Evaluation of Retrofitting a Conventional Cooling Tower into a Hybrid Set in an Oil Refinery

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Abstract:

The combined use of wet cooling towers and heat exchangers (air-coolers) for cooling water is already a known technology. The objective is to reduce the evaporation where there is water scarcity or environmental standards mandatory. Before entering the conventional cooling tower, water is pre-cooled by an air-cooler equipment.

The addition of conventional air-coolers require a degree of water treatment stock much higher than that practiced in wet cooling towers, since the dirt and scaling can cause a marked reduction in performance.

An air cooler made with two-phase closed thermosyphons have the advantage of having external flow of currents on both sides, facilitating the cleaning operation of the exchange surfaces in contact with water that is cooled.

In this work, a numerical simulation model of the cooling tower was implemented in the TRNSYS simulation package. This model was calibrated and validated by comparison with real operation data in a historical year of the existing cooling tower, on an hourly basis. After validation, a heat pipe air cooler was introduced in the simulation environment. In addition, a system of partial bypass of the circulating water was also implemented in order to allow adjustment of water temperature that is delivered to refinery. The procedure adopted was to simulate scenarios in TRNSYS thermal conductance, analyzing the water savings afforded by each conductance suggested. At the same time, a code design of heat exchangers was used in combination with mathematical programming routines for the proposition of the lowest cost heat pipe air cooler that meet the desired thermal load. The results establish the relationship between the size of the air-cooler to the amount of water conserved.

Keywords:

Heat Pipes, Heat Exchangers, Mathematical Programming, TRNSYS, Optimization.

1. Introduction

Cooling towers use evaporative heat transfer to reduce process water temperature. In mostly cases, the 2 to 5% of water lost to evaporation is irrelevant, but in cases of water scarcity, the amount of make-up water can be an important issue.

The combined use of wet cooling towers and heat exchangers (air-coolers) for cooling water, with the objective to conserve water and reduce water condensation plumes is a known technology, called hybrid cooling towers, as described by ASHRAE [1,2]. However, the investment for the construction of hybrid towers is substantially greater than that of building wet towers, and the applications of this technology are restricted to cases where there are pressing environmental factors such as water scarcity or mandatory environmental standards.

The addition of conventional air-coolers (water flowing inside finned tubes, heat exchange with the external air flow) requires a better treatment of circulating water than that practiced in wet cooling towers, because fouling can cause decreasing in thermal performance.

An air-cooler made with two phase closed thermosyphons could have the advantage of external flow of both currents (air and water). This gives robustness to equipment by facilitating the cleaning operation of the exchange surfaces in contact with water that is cooled. A two-phase closed thermosyphon is a kind of heat pipe without porous media. It works in applications where the condenser is above to the evaporator, and gravity is used for returning the condensed working fluid to the evaporator section of the heat pipe. In the case studied, the water circulating between processes and cooling towers in a Brazilian oil refinery contains impurities and dirtiness that make the use of conventional air coolers inviable.

Among various types of hybrid towers, a configuration is opted that is a combination of an air-cooler with a wet tower, built as separate plants, as shown in Figure 1.

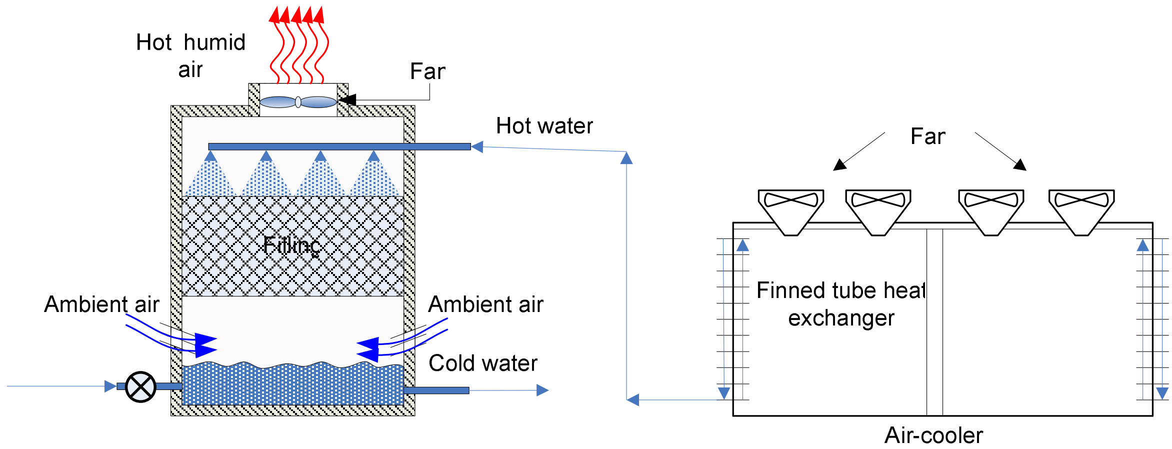

Fig. 1. Tower hybrid formed by the combination of wet and dry towers in separate plants.

Despite the disadvantage of investing in more fans, the use of separate plants eliminates the problem of lost productivity during installation and permits the option of returning to operate without air-coolers, when necessary cleaning and maintenance. Moreover, there is no need of reengineering the original tower.

2. Case Description

A water cooling facility in an oil refinery in Brazil was the case proposed for the study. The facility consists of two cross-currents cooling towers that are composed of eight cells, resulting in total of 46,000 m³/h water flow circulating (16 cells total). There is a water make-up needed of 800 m³/h, 100 m³/h of purge to control water scaling and 700 m³/h are lost to evaporation that is a considerable volume of water taken from the local river. The aim of the case study is to reduce the make-up water consumption by using hybrid cooling towers.

For sizing the heat pipe air coolers, a historical year of hourly operation data and hourly weather data was used. The meteorological data, temperatures inside cooling tower, relative speed of the fans, mass flow rate, solar irradiation, wind speeds, relative humidity, atmospheric pressure, precipitation were collected for the period from 11/01/2006 to 10/31/2007. Temperatures of the main water stream were plotted in Figure 2 for this historical weather / operation year.

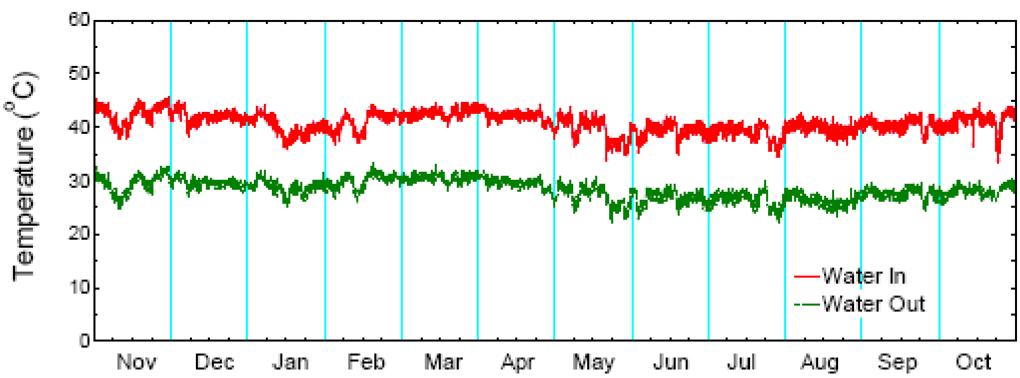

Fig. 2. Water temperatures in the cooling tower

Firstly a simulation model was implemented in TRNSYS [5] for the existing cooling tower. The model was fed with the hourly weather historical data and thermal load data. Then the model set of parameters was calibrated in order to find the better reproduction of the real tower using the simulation model.

Once the virtual cooling tower could reproduce the real one, it will be possible to couple a heat pipe air cooler to the wet tower with aid of the TROCATER software by Borges, Mantelli [3]. Several virtual air coolers can be sized, so it is possible to establish a relationship between air cooler size and water savings.

3. Mathematical model of the tower

In a cooling tower a hot water current is in direct contact with air current. As result, cooling water occurs due to the transfer of sensible heat (temperature difference between air and water) and due to mass transfer (water evaporation).

The currents of air and water can be arranged in countercurrent or cross-currents and are generally composed of multiple cells and share a common pit. Also, many towers have filling, which increase the wet surface in contact with air, providing a higher mass transfer. Water loss is compensated by the tower water make-up. Figure 3 represented a cooling tower countercurrent with a single cell and filling.

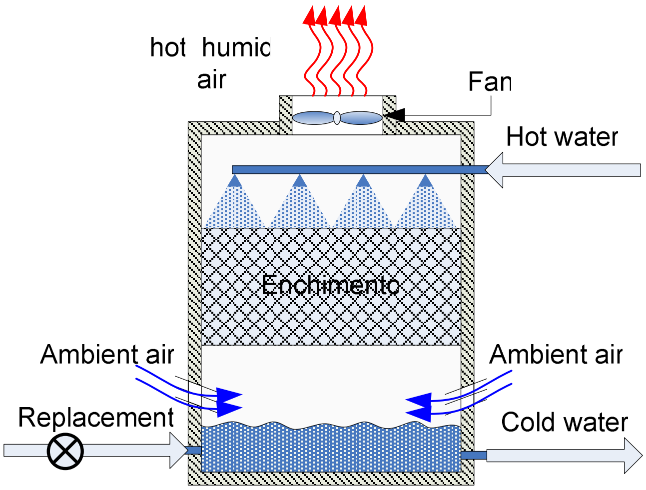

Fig. 3. Cooling tower countercurrent schematic with a single cell and filling.

The model of the effectiveness was used in this unit of TRNSYS and the main equations used are shown below reminding that these equations are for cross flow.

$$\varepsilon_a = \frac{1}{m^*} \bullet (1 - \exp(-m^* \bullet (1 - \exp(-Ntu)))) \,, \qquad (1)$$

$$m^* = \frac{\dot{m}_a}{\dot{m}_{w,i} \bullet (Cp_w / C_s)} \,, \qquad (2)$$

$$Ntu = C \cdot \left(\frac{\dot{m}_w}{\dot{m}_a} \right)^{n+1} , \qquad (3)$$

$$C_s = \left[\frac{dh_s}{dT} \right]_{T=T_w} , \qquad (4)$$

$$T_{w,o} = \frac{\dot{m}_{w,i} \cdot Cp_w \cdot (T_{w,i} - T_{Ref}) - \dot{Q}_{cell}}{\dot{m}_{w,o} \cdot Cp_w} + T_{Ref} , \quad (5)$$

$$\omega_{a,o} = \omega_{S,w,e} + (\omega_{a,i} - \omega_{S,w,e}) \cdot \exp(-Ntu) , \qquad (6)$$

For the towers, it was considered that both have the same filling geometry and operating conditions. So, have the same "C" and "m". The limits to "C" are 0.5 and 5.0 for "m" is -1.1 and -0.35. For the determination these constants was used the method of trial and error, have been attributed values to them until they reached the lowest mean-square deviation possible. Were obtained the following values: C = 1.28 and m = -0.75; to a mean-square difference of 0.18 °C.

The volume of the cooling tower pit was estimated by the same technique, since data were not transferred. As a very large volume implies a large thermal inertia and a more linear behavior over the year and a very small volume, low thermal inertia and unstable behavior, knowledge of this volume is essential for the characterization of the tower. Through comparison with the temperature of the sending tower real, is found the value of 10 m^3. The maximum flow for each cell is given by the average flow, in other words, flow rate total divided by the number of cells (46,000/16 = 2875 m^3/h).

4. Implementation of the model in TRNSYS

The model used for simulation of wet towers was developed by Braun (1989) [4] and implemented in TRNSYS [7] as a standard component.

The mathematical model is composed of two towers with double cross-current as in the oil refinery, see Figure 4.

To read the weather and operating conditions of the towers are two units used Type 9e (Data Reader for Generic Data Files - Free format). The same types of units are used for reading the numbers of active cells and their relative velocities (for fans). For each one of the 16 fans that compose the two towers there is a relative velocity (the ratio between the actual flow and maximum air flow).

Four units Type 65d (online graphical plotter) were placed for instant viewing of simulation results. They are: Cond_ar (condition of the air) Rad_Prec (radiation and precipitation), Temperature and Flow. The water data that returns to the towers is a sum, so was put a unit "Equation" (divide vazões) to the flow division to each tower. After these, another unit "Equation" (soma vazões) was posted to flow rates sum and other calculations, as the average water temperature sending (simulated).

Two other integrative units (T_med_real and T_med_calc) were used to average temperature calculated over the period and to calculate the mean-square deviation.

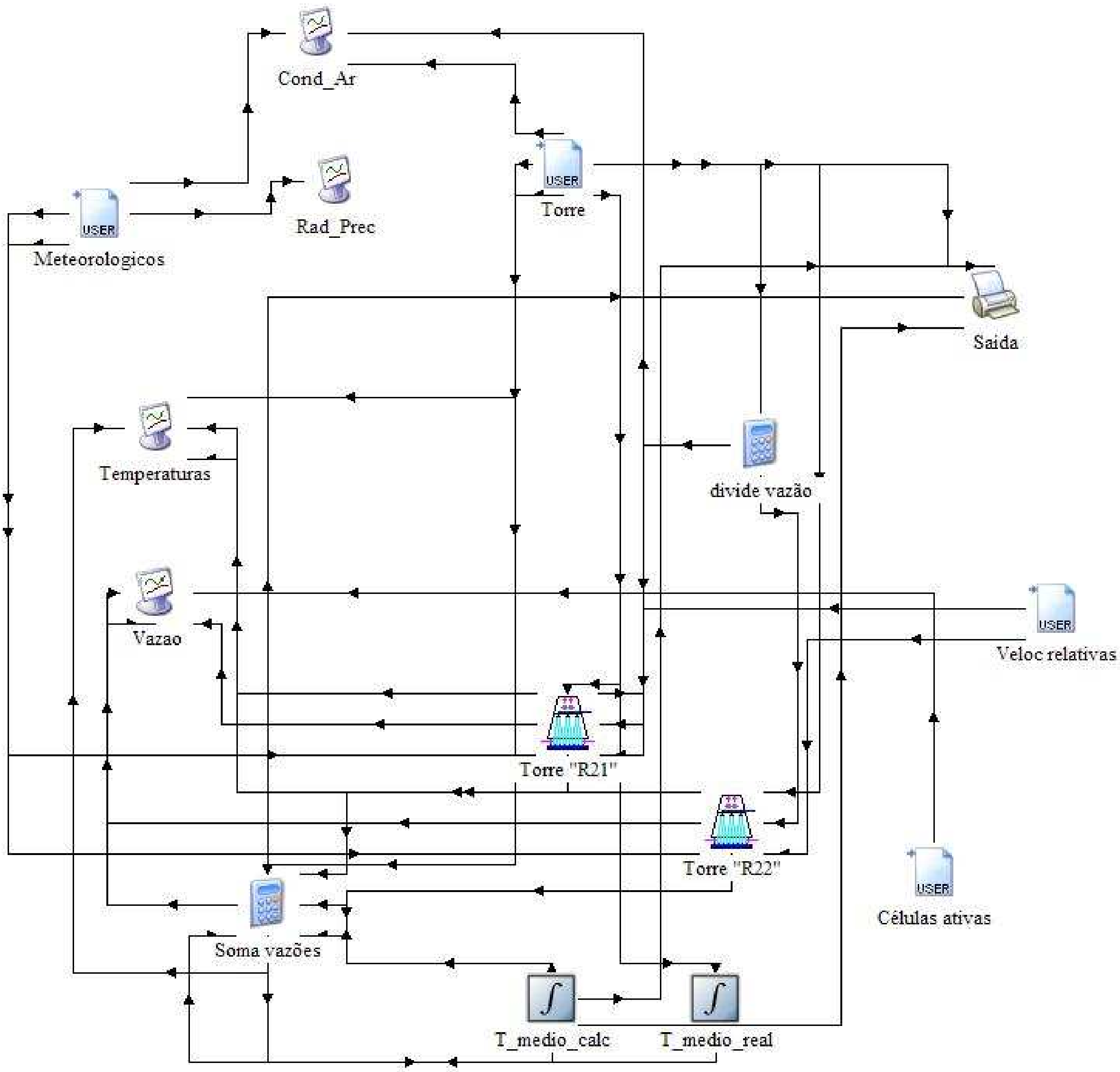

Fig. 4. Diagram of flow information between TRNSYS components.

5. Simulation of the existing cooling tower

For the implemented model and with meteorological data transferred by the refinery, was obtained a mean-square difference of 0.18 ° C between the temperatures of sending (of the towers to process) real and simulated. We can see part of this result in Figure 5. The mean-square difference equation is as follows:

$$DQM = \frac{\sqrt{\sum_{0}^{8760}[(T_{envio,simulado} - T_{envio,real})^2]}}{8760}, (7)$$

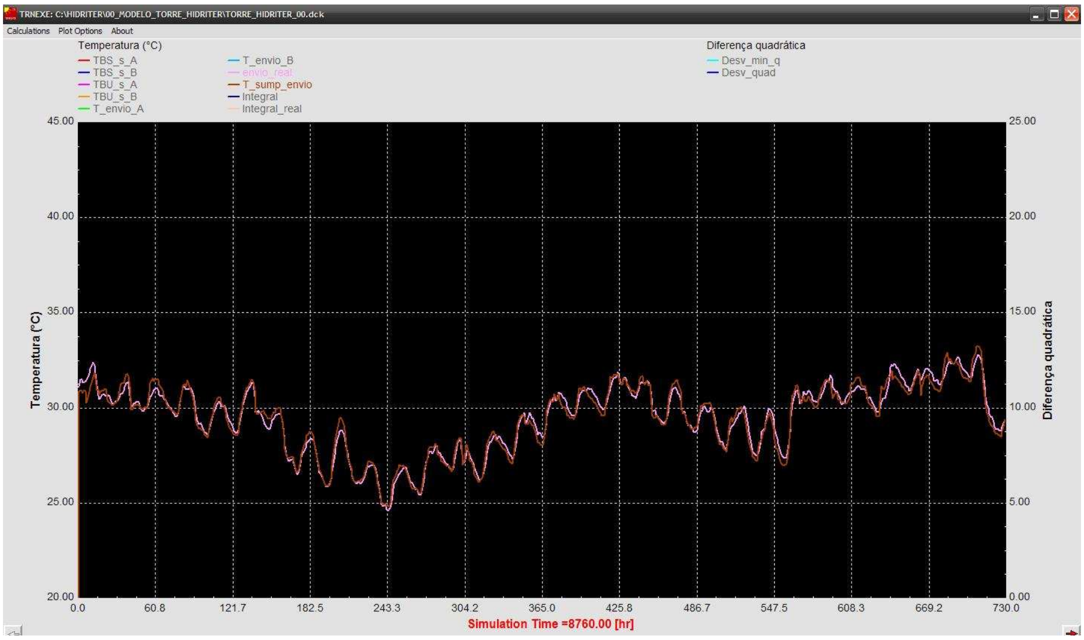

Fig. 5. Interface with results of comparison of sending temperatures of real towers and simulated for the 730 initial hours, lines practically overlapping.

With this excellent result of the simulation, it can be stated that the model implemented in TRNSYS for the transient regime of operation reproduced with precision the towers in the refinery.

6. Procedure adopted to size the air-cooler

To evaluate the air-cooler influence in the implemented model was introduced an air-cooler that pre-cools the water return process, upstream of wet towers. Later, it was implemented a system of partial bypass of the circulating water to permit the adjustment of sending water temperature of the process. In this way, if the ensemble air-cooler/humid tower over-cools the water to temperatures below the desired 30 °C, some amount of by-pass will ensure the sending to the process at 30 °C. All water that passes through the bypass doesn’t suffer any kind of evaporation, reducing the overall quantity of water evaporated.

Also, it was placed a dynamic control of the number of active cells in the tower, including modulation of ventilation in the active cell to adjust flow reduction provided by the by-pass.

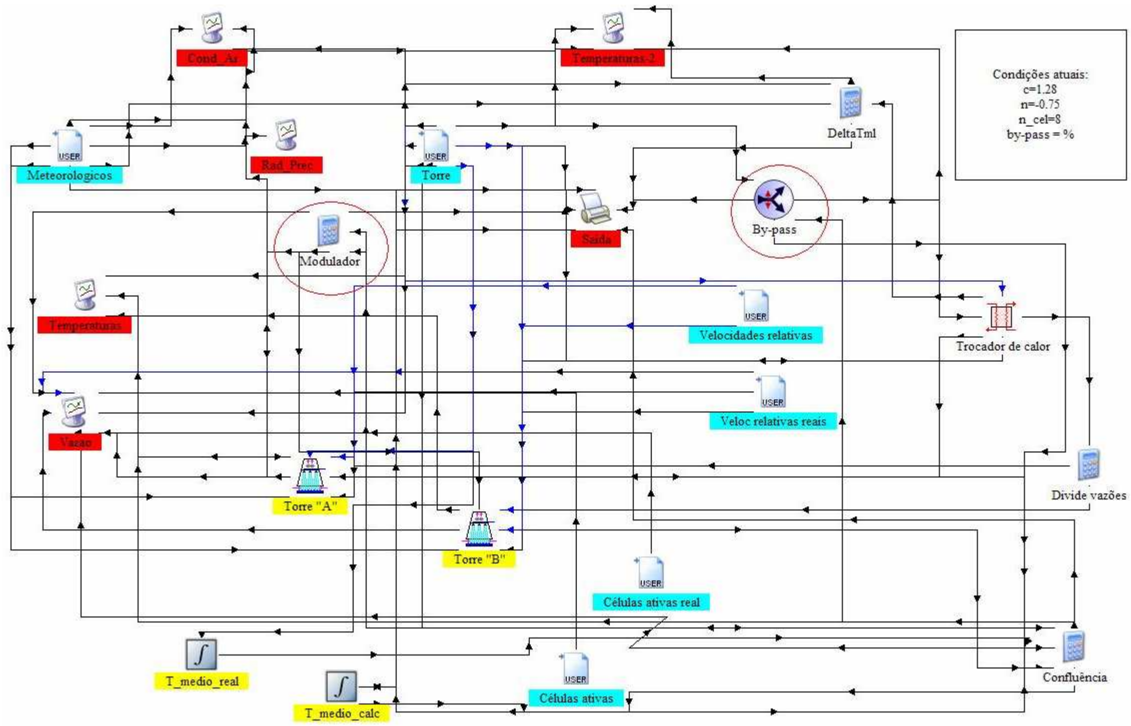

Fig. 6. Interface of the hour simulation mode with by-pass and modulation of relative speed fans.

In the TRNSYS simulation environment, the air-cooler can be represented by a global coefficient of heat transmission, a thermal conductance. The procedure adopted is to simulate scenarios of the thermal conductance in TRNSYS, analyzing water savings obtained by each conductance suggested. At same time, it uses a project code of heat exchangers (TROCATER by Borges, Mantelli [3] or DIMTER by Isoppo, Borges, Mantelli [6]) for the proposition of equipment that attend the specified conductance, calculating the size of the equipment and the number of heat pipes. In this way, will to relate the size of the air-cooler with the amount of conserved water.

The scenarios proposed for the conductance of air-cooler should vary since zero (when the bypass is also 0% and didn't retain any water) until a maximum value of conductance. For proposition that maximum, it was proposed that the project of the air-cooler provide 5 °C of reduction in water temperature of the process return, based on the annual average conditions of the temperature. The value for this maximum conductance was $11x10^6$ W /°C.

A standart configuration for all air-coolers dimensioned was proposed, so each configuration differ one to another only by the number of tubes and rows. The remaining characteristics follow the same standart. The standart equipment is an air-cooler installed on the ground, which is a parallelepiped with approximate height of 10 m, 100 m width and length enough for installation of fans on top of this parallelepiped. The panels with heat pipes would be positioned on both faces of 100 m x 10 m. The tubes have a total length of 7.7 m, 6 m with fins, as shown in Table 1.

Table 1. Standard configurations for all air-coolers dimensioned.

Length of the evaporator	m	1.7
Length of condenser	m	6
Diameter of tubes	mm	50.8
Geometric arrangement of the tube bundle		45º
Width of the exchanger	m	100
Spacing between tubes of a row	mm	150
Working fluid		Water

Height of fins on the condenser	mm	27
Thickness of the fins on the condenser	mm	1.5
Spacing between fins on the condenser	mm	6

Comparing the graphics of the annual simulation in transient regime before and after implementation of the bypass and the dynamic modulation of the number of active cells in the tower, you can see in Figure 7 and Figure 8 that in some moments of higher thermal load of air-cooler (when there are large differences in temperature between the water return process and the ambient air), is performed a load modulation in a cell tower. Figure 7 shows the fan relative speed as a constant and in Figure 8 indicates the variation caused by the implementation of the load modulation of the cell. But this modification had a little effect on the results in the flow and temperature.

The variable FAN3 (fan relative speed), in red, indicates the efficiency of the cell fan 3, Tower A, modulated by the control. It was the only cell modulated, and the impacts are not perceptible in the final temperatures and flow rates. This indicates that the approximations with fixed values can be reasonable.

Table 2 presents the simulation results for various levels of conductance of the heat exchanger.

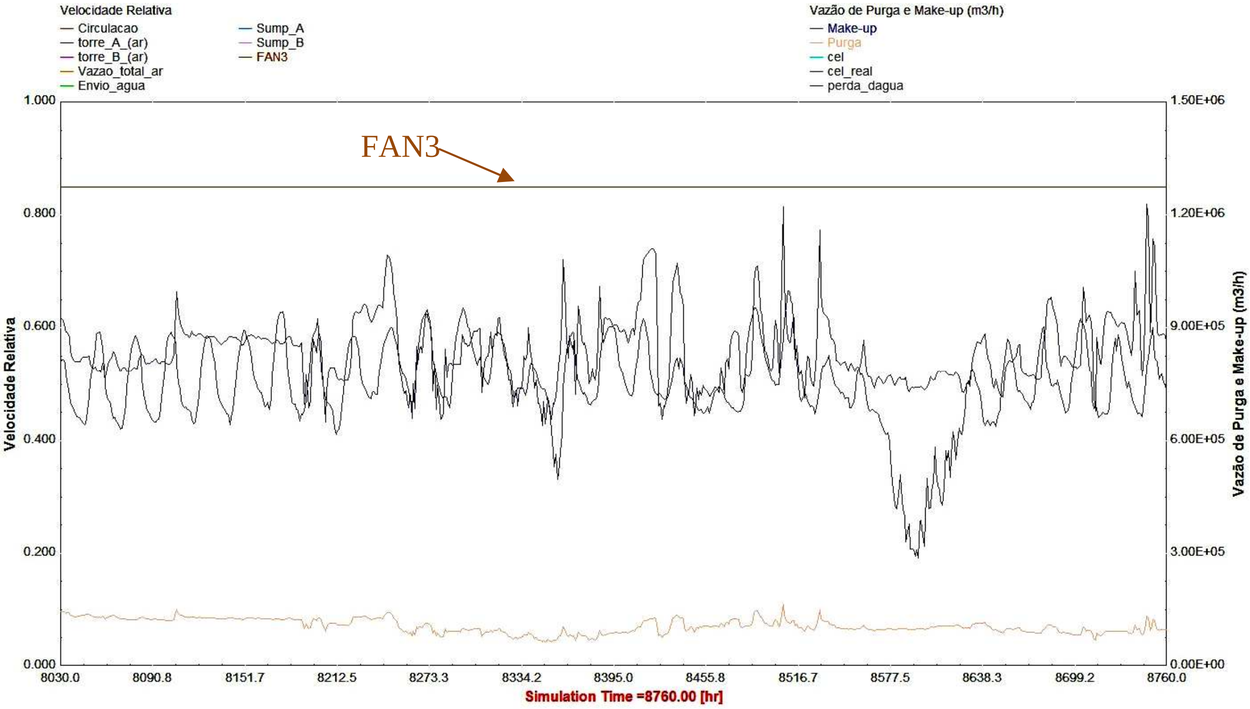

Fig. 7. Section from hourly simulation graph showing preliminary constant relative speed of the fan (FAN3 = 0.85).

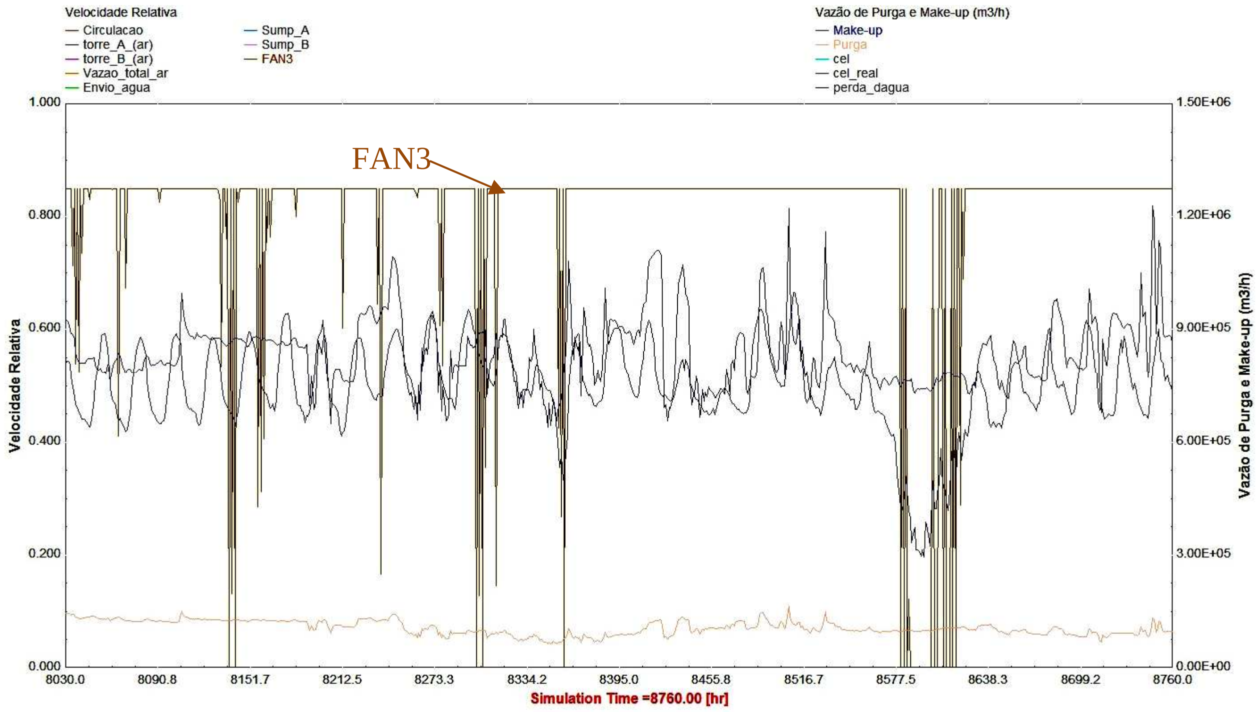

Fig. 8. Section from the final simulation graph shows the operation modulation of the fan speed (ranging FAN3).

Table 2. Results of the sizing of-Air Coolers

UA, W/K	Evaporated Water, m³/h	Mass Flow rate of annual average water, kg/h	By-pass, [%]	Average LMDT, ºC	Number of pipes	Saved water, %
$11{,}42.10^6$	579	$3{,}83.10^7$	7,9	11,0	37310	18,8
$9{,}13.10^6$	593	$3{,}86.10^7$	7,3	11,9	30648	16,8
$6{,}85.10^6$	611	$3{,}90.10^7$	6,4	13,0	22653	14,3
$4{,}56.10^6$	635	$3{,}94.10^7$	5,3	14,5	15990	11,0
$2{,}28.10^6$	665	$4{,}01.10^7$	3,9	16,5	7995	6,8
0,00	713	$4{,}17.10^7$	0,0	-	0	-

There were small changes in the amount value of water conserved by the number of tubes, as shown in Figure 9.

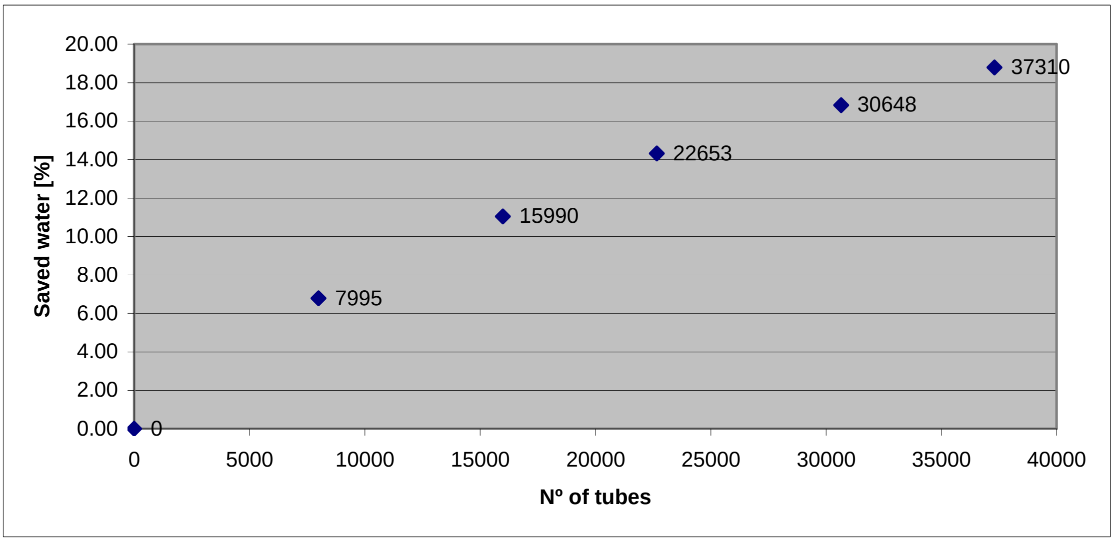

Fig. 9. Fraction of water retained in depending on the number of heat pipes installed in air-cooler.

The level of average by-pass according on the amount of conserved water is shown in Figure 10.

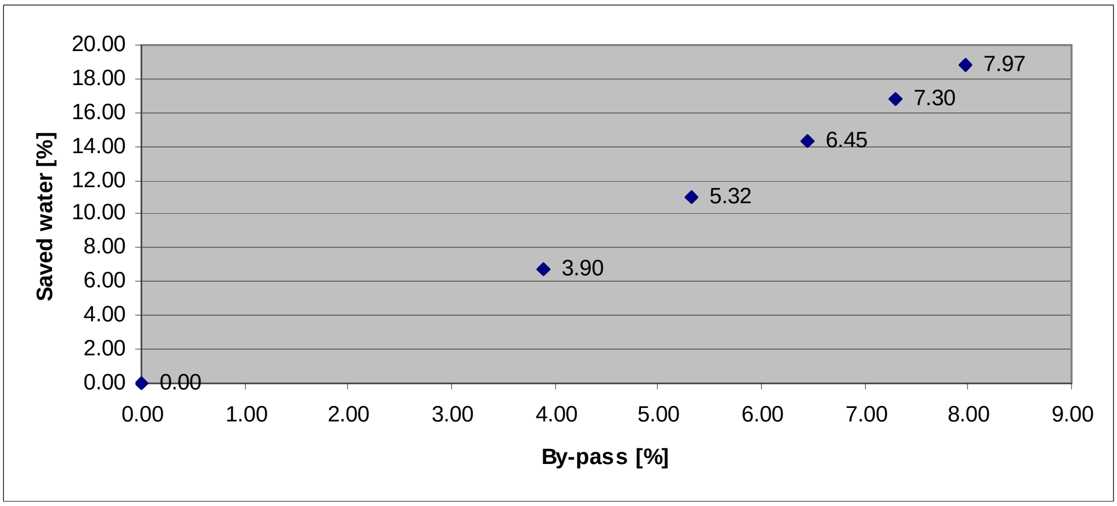

Fig. 10. Amount of water saved depending on annual average by-pass.

A heat exchanger with 8000 tubes saves initially 7% of the water evaporated. However, improvements can be obtained by segregation and by-pass of currents more cold coming from the process, as discussed in the following section.

7. Conclusion

Hybrid cooling towers are interesting equipments for process industry in regions of water scarcity. A design model for sizing hybrid cooling towers that uses heat pipes in the air cooler was developed in this work. The model showed itself a useful tool for sizing cooling towers, allowing one to choose the better compromise between equipment size (number of heat pipes) and annual water savings for a typical meteorological year. For the case Studied, a feasible configuration with 8000 heat pipes was chosen, and it yields a 7% water savings. Further work is recommended for establishing compromise between Annualized Life Cycle Cost of each configuration and annual water savings. Also, an optimization of the heat pipes sizing to a best configuration can be make a big difference in the equipment, making it more compact and efficient.

Acknowledgements

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Nomenclature

ε_a	effectiveness of air
$\dot{m}_a$	mass flow rate of air, kg/h
$\dot{m}_{w,i}$	mass flow rate of water input, kg/h
$\omega_{a,o}$	mass rate flow of water output, kg/h
Cp_w	constant pressure specific heat of water, kJ/(kg K)
C_s	specific heat of saturated air at water temperature, kJ/(kg K)
Ntu	mass transfer number of transfer units
m^*	ratio of air and water effective capacitance for humid conditions
C	empirical constant for each type of tower
n	empirical exponent for each type of tower
h_s	enthalpy of saturated air, kJ/kg
T_w	water temperature, ºC
$T_{w,i}$	water temperature input, ºC
$T_{w,o}$	water temperature output, ºC
$T_{\mathrm{Re}\,f}$	temperature of reference (0 ºC)
$\dot{Q}_{cell}$	overall tower cell heat transfer rate, kJ/h
$\omega_{S,w,e}$	effective absolute humidity at saturation, kg of H2O/kg of dry air
$\omega_{a,i}$	humidity air input, kg of H2O/kg of dry air
$\omega_{a,o}$	humidity air output, kg of H2O/kg of dry air

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