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Management of a Cooling Tower System by Experimental Characterization

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The aim is to show a methodology to characterize the cooling tower performance, when submitted to diverse operational conditions. The experiments were carried out in a pilot plant and a correlation between the cooling tower performance and the principal process variables (air and water mass flow rates) was obtained. The methodology developed can be applied in industrial cooling towers because the measures are usually available in typical plants. A parametric simulation study was developed to investigate the influence of gas flow rate, liquid flow rate and cooling water height of filling in the thermal demand of a cooling water system. The proposed study and analysis should be useful for performance analysis of real-world cooling water and the Management of Cooling Tower System.

Introduction

Operational reduction cost has gained widespread acceptance nowadays, as well as the rational use of water in the facilities. The cooling tower is a device that can greatly contribute to this rational use, since it operates in a close circuit without spending much wate.

Notwithstanding the importance of this device in the operational process, it does not receive the necessary attention in the industrial plant, except in the design or specification stages. Usually, the data are based on a commercial catalogue, without further checking after the installation of the cooling tower. It is observed that in the industrial process, when failures or interruptions occur, the first step of the solution is searching out the operation area and the focus will rarely be in the utilities, and the cooling tower is an example.

In the literature, a relatively large number of works about cooling towers is available; however, there is a lack of studies concerning process variables and performance experimental data, some exceptions are (Yingjian et al., 2011; Cortinovis et al., 2009; Papaefthimiou et al., 2006). The variables that are established in the cooling tower specification are: heat load to be removed from the process, water flow circulation, range (temperature difference between inlet and outlet water in the cooling tower) and approach (difference between outlet cooled water temperature and the wet bulb temperature of the inlet air).

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Experimental characterizations

According to (Geankoplis, 2003) and (McCabe et al., 2005) the total height of the contact section of an evaporative cooling tower is determined by Equation (1).

$$\int_{T_{w1}}^{T_{w2}} \frac{L'.c_L.dT_w}{K_G.a_i.\left(H^*_{air} - H_{air}\right)} = Z_T \tag{1}$$

The mathematical model was developed with the following assumptions:
(h.1) the process is at steady state; (h.2) specific heat of water and dry air is constant along the column; (h.3) air and water have plug flow; (h.4) heat and mass transfer coefficients are constant along the column; (h.5) there is no heat and mass transfer between the system and the surrounding; (h.6) the water flow rate is assumed constant along the column; (h.7) the cross section area of the tower is assumed uniform; (h.8) there is no variation in the performance factor along the column; (h.9) the liquid heat transfer coefficient is much larger than the air heat transfer coefficient, so the liquid-gas interfacial temperature is assumed equal to the water temperature.
Assuming equilibrium at the air-water interface, the air enthalpy at the interface H^*_{air} becomes the saturation enthalpy (Yingjian et al., 2011). As suggested by (Foust et al., 1980) Equation (3) for specific enthalpy of saturated air may be obtained from experimental data regression, between temperatures from 15°C to 50°C:

$$H^*_{air} = 155.52.T_w^2 - 3693.1.T_w + 69345 \tag{2}$$

The enthalpy balance in the cooling tower can be expressed by:

$$H_{air} = \left[\frac{L'.c_L.\left(T_{w1} - T_w\right)}{G'}\right] + H_{air,1} \tag{3}$$

Replacing Equations (2) and (3) in Equation (1) and integrating this results K_G.a value expressed by:

$$K_G.a_i = \frac{L'.c_L}{Z_T.\sqrt{b^2 - 4.a.c}}.\left[\ln\left(\frac{2.a.T_{w1} + b - \sqrt{b^2 - 4.a.c}}{2.a.T_{w1} + b + \sqrt{b^2 - 4.a.c}}\right) - \ln\left(\frac{2.a.T_{w2} + b - \sqrt{b^2 - 4.a.c}}{2.a.T_{w2} + b + \sqrt{b^2 - 4.a.c}}\right)\right] \tag{4}$$

$$\text{where: } a = 155.52\text{ ; } b = -\left(3693.1 - \frac{L'.c_L}{G'}\right)\text{; } c = \left(69345 - \frac{L'.c_L.T_{w1}}{G'} - H_{air,1}\right)$$

Pilot plant description

The experiments were conducted in a pilot plant, depicted in Figure 1. The evaporative cooling tower used in this study is a cross flow mechanical draft, (TR-01), with nominal capacity of 90 kW and "GRT" package (polypropylene grid fill block). The rig of TR-01 is shown in figure 2. Four shell and tube heat exchangers are used in the facility. The cooling water circulates inside the tubes and the process fluid (hot water) is on the shell side. After the cooling water goes through the heat exchangers it returns to the cooling tower.

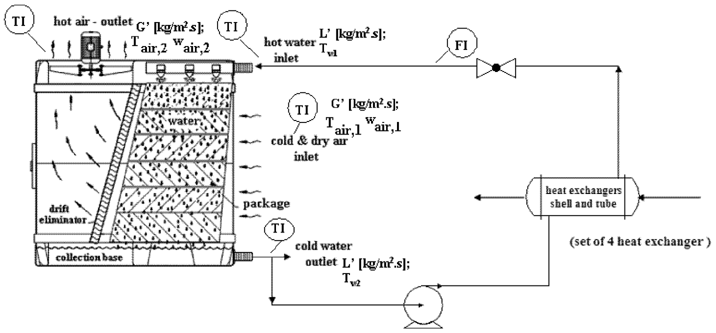

Figure 1: Simplified scheme of the cooling system .

Input data

The proposal of this topic is to characterize the performance of a cross flow cooling tower submitted to diverse operational conditions.

The cooling tower performance parameter $K_G.a_i$ is obtained through Equation (4). The required input data are inlet water temperature, T_{w1}, outlet water temperature,T_{w2}, dry bulb temperature of inlet air, $T_{db,1}$, wet bulb temperature of inlet air, $T_{wb,1}$, and air pressure, P.

It should be emphasized that little deviations of temperature measurement greatly interfere in the results, thus great care should be taken, mainly in runs in which the temperature difference is very small (susceptible to large uncertainties).

A relatively large number of experiments were conducted (82 tests) to ensure the results consistency and the methodology validation.

Results

The general cooling tower can be defined by an empirical model according to Equation (5) (Fredman et al., 1995).

$$K_G.a_i = \alpha.L'^{\beta}.G'^{\gamma} \qquad (5)$$

The following correlation equation was obtained through the experimental data:

$$K_G.a_i = 0.17.L'^{0.57}.G'^{0.91} \qquad (6)$$

For this model, the explained variance obtained was 74%, which may be considered an acceptable result (Box et al., 1978; Montgomery, 1984).

Simulation of a cooling water system

After the experimental characterization of the cooling tower performance (see Equation (6)), some study cases from mathematical simulations are presented below to support the cooling system management.

The set of equations that represent the thermal model and cooling tower model are presented below:

$$Q = \dot{L}.c_L.(Tw_1 - Tw_2) \tag{7}$$

$$K_G.a_i = \alpha.L'^{\beta}.G'^{\gamma} \tag{8}$$

$$T_{w1} = \frac{-b.[\exp(m)-1]-\sqrt{b^2-4.a.c}.[\exp(m)+1]}{2.a.[\exp(m)-1]} \tag{9}$$

$$L' = \dot{L}/A \tag{10}$$

where :

$$m = \frac{K_G a_i.Z_T.\sqrt{b^2-4.a.c}}{L'.c_L} + \ln\left(\frac{2.a.Tw_2 + b - \sqrt{b^2-4.a.c}}{2.a.Tw_2 + b + \sqrt{b^2-4.a.c}}\right)$$

Table 1 presents the conditions and parameters of the base case chosen as reference.

Table 1 – Base case conditions and parameters

absolute humidity of the air	0.0113 kg water/kg dry air
package height	0.90 m
cross section area	0.54 m²
cooling tower parameter α	0.17
cooling tower parameter β	0.57
cooling tower parameter γ	0.91
water flow rate	2.81 m³/h
air flow rate	1.25 kg/h
heat duty	22.6 kW
outlet water temperature	32.0 ºC

The interactions of the cooling water system were studied by a parametric simulation based on Equations (7) – (10). The variables investigated are: gas flow rate, G, liquid flow rate, L, and cooling water height of filling , Z. The parameters G_1 , L_1 , Z_1 and Q_1 correspond to the base case (case 1).

Table 2 presents different combinations of the variables and results obtained for the thermal demand, Q, inlet water temperature, T_{w1}, and the cooling tower performance parameter, $K_G.a_i$.

Table 2: Parametric simulation of the cooling tower

Case	L/L_1	G/G_1	Z/Z_1	Q/Q_1	$K_G.a_i$ [kg/m³.s]	T_{W1} [°C]
1	1	1	1	1.0	0.45	38.9
2	1	2	1	2.9	0.85	51.8
3	1	1	2	2.6	0.45	50.0
4	1	2	2	6.4	0.80	76.4
5	2	1	1	1.6	0.67	37.5
6	2	2	1	3.2	1.18	43.1
7	2	1	2	3.5	0.67	44.1
8	2	2	2	6.6	1.18	54.9

The analysis of cases 1, 2, 3 and 5 shows that the influence of G and Z are greater than of L in the increase of thermal demand Q. $K_G.a_i$ is more affected by G than by L, as expected by Equation (6). The range (T_{w2}-T_{w1}) increases for cases 2 and 3 due the greater thermal demand and low water flow rate.

The analysis of cases 1, 4, 6, 7 and 8 confirms that the influence of L is not very significant in the increase of thermal demand. This can be observed comparing cases 4 and 8.

It is interesting to note that just increasing both L and G by a factor 2 (case 6) the thermal demand may be increased by a factor greater than 3. This is a case that may be a typical operational condition to improve the heat duty of the cooling tower.

Conclusions

This study presents a procedure to characterize the performance of a pilot cooling tower submitted to diverse operational conditions. The results were expressed as mass transfer coefficient as a function of the air and water flow rates.

A parametric simulation study was developed to investigate the influence of different parameters in the thermal demand of the cooling water system, and the results show that the gas flow rate and height of filling contribuite to increase the thermal demand when comparared with the liquid flow rate.

This study and analyse is effective to manage the cooling tower system.

Nomenclature

A	cross section area [m²]
c_L	specific heat of water [J.(kg.°C)$^{-1}$]
G	air mass flow rate [kg dry air.s^{-1}]
G’	air mass flux [kg dry air.(m².s)$^{-1}$]
H_{air}	specific enthalpy of air [kJ.(kg dry air)$^{-1}$]
$H_{air,1}$	specific enthalpy of inlet air [kJ.(kg dry air)$^{-1}$]
H^*_{air}	specific enthalpy of saturated air [kJ.(kg dry air)$^{-1}$]
$K_G.a_i$	performance factor of cooling water [kg.(m^3.s)$^{-1}$]

L	water volumetric flow [m^3.h^{-1}]
L'	water mass flux [kg (m^2.s)$^{-1}$]
$\dot{L}$	water mass flow [kg/s]
m	parameter of equation
P	air pressure [Pa]
Q	thermal demand [W]
T_w	water temperature [°C]
T_{w1}	inlet water temperature [°C]
T_{w2}	outlet water temperature [°C]
T_{air1}	air temperature at the bottom [°C]
Z_T	total height of cooling water contact section [m]
α	parameter of Equation (13)
β	parameter of Equation (13)
γ	parameter of Equation (13)

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