THE EVALUATION OF THE IMPORTANCE OF ADDITIVES IN COOLING TOWER OPERATIONS

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ABSTRACT

Cooling water production is very important to oil refineries, and cooling towers are associated with high costs. An analysis of blowdown and make-up streams, cycles of concentration, use of biocides, and corrosion and scale inhibitors, can be performed to find alternatives to reduce process costs. Furthermore, a cooling system with chemical additives is advantageous because it prolongs the lifespan of the cooling tower. It also permits the elevation of the concentration cycle, consequently, reducing the cost of make-up water and minimizing inhibitors. This work seeks the optimization of cooling tower in terms of make-up water and suggests the use of chemical additives for reducing costs. The optimization was performed for scenarios with different make-up water compositions, and the Puckorius Scaling Index (PI) was evaluated to assure the quality of the water. The results showed that the lowest cost is obtained with the highest allowed cycle of concentration, according to the Puckorius Scaling Index interval.

KEYWORDS

cooling tower; optimization; cost

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1. INTRODUCTION

The main use of the water in oil refineries is for cooling the processes or equipment by reducing or removing the heat from them. The water is normally used as a cooling fluid, because it has high specific heat, low viscosity, high thermal conductivity, and high density (Omni, 1989).

Because of the increasing scarcity of water resources and the capacity of the oil refineries, the adoption of measures that ration the use of water is important, such as the reuse of industrial wastewater. Thus, wastewater reuse in the cooling tower and the optimization of the operational conditions are essential for reaching an attractive cost-benefit relationship.

Some important parameters in the operation of a cooling tower are the heat load (the amount of heat transferred from the water to the air stream), the recirculating water flow rate, the range (the difference between inlet and outlet temperatures of the water in the tower), and the approach (the difference between the outlet water temperature and the wet-bulb temperature of the air).

Some studies in the literature relate the cooling tower optimization, such as Castro et al. (2000), Kim et al. (2001), Cortinovis et al. (2009), Serna-González et al. (2010), and Souza (2010).

Castro et al. (2000) developed an operational cost minimization model for a cooling water system that supplies a heat exchanger network. In this work, the model includes the energy cost and the make-up water cost, and nonlinear programming is used to solve it. The results showed that the forced removal of a part of the water that enters the tower with the make-up water is an optimal solution for situations that require additional heat removal. Case studies showed that the wet-bulb temperature is the variable that most influences the tower performance.

Kim et al. (2001) optimized a cooling tower, determining the minimum total cost of the cooling system. From the capital cost (a function of the circulating water flow, range, approach, and the wet-bulb temperature) and the operational cost (the power consumed by the fan and the pump), the optimal conditions were achieved. This work proposes that the total optimal cost may not always be obtained with the minimum water flow.

Cortinovis et al. (2009) developed an operational cost minimization model for a system composed of a crossflow cooling tower and a network of heat exchangers, using nonlinear programming. The objective function is given by the cost of electricity consumed by the pumps and fans, and the make-up water cost. From the case studies, the most important variables to reduce the operational costs are circulating water flow rate, air flow rate, and flow rate of the forced removal of a part of the water that enters the tower with the make-up water.

The work of Serna-González et al. (2010), a model shows a formula to minimize the total annual cost of a counter flow cooling tower, using the mixed-integer nonlinear programming. In this study, an objective function includes the capital and operational costs. The obtained results showed that operational costs are proportional to the range, while capital costs depend on the optimal relation between range and air flow. Besides, the cooling tower packing area was considered an important variable for influencing the total annual cost.

Souza (2010) used linear-programming to minimize the cooling tower operational cost, including water, cost of effluent treatment, and cost of water treatment. Because of the high cost of the water treatment, the optimal operational cost was obtained for the minimum blowdown flow and, consequently, the maximum cycle of concentration.

Then, the entire work analyzed the operational cost of the cooling tower. However, they did not consider the cost of additives, which are important for avoiding the formation of deposits, fouling, corrosion and biodeposits, and for prolonging the cooling tower lifespan.

Therefore, this work consists of the cooling tower optimization in terms of make-up water and the reduction of chemical additives costs. The optimization was performed for scenarios with different make-up water compositions, and the Puckorius Scaling Index (IP) was evaluated to assure the quality of the water.

2. METHODOLOGY

2.1 Cooling tower equations

The cooling system studied in this work is shown in Figure 1, which represents an open recirculating cooling tower.

In cooling systems, the make-up water is used to replace the losses caused by evaporation, drift, blowdown, and possible leaks (Femp, 2011). Equation 1 represents the make-up flow rate ($\dot{Q}_m$):

$$\dot{Q}_m = \dot{Q}_b + \dot{Q}_e + \dot{Q}_d + \dot{Q}_l \quad (1)$$

where $\dot{Q}_b$ is the blowdown water flow rate, $\dot{Q}_e$ is the water flow rate lost by evaporation, $\dot{Q}_d$ is the water flow rate lost by drift, and $\dot{Q}_l$ is the water flow rate lost by possible leaks.

Considering that the salt concentration in the water lost by evaporation is equal to zero and that the salt concentration in the streams of blowdown, drift and leaks is equal to c_s ; the make-up water flow rate is expressed by Equation 2. The cycle of concentration (CC) is represented by Equation 3 (Perry, 2008). The higher the concentration of the dissolved salts, the greater the number of cycles of concentration and the need for use of scale and corrosion inhibitors are:

$$\dot{Q}_m \cdot c_m = c_s \cdot (\dot{Q}_b + \dot{Q}_d + \dot{Q}_l) \quad (2)$$

$$CC = \frac{c_s}{c_m} \quad (3)$$

where c_m is the salt concentration in the make-up water, and c_s is the salt concentration in the recirculating water.

In the cooling tower, the amount of latent heat of vaporization can be equal to the sensible heat lost by the water droplets of the stream that was not evaporated, as shown in Equation 4 (Pereira, 2001):

$$\dot{Q}_e \cdot \lambda = (\dot{Q}_w - \dot{Q}_e) \cdot c_{pw} \cdot (T_{w1} - T_{w2}) \quad (4)$$

where c_{pw} is the water specific heat, T_{w1} is the inlet water temperature, T_{w2} is the outlet water temperature, λ is the water latent heat of evaporation, $(\dot{Q}_w - \dot{Q}_e)$ is the flow rate of the stream that was not evaporated, and $\dot{Q}_w$ is the recirculating water flow rate.

Figure 1. Illustration of an open recirculating cooling system.

Considering that $c_{pw} = 4.18 \text{ kJ}/(\text{kg} \cdot ^\circ\text{C})$ at 25°C , $\lambda = 2.42 \cdot 10^3 \text{ kJ}/\text{kg}$ at 25°C , and $5^\circ\text{C} < (T_{w1} - T_{w2}) < 20^\circ\text{C}$, the water flow rate lost by evaporation can be simplified to Equation 5 (Pereira, 2001). It gives an approximate value of the evaporation stream in the open recirculating cooling tower in tropical countries (Veiga, 2010).

$$\dot{Q}_e = 0.00173 \cdot \dot{Q}_w \cdot (T_{w1} - T_{w2}) \quad (5)$$

The drift can be estimated by Equation 6 (Perry, 2008):

$$\dot{Q}_d = 0.001 \dot{Q}_w \quad (6)$$

The maximum cycle of concentration can be determined according to the contaminants concentration in the cooling water, like calcium carbonate, calcium sulfate, and silica. For example, the maximum silica concentration in the recirculating water must be 180 ppm. Then, the maximum cycle of concentration (CC_{max}) according to silica levels is represented in Equation 7 (Pereira, 2001):

$$CC_{max} = \frac{180}{(c_{SiO_2m})} \quad (7)$$

where c_{SiO_2m} is the silica concentration in the make-up water.

The inhibitors dosages depend on many factors, like the operating characteristics of the cooling system and the quality of the cooling water. Some examples of initial and maintenance dosages of corrosion inhibitors are shown in Table 1 (Basham et al., 2005).

Equation 8 calculates the slug dose of chemical additives (D_a) used to establish an initial dosage of the corrosion inhibitors to form a passivation film (Pereira, 2001). The initial concentration of the

Table 1. Initial and maintenance dosages of corrosion inhibitors in cooling systems.

Corrosion inhibitor/active ingredient	Initial dosage (mg/L)	Maintenance dosage (mg/L)	Film formation time (days)
Anodic Inhibitor (phosphate)	40-60 as PO_4^{-3}	15-20 as PO_4^{-3}	5-6
Cathodic Inhibitor (zinc)	10-20 as Zn^{+2}	3-5 as Zn^{+2}	5-6
Copper corrosion inhibitor (tolyltriazole)	10-20 as TTA	1-2 as TTA	5-6

chemical additive is approximately 2-3 times its maintenance level (**Cheremisinoff & Cheremisinoff, 1981**).

$$D_a = \frac{c_{a0} \cdot V}{1000} \quad (8)$$

where c_{a0} is the initial concentration of the chemical additive in the recirculating water, and V is the volume of water in the cooling system.

Equation 9 estimates the continuous dose of chemical additives ($\dot{m}_a$) used to maintain the concentration of cooling water inhibitors to prevent corrosion and deposition (**Cheremisinoff & Cheremisinoff, 1981**):

$$\dot{m}_a = \frac{c_a \cdot \dot{Q}_m}{(CC \cdot 1000)} \quad (9)$$

where c_a is the maintenance concentration of the chemical additive in the recirculating water.

Furthermore, chlorine is a biocide used largely in cooling water systems. The free chlorine residual concentration consists of the amount of chlorine that is available for biocidal action after adding the dose and meeting the system demands (**Rajagopal et al., 2012**). The free chlorine residual concentration in open recirculating systems is generally about 0.1-0.5 mg/L (**GE, 2017**). Equation 10 estimates the dosage of chlorine solution ($\dot{m}_{sol}$), such as sodium hypochlorite solution (**Cheremisinoff & Cheremisinoff, 1981**):

$$\dot{m}_{sol} = \frac{c_{cl} \cdot \dot{Q}_w}{\%p/p \cdot 1000} \quad (10)$$

where c_{cl} is the concentration of chlorine in the

recirculating water and $\%p/p$ is the weight percent of active chlorine in the solution.

The Puckorius Scaling Index (PI) of the water is used to assess the calcium carbonate scale potential in the cooling system. Equation 11 represents such index (**Gentil, 2003**):

$$PI = (2 \cdot pH_s) - pH_{eq} \quad (11)$$

where pH_s is the saturation pH, and pH_{eq} is the equilibrium pH.

The saturation pH is calculated by Equation 12, composed by the coefficients A, B, C, and D; which can be calculated by Equations 13, 14, 15, and 16, respectively (**Roberge, 2007**):

$$pH_s = (9.3 + A + B) - (C + D) \quad (12)$$

$$A = \frac{\text{Log}(c_{TDS}) - 1}{10} \quad (13)$$

$$B = -13.12 \cdot \text{Log}(T_m + 273) + 34.55 \quad (14)$$

$$C = \text{Log}(c_{Ca^{2+}}) - 0.4 \quad (15)$$

$$D = \text{Log}(c_{ATC}) \quad (16)$$

where c_{TDS} is the total dissolved solids in the recirculating water, T_m is the make-up water temperature, $c_{Ca^{2+}}$ is the calcium hardness in the recirculating water, and c_{ATC} is the total alkalinity in the recirculating water.

Equation 17 calculates the equilibrium pH (pH_{eq}):

$$pH_{eq} = 1.47 \cdot \text{Log}(c_{ATC}) + 4.54 \quad (17)$$

The cooling water scaling conditions according to the PI is presented in Table 2 (Carrier, 1965 apud Mirre, 2012).

2.2 Cooling tower costs

The total cost of the cooling tower includes the capital cost and the operational cost, as shown in Equation 18 (Serna-González et al., 2010):

$$C_{TOT} = CAPEX \cdot F + OPEX \quad (18)$$

where F is the annualized factor of capital cost, $CAPEX$ is the capital cost, and $OPEX$ is the operational cost.

The capital cost based on the tower fill volume is shown in Equation 19 (Serna-González et al., 2010):

$$CAPEX = C_{CTV} \cdot A_{fr} \cdot Z \quad (19)$$

Where C_{CTV} is the cooling tower cost based on fill volume, A_{fr} is the cross-sectional area of the cooling tower, and Z is the fill height.

The operational cost, which is shown in Equation 20, was based on the make-up water, the electricity consumed by the fan and the pump, and the use of chemical additives.

$$\begin{aligned} OPEX = & H_Y \cdot C_{cm} \cdot \dot{Q}_m + \\ & + H_Y \cdot C_{ce} \cdot (POW_p + POW_f) + \\ & + H_Y \cdot (\dot{m}_{sol} \cdot C_{cs}) + \sum_n^{NT} D_{a,n} \cdot C_{ca,n} + \\ & + \sum_n^{NT} H_Y \cdot (C_{ca,n} \cdot \dot{m}_{a,n}) \end{aligned} \quad (20)$$

Where H_Y is the yearly operating time, C_{cm} is the make-up water cost coefficient, C_{ce} is the electricity cost coefficient, POW_p is the pump power, POW_f is the fan power, C_{cs} is the cost coefficient of chlorine solution (sodium hypochlorite), $D_{a,n}$ is the slug dosage of the chemical additive n , $C_{ca,n}$ is the cost coefficient of the chemical additive n , $\dot{m}_{a,n}$ is the continuous dosage of the chemical additive n , and NT is the total number of chemical additives except the biocide (chlorine).

Table 2. The cooling water scaling conditions according to the PI.

Puckorius Index (PI)	Characteristic of the cooling water
$4 < PI \leq 5$	Strong scale formation
$5 < PI \leq 6$	Slight scale formation
$6 < PI \leq 7$	Little corrosion or scale formation (stable)
$7 < PI \leq 7.5$	Significant corrosion
$7.5 < PI \leq 9$	Strong corrosion
$PI > 9$	Very strong corrosion (intolerable)

2.3 Case study

This work consists of an analysis of how to achieve the minimization of the make-up water and a reduction in costs of chemical additives used in the cooling tower of the Coking Unit of the Gabriel Passos Refinery (REGAP), located in Betim, MG – Brazil. The cooling system was optimized for different make-up water scenarios, and the Puckorius Scaling Index (PI) was evaluated to assure the quality of the water.

2.3.1 Make-up water scenarios

The make-up water scenarios studied in this work are presented in Table 3. The make-up water scenarios M1, M2, M3, and M4 correspond to the possible options for the cooling tower of REGAP studied by Veiga (2010). The scenario M5 represents the groundwater of the São Domingos River Basin, located in Rio de Janeiro, Brazil (Santos, 2009). Scenario M6 represents the water quality standards for the make-up water of the cooling tower of the Galeão, Rio de Janeiro's International Airport (Carvalho & Machado, 2010).

2.3.2 Chemical additives

The chemical additives used in the cooling tower of REGAP studied by Veiga (2010) are reported in Table 4. The initial recommended doses of polyacrylate, phosphate, zinc, and azole were 20 mg/L, 50 mg/L, 15 mg/L, and 15 mg/L, respectively.

Table 3. Make-up water scenarios.

Parameter	M1	M2	M3	M4	M5	M6
Temperature (K)	313	313	313	313	301.7	297.9
Total dissolved solids (mg/L)	272	340	633.08	876.75	237	500
Total alkalinity (mg CaCO ₃ /L)	50	22	30	30	188	29
Chloride (mg Cl/L)	50	68	100	60	20.16	29
pH	6.9	6.9	7.0	6.9	7.08	7
Calcium hardness (mg CaCO ₃ /L)	46	80	28	19	13.75	125
Silica (mg SiO ₂ /L)	6.0	7.4	-	-	21.9	21

Table 4. Chemical additives used in the cooling tower.

Chemical Additive/ Active ingredient	Product/ Concentration of active ingredient	Price (R\$/kg)	Residual concentration of active ingredient in the recirculating water (mg/L)
Dispersant (polyacrylate)	DISPERSOLTC5H (40%*)	14.156 **	2
Anodic Inhibitor (phosphate)	DODICOR SA4 (30%*)	2.646**	8
Cathodic Inhibitor (zinc)	DODICOR SA10 (30%*)	7.716**	3
Inhibitor of Cu and its alloys (azole)	DODICOR SA20 (45%*)	9.080**	1
Biocide (chlorine)	NaClO (10%*)	0.73	0.5

(*) Data refers to the approximate value of the concentration of active ingredient in the chemical additives with similar formulations used in open recirculating cooling systems.

(**) Data refers to March, 2012 (Petrobras, 2015)

2.3.3 Cooling tower fill

Although the cooling tower of REGAP is counterflow, the Brentwood's V-Bar Crossflow Splash Fill was selected because of the available data of Brentwood's fills. They are of adequate height ($Z=10.97$ m) for the high recirculating water flow ($\dot{Q}_w=2300$ m³/h), besides being recommended for situations that have high probability of fouling (Brentwood, 2015).

2.3.4 Capital cost

In this work, the capital cost was based on the cooling tower fill volume. The cost based on the tower fill volume (C_{CTV}) is 2006.6 US\$/m³, and the annualization factor is equal to 0.2983 year⁻¹ (Serna-González et al., 2010). Besides, the conversion rate is 0.38 US\$/R\$ (Banco Central, 2015).

2.3.5 Pump

This study selected a KSB Meganorm centrifugal pump, which can pump water and provide flow rates up to 3700 m³/h. The KSB Meganorm

350/370A centrifugal pump, selected for the recirculating water flow (2300 m³/h), presents the head equal to 19 m and shaft power equal to 164.05 kW (KSB, 2015).

2.3.6 Fan

The fans move air through the tower. Equation 21 determines the fan power (Castro et al., 2000):

$$POW_f = 0.0548 \cdot \frac{\dot{m}_{air}}{\rho_{air}} \cdot 0.001 \quad (21)$$

2.3.7 Water and electricity costs

The water and electricity costs are necessary for the calculation of the make-up water cost and the electricity consumed by the pump and the fan.

The water cost coefficient for the make-up water scenarios M1, M2, M3, and M4 was R\$ 1.00/m³, which represents the price of reuse water of the effluent of the refinery used in REGAP (Souza, 2015). The cost coefficient for M5 was R\$ 0.70/m³, which corresponds to the cost of the water obtained from the Ibirité Lagoon (Minas Gerais, Brazil) (Souza, 2015). The cost coefficient

for M6 was R\$ 2.90/m³, which represents the cost of the reuse of the secondary effluent from the effluent treatment station at Rio de Janeiro's International Airport (ETE APOIO) by using reverse osmosis (Carvalho & Machado, 2010).

Finally, the electricity cost coefficient was R\$ 0.4038/kWh, which corresponds to the electricity cost for the industry in Brazil (Firjan, 2015).

2.4 Optimization model

In this study, the cost of the make-up water and the chemicals of the cooling tower was minimized for two cases, according to the Puckorius Index interval. Thus, case 1 considers $5.1 \leq PI \leq 7.5$ and the use of chemical additives; case 2 considers $6.1 \leq PI \leq 7$ and the absence of chemical additives.

The cycle of concentration is the decision variable of the optimization model. The operational range of the cycle of concentration is $1 < CC \leq 16.5$, in which the minimum value represents the absence of water recirculation and the maximum value represents maximum water recirculation ($\dot{Q}_b = 0$). Besides, the maximum silica concentration in the recirculating water must be 180 ppm ($CC \leq \frac{180}{c_{SiO_2m}}$).

The nonlinear model was implemented in the GAMS software, using the CONOPT 3 solver (Rosenthal, 2014). This solver is based on the Generalized Reduced Gradient (GRG) method. Although the optimization model is simple, GAMS facilitates the analysis of different case studies by being able to adapt quickly to new situations. Then, the optimization model can be written as:

Minimize $C_{TOT} = CAPEX \cdot F + OPEX$
Subject to:
$CAPEX = C_{CTV} \cdot A_{fr} \cdot Z$
$OPEX = H_Y \cdot C_{cm} \cdot \dot{Q}_m + H_Y \cdot C_{ce} \cdot (POW_p + POW_f) + H_Y \cdot (\dot{m}_{sol} \cdot C_{cs})$
$+ \sum_{NT} D_{a,n} \cdot C_{ca,n}$
$+ \sum_n H_Y \cdot (C_{ca,n} \cdot \dot{m}_{a,n})$
$\dot{Q}_m = \dot{Q}_b + \dot{Q}_e + \dot{Q}_d + \dot{Q}_l$
$\dot{Q}_e = 0.00173 \cdot \dot{Q}_w \cdot (T_{w1} - T_{w2})$
$\dot{Q}_d = 0.001 \dot{Q}_w$

$CC = \frac{(\dot{Q}_b + \dot{Q}_d + \dot{Q}_l + \dot{Q}_e)}{(\dot{Q}_b + \dot{Q}_d + \dot{Q}_l)}$	
$\dot{m}_{a,n} = \frac{c_{a,n} \cdot \dot{Q}_m}{(CC \cdot 1000)}$	
$PI = (2 \cdot pH_s) - pH_{eq}$	
$pH_{eq} = 1.47 \cdot \text{Log}(c_{ATc}) + 4.54$	
$pH_s = (9.3 + A + B) - (C + D)$	
$A = \frac{\text{Log}(c_{TDSc}) - 1}{10}$	
$B = -13.12 \cdot \text{Log}(T_m + 273) + 34.55$	
$C = \text{Log}(c_{Ca^{2+}c}) - 0.4$	
$D = \text{Log}(c_{ATc})$	
$CC = \frac{c_{ATc}}{c_{ATm}}$	
$CC = \frac{c_{TDSc}}{c_{TDSm}}$	
$CC = \frac{c_{Ca^{2+}c}}{c_{Ca^{2+}m}}$	
$CC \leq \frac{180}{c_{SiO_2m}}$	
$1 < CC \leq 16.5$	
$D_{a,n} = \frac{c_{a0,n} \cdot V}{1000}$	
$\dot{m}_{sol} = \frac{c_{cl} \cdot \dot{Q}_w}{\%p/p \cdot 1000}$	
Case 1	Case 2
$5.1 \leq PI \leq 7.5$	$6.1 \leq PI \leq 7$
$c_{a,d} = \frac{2}{0.4 \cdot \frac{20}{0.4}}$	$c_{a,n} = 0$
$c_{a0,d} = \frac{8}{0.3 \cdot \frac{50}{0.3}}$	$c_{a0,n} = 0$
$c_{a,ci} = \frac{3}{0.3 \cdot \frac{15}{0.3}}$	$c_{cl} = 0$
$c_{a0,ci} = \frac{1}{0.45 \cdot \frac{15}{0.45}}$	
$c_{a,ai} = \frac{1}{0.45 \cdot \frac{15}{0.45}}$	
$c_{a0,ai} = \frac{1}{0.45 \cdot \frac{15}{0.45}}$	
$c_{a,cui} = \frac{1}{0.45 \cdot \frac{15}{0.45}}$	
$c_{a0,cui} = \frac{1}{0.45 \cdot \frac{15}{0.45}}$	
$c_{cl} = 0.5 \quad \%p/p = 0.1$	

The values for the parameters considered in this work are shown in Table 5.

3. RESULTS AND DISCUSSIONS

The results of the optimization of a cooling tower of 10.97 m fill height and 4.27 m horizontal fill air travel are presented for the make-up water scenarios M1, M2, M3, M4, M5, and M6 (Tables 6

Table 5. Data for the case study.

Parameter	Value
F (year ⁻¹)	0.2983
C_{CTV} (R\$/m ³)	5280.53
A_{fr} (m ²)	18.2
Z (m)	10.97
H_Y (h/year)	8000
ρ_{air} (kg/m ³) at 20°C	1.2041*
ρ_w (kg/m ³) at 37.5°C	993*
T_{w1} (K)	307.15**
T_{w2} (K)	298.15**
$\dot{Q}_w$ (m ³ /h)	2300**
$\dot{Q}_l$ (m ³ /h)	0.01**
V (m ³)	903**
$\dot{m}_w/\dot{m}_{air}$	0.56
C_{cm} for M1, M2, M3, M4 (R\$/m ³)	1.00
C_{cm} for M5 (R\$/m ³)	0.70
C_{cm} for M6 (R\$/m ³)	2.90
C_{ce} (R\$/kWh)	0.4038
POW_p (kW)	164.05
POW_f (kW)	185.61

(*) The densities were assumed constant.

(**) Operational data of the cooling tower of the Coking Unit of REGAP (Veiga, 2010).

and 7), considering the Puckorius Index intervals (Cases 1 and 2).

Figures 2, 3, 4, 5, 6, and 7 show the operational cost versus the cycle of concentration and the

operational cost versus the Puckorius Index for M1, M2, M3, M4, M5, and M6, respectively.

Although the higher cycle of concentration permits the reduction of the make-up water and chemical flow rates, the results show that the total cost of case 1 ($5.1 \leq PI \leq 7.5$) for all make-up water scenarios is higher than the one of case 2 ($6.1 \leq PI \leq 7$). However, the use of chemical additives prolongs the lifespan of the cooling system and maintains the efficiency of the heat transfer process. Furthermore, the cost of additives of case 1 was lower than the capital cost, which reinforces the importance of their use in the process.

The power cost has a significant value and it was considered constant at all cycles of concentration. Nonetheless, the higher the cycle of concentration, the higher the salt concentration in the recirculating water, which is connected with the density and viscosity of the water. Thus, variations in pumping as a function of liquid properties like density and viscosity can change the results.

The Puckorius Index equal to 5.1 indicates a slight scale formation. Therefore, the use of inhibitors and dispersants is essential in case 1. Besides, the use of chemical additives is

Table 6. Optimization results for the make-up water scenarios M1, M2, M3, and M4.

Variables	M1 Case 1	M1 Case 2	M2 Case 1	M2 Case 2	M3 Case 1	M3 Case 2	M4 Case 1	M4 Case 2
Puckorius Index (PI)	5.1	6.1	5.1	6.1	5.1	6.1	5.1	6.1
Cycle of concentration	6.97	4.5	9.78	6.3	12.16	7.86	14.26	9.21
Make-up flow rate (m ³ . h ⁻¹)	41.81	46.04	39.89	42.55	39.02	41.03	38.51	40.17
Capital Cost (R\$. year ⁻¹)	314,727	314,727	314,727	314,727	314,727	314,727	314,727	314,727
Power Cost (R\$. year ⁻¹)	1,129,562	1,129,562	1,129,562	1,129,562	1,129,562	1,129,562	1,129,562	1,129,562
Make-up water cost (R\$. year ⁻¹)	334,499	368,321	319,122	340,366	312,163	328,283	308,092	321,371
Chemicals cost (R\$. year ⁻¹)	80,278	0	76,608	0	74,947	0	73,975	0
Total cost (R\$. year ⁻¹)	1,859,067	1,812,609	1,840,019	1,784,655	1,831,399	1,772,573	1,826,356	1,765,660

Table 7. Optimization results for the make-up water scenarios M5 and M6.

Variables	M5 Case 1	M5 Case 2	M6 Case 1	M6 Case 2
Puckorius Index (PI)	5.1	6.1	5.2	6.1
Cycle of concentration	5.50	3.56	8.57	5.77
Make-up flow rate ($\text{m}^3 \cdot \text{h}^{-1}$)	43.76	49.83	40.54	43.32
Capital Cost (R\$. year ⁻¹)	314,727	314,727	314,727	314,727
Power Cost (R\$. year ⁻¹)	1,129,562	1,129,562	1,129,562	1,129,562
Make-up water cost (R\$. year ⁻¹)	245,077	279,030	940,546	1,004,949
Chemical costs (R\$. year ⁻¹)	84,004	0	77,850	0
Total cost (R\$. year ⁻¹)	1,773,370	1,723,319	2,462,685	2,449,238

advantageous because it permits the elevation of the cycle of concentration and, consequently, the reduction of the make-up water cost.

The optimal cycle of concentration of M4 in case 1 (CC=14.26) was very close to the maximum cycle of concentration (16.5). Thus, among the possible kinds of make-up water of the cooling tower of REGAP studied by [Veiga \(2010\)](#), M4 presented the optimal cycle of concentration, having the lowest total cost.

Although the optimal cycles of concentration of M5 in cases 1 and 2 were lower than the ones obtained for M1, M2, M3, and M4, the make-up

water cost of M5 was lower because of its lower cost coefficient (R\$ 0.70/ m^3). Therefore, the total cost was also lower than the cost of the possible kinds of make-up water in the cooling tower of the Coking Unit of REGAP.

Different from the other scenarios, the Puckorius index of M6 in case 1 (PI=5.2) was not the minimum because of the maximum allowed concentration of silica. The make-up water cost of M6 was high because of the high cost coefficient for this kind of water (R\$ 2.90/ m^3). Consequently, M6 presented the highest total cost studied in this work.

Figure 2. Operational cost versus the cycle of concentration (a) and the operational cost versus the Puckorius Index (b) for the make-up water scenario M1.

Figure 3. Operational cost versus the cycle of concentration (a) and the operational cost versus the Puckorius Index (b) for the make-up water scenario M2.

Figure 4. Operational cost versus the cycle of concentration (a) and the operational cost versus the Puckorius Index (b) for the make-up water scenario M3.

Figure 5. Operational cost versus the cycle of concentration (a) and the operational cost versus the Puckorius Index (b) for the make-up water scenario M4.

Figure 6. Operational cost versus the cycle of concentration (a) and the operational cost versus the Puckorius Index (b) for the make-up water scenario M5.

Figure 7. Operational cost versus the cycle of concentration (a) and the operational cost versus the Puckorius Index (b) for the make-up water scenario M6.

The results showed that the minimum cost is obtained with the higher cycle of concentration that is allowed according to the Puckorius Index interval and the maximum allowed concentration of silica.

4. CONCLUSIONS

As one of the main purposes of water in oil refineries is cooling the processes or equipment, models that minimize the costs associated with cooling towers are advantageous.

From the optimization model and the operational data of the cooling tower of REGAP, some case studies were performed with different compositions of make-up water, to minimize the make-up water and chemical additives costs. The results showed that the minimum cost is obtained with the highest allowed cycle of concentration according to the Puckorius Scaling Index interval. Although all scenarios presented the lowest total cost in the cases that did not include the use of chemical additives, the presence of dispersant, inhibitors, and biocides prolong the lifespan of the cooling system and maintains the operational efficiency. Furthermore, the presence of chemical

additives allows a higher cycle of concentration and, consequently, the minimization of the make-up water and chemical costs, besides reducing the negative environmental impacts associated with the blowdown.

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NOMENCLATURE

Greek Letters

λ Water latent heat of evaporation (kJ/kg)
 ρ_w Water density (kg/m³)
 ρ_{air} Air density (kg/m³)

Symbols

$\%p/p$ Weight percent of active chlorine in the chemical additive (%)
 A Coefficient based on the TDS
 A_{fr} Cross-sectional area of the cooling tower (m²)
 B Coefficient based on temperature
 C Coefficient based on calcium hardness
 c_a Chemical additive concentration in the recirculating water (mg/L)
 $c_{a,ai}$ Anodic inhibitor concentration in the recirculating water (mg/L)
 $c_{a,ci}$ Cathodic inhibitor concentration in the recirculating water (mg/L)
 $c_{a,cui}$ Inhibitor of Cu and its alloys concentration in the recirculating water (mg/L)
 $c_{a,d}$ Dispersant concentration in the recirculating water (mg/L)
 $c_{a,n}$ Concentration of the chemical additive n in the recirculating water (mg/L)
 c_{a0} Initial concentration of the chemical additive in the recirculating water (mg/L)
 $c_{a0,n}$ Initial concentration of the chemical additive n in the recirculating water (mg/L)
 $Capex$ Capital cost of the cooling tower (R\$/year)

c_{ATc} Total alkalinity in the recirculating water (mg/L)
 c_{ATm} Total alkalinity in the make-up water (mg/L)
 CC Cycle of concentration
 c_{cl} Concentration of chlorine in the recirculating water (mg/L)
 $c_{Ca^{2+}c}$ Calcium hardness in the recirculating water (mg/L)
 $c_{Ca^{2+}m}$ Calcium hardness in the make-up water (mg/L)
 $C_{ca,n}$ Cost coefficient of the chemical additive n (R\$/kg)
 C_{ce} Electricity cost coefficient (R\$/kWh)
 C_{cm} Make-up water cost coefficient (R\$/m³)
 C_{cs} Cost coefficient of chlorine solution (sodium hypochlorite) (R\$/kg)
 CC_{max} Maximum cycle of concentration
 C_{CTV} Cooling tower cost based on fill volume (R\$/m³)
 c_m Salt concentration in the make-up water (mg/L)
 c_{pw} Water specific heat (kJ/(kg . °C))
 c_s Salt concentration in the recirculating water (mg/L)
 c_{SiO_2m} Silica concentration in the make-up water (mg/L)
 $c_{TDS c}$ Total dissolved solids in the recirculating water (mg/L)
 $c_{TDS m}$ Total dissolved solids in the make-up water (mg/L)
 C_{TOT} Total cost of the cooling tower (R\$/year)
 D Coefficient based on total alkalinity
 D_a Slug dose of the chemical additive (kg)
 $D_{a,n}$ Slug dose of the chemical additive n (kg)
 F Annualization factor (year⁻¹)
 H_Y Yearly operating time (h/year)
 $\dot{m}_{air}$ Air mass flow rate (kg/h)
 $\dot{m}_{a,n}$ Continuous dose of the chemical additive n (kg/h)
 $\dot{m}_{sol}$ Dosage of sodium hypochlorite solution (kg/h)
 $\dot{m}_w$ Recirculating water mass flow rate (kg/s)
 n Chemical additive
 NT Total number of chemical additives used in the cooling tower except chlorine
 $Opex$ Operational cost of the cooling tower (R\$/year)

pH_{eq} Equilibrium pH
 pH_s Saturation pH
 PI Puckorius Scaling Index
 POW_f Fan power (kW)
 POW_p Pump power (kW)
 $\dot{Q}_b$ Blowdown water flow rate (m³/h)
 $\dot{Q}_d$ Water flow rate lost by drift (m³/h)
 $\dot{Q}_e$ Water flow rate lost by evaporation (m³/h)
 $\dot{Q}_l$ Water flow rate lost by possible leaks (m³/h)
 $\dot{Q}_m$ Make-up water flow rate (m³/h)
 $\dot{Q}_w$ Recirculating water flow rate (m³/h)
 TTA Tolyltriazole
 T_m Make-up water temperature (K)
 T_{w1} Inlet water temperature (K)
 T_{w2} Outlet water temperature (K)
 V Volume of water in the cooling system (m³)
 Z Fill height (m)

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