a guideline, looking for support on energy efficiency labeling programs.

The main conclusions are:

a) $\downarrow T_{db}$ for $\downarrow m_{Air}$, reaching ΔT~5.0°C and corresponding ΔΦ~20%, when comparing outlet and inlet airflow parameters;

b) EAC effectiveness reaches maximum values for lower rotor angular speeds (ε_{EAC} ~90%@1300 RPM), in comparison to higher ones;

c) For a constant rotor angular speed, EAC performance (CP, ε_{EAC} and others) is strongly dependent on air ambient conditions m_{Air} increases from ~13.8 kg.s^{-1} up to ~16.5 kg.s^{-1} when rotor angular speeds goes from 1300 RPM to 1500 RPM.

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REFERENCES

ABNT – Associação Brasileira de Normas Técnicas, 1987. *NBR 10.085: Medição de temperatura em condicionamento de ar*. 14p. (*in Portuguese*)

ABNT – Associação Brasileira de Normas Técnicas, 1990. *NBR 11.215: Equipamentos unitários de ar-condicionado e bomba de calor – Determinação da capacidade de resfriamento e aquecimento*. 27p. (*in Portuguese*)

ABNT – Associação Brasileira de Normas Técnicas, 2006. *NBR 15.372: Resfriadores de ar para refrigeração – Métodos de ensaio*. 23p. (*in Portuguese*)

Asvapoositkul, W., and Treeutok, S., 2012, A simplified method on thermal performance capacity evaluation of counter flow cooling tower, Applied Thermal Engineering, Vol. 38, , No.__, pp. 160-167.

AWE – Alliance for Water Efficiency. Available in <www.allianceforwaterefficiency.org/evap_cooling_intro.aspx>), accessed on April, 2016.

Balbinot, A., and Brusamarello, V. J., 2010, *Instrumentação e Fundamentos de Medidas – Vol. 1*, LTC. 385p. (*in Portuguese*)

Barros, P.S., Ferreira, R.A.S., 2014, "Convection influence on the cooling rate". 15th Brazilian Congress of Thermal Sciences and Engineering – ENCIT 2014, Belém, Brazil.

Braga, A.H.G., et al., 2013, "Modeling of Cooling Evaporative System, with Design and Comparison Between Drivers and Modern Classic Used in Climate of Environments". 22nd International Congress of Mechanical Engineering - COBEM 2013, Ribeirão Preto, Brazil.

Braga, A.H., Braga, C.S., Medeiros, J.M., 2010, "Temperature and Humidity on Evaporative Cooling Systems Actuated by Classical Controllers". 13th Brazilian Congress of Thermal Sciences and Engineering- ENCIT 2010, Uberlândia, Brazil.

Braga, A.H.G., Medeiros, J.M., Braga, C.S., Carvalho, J.A.Y., 2010, "Modelagem e sistema de controle clássico aplicado em resfriadores evaporativos para climatização de ambientes". 6th National Congress of Mechanical Engineering- CONEM 2010, Campina Grande, Brazil.

BRASIL. Ministério de Minas e Energia, Ministério da Ciência e Tecnologia, Ministério do Desenvolvimento, Indústria e Comércio Exterior. Portaria Interministerial no 323, de 26 de maio de 2011. Aprova programa de metas para Condicionadores de Ar. Estabelece os níveis mínimos de eficiência energética para Condicionadores de Ar, caracterizados nos termos dos arts. 1o e 2o do Anexo I à Portaria Interministerial MME/MCT/MDIC no 364, de 24 de dezembro de 2007. Brasil, 2011b. Disponível em: <http://www.mme.gov.br/documents/10584/1139097/Portaria_Interministerial_nx_323_2011.pdf/8ea50087-5fd0-4f65-ab23-c95dda53907a>. Acesso em 15 apr. 2016.

BRASIL. Ministério do Desenvolvimento, Indústria e Comércio Exterior. Portaria n.º 007, de 04 de janeiro de 2011. Aprova a revisão dos Requisitos de Avaliação da Conformidade para Condicionadores de Ar. Brasil, 2011. Disponível em: <http://www.inmetro.gov.br/legislacao/rtac/pdf/rtac001655.pdf > Acesso em 15 apr. 2015.

BRASIL. Ministério do Desenvolvimento, Indústria e Comércio Exterior. Instituto Nacional de Metrologia, Qualidade e Tecnologia – INMETRO. Portaria n. º 410, de 16 de agosto de 2013. Aprova revisão das classes de eficiência energética e o formato da etiquetas de conservação energética ENCE para condicionadores de ar. 2013. Disponível em: <http://www.inmetro.gov.br/legislacao/rtac/pdf/RTAC002015.pdf> Acesso em 15 apr.2016.

Camargo. J.R., 2009. *Resfriamento Evaporativo: Climatização Ecológica*. Rio de Janeiro, Ciência Moderna.

ECOBRISA, 2016. Models available in <http://ecobrisa.com.br/>, acessed on Dec, 2023.

Eastop, T.D.; Croft, D.R., 1990, *Energy efficiency for engineers and technologists*, Longman Pub Group, Essex, England, 400p.

Ferro, B.N., 2015, "Gestão de um projeto de uma torre de arrefecimento industrial: Estudo de caso.", MsC. Dissertation, Instituto Superior de Engenharia de Lisboa (Departamento de Engenharia Mecânica), Lisboa (Portugal).

Henn, E.A.L., 2019, *Máquinas de fluido*, 4th ed. Editora UFSM, Santa Maria-RS. 496p. (*in Portuguese*). ISBN: 9788573913279.

ISO – International Organization for Standardization, 2010. "ISO 5.151: Non-ducted air conditioners and heat pumps – Testing and rating for performance". 73p.

<https://www.iso.org/obp/ui/#iso:std:iso:5151:ed-2:v1:en>

ISO – International Organization for Standardization, 2011. “ISO 13.253: Ducted air conditioners and air-to-air heat pumps – Testing and rating for performance”. 89p. <https://www.iso.org/obp/ui/#!iso:std:54064:en>

INMETRO – Instituto Nacional de Metrologia, Qualidade e Tecnologia, 2014. “Programa de etiquetagem PROCEL. Coeficiente de eficiência energética para produtos de condicionamento de ar comercializados no Brasil e etiquetados pelo PROCEL”. Rio de Janeiro-RJ. Disponível em: <http://www.inmetro.gov.br>. Acesso em 15 apr. 2016.

Lelis, A.V.R., et al., 2014, “Evaporative Cooling System Efficiency Numerical Analysis”. 15th Brazilian Congress of Thermal Sciences and Engineering – ENCIT 2014, Belém, Brazil.

Nóbrega, C.E.L., Brum, N.C.L., 2009, “Numerical simulation of desiccant assisted evaporative cooling systems”. 20th International Congress of Mechanical Engineering - COBEM 2009, Gramado, Brazil.

Oliveira, A.M., 2007, “Experimental investigation of heat and mass transfer in an evaporative cooler made of porous ceramic”. 19th International Congress of Mechanical Engineering - COBEM 2007, Brasília, Brazil.

Pessoa, J.L.N; Ghisi, E., 2015. “Estado da arte em eficiência energética: sistemas de condicionamento de ar”. Report from CB3E – Centro Brasileiro de Eficiência Energética em Edificações, UFSC, Florianópolis-SC. 31p.

Santos, J.C., et al., 2008, “Modelagem e solução analítica do problema de transferência de calor e massa em resfriadores evaporativos diretos”. 5th National Congress of Mechanical Engineering- CONEM 2008, Salvador, Brazil.

Shapiro, H.N., Moran, M.J., 2009. *Príncipios de termodinâmica para engenharia*. 7ª ed. Rio de Janeiro, LTC. 864p.

Seneviratne, M., 2007, *A practical approach to water conservation for commercial and industrial facilities*, Elsevier Science, Essex/England, 400p. http://store.elsevier.com/A-Practical-Approach-to-Water-Conservation-for-Commercial-and-Industrial-Facilities/Mohan-Seneviratne/isbn-9780080525068/

Wang, J.H., Wu, J.H., Hu, S.S., and Huang, B.J., 2009, Performance of ejector cooling system with thermal pumping effect using R141b and R365mfc, Applied Thermal Engineering, Vol. 29, No.__, pp. 1904-1912.

Yingjian, L., Xinkui, Y., Qi, Q., and Jienzhi, L., 2011, The study on the evaporation cooling efficiency and effectiveness of cooling tower of film type, Energy Conversion and Management, Vol. 52, No.__, pp. 53-59.