Relation of the Volumetric Mass and Heat Transfer Coefficients in a Cooling Tower

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Abstract

The design of a laboratory scale cooling tower with acrylic film type packing is presented to make an experimental study on terms of the volumetric mass transfer coefficient \((k_{ya})\). The performance of the tower was evaluated at a flow ratio of water to air \((L/G)\) of 1.7. The water inlet temperature decreased from 48°C to 41.6°C. The tower efficiency was 25%. The volumetric mass transfer coefficient \((k_{ya})\) behaves differently in two zones that depend on the relation of the volumetric heat transfer coefficient to the volumetric mass transfer coefficient \(-h_{ya}a / k_{ya} = m\).

The first zone, where the gas phase and the liquid phase have the similar strength of heat resistance, is in the range of \(-m\) values [3-25]. The second zone, where the resistance to the heat flow is dominated by the gas phase, has the range of \(-m\) [25-\(\infty\)]. It was found the following relation in the tower: \(k_{ya}a^{1.512}h_{ya}a^{-0.512} = 4217.8\)

Keywords: Cooling tower, efficiency, volumetric mass transfer coefficient

1. Introduction

The energy saving is important for highly efficient cooling systems in different industrial processes. Common applications include cooling of water used in chemical plants, power stations, oil refineries, petrochemical and laboratories of unit operations in universities. The advantage of cooling towers with common shell-
and-tube heat exchangers is the low investment. Besides, the direct contact liquid gas makes the heat transfer highly efficient [1].
To enhance the efficiency of cooling towers, different types of packing are placed inside to increase the liquid - gas contact area [2-4]. The two most important parameters directly related with the tower packing are the volumetric mass transfer coefficient \( k_{ya} \) and the volumetric heat transfer coefficient which most of the time are taken constant [5] when operating the towers. However, there are studies that demonstrated that \( k_{ya} \) is not constant and depend on the operating conditions of the system, such as the experimental investigation of a direct contact evaporative cooling tower filled with a “VGA” type packing [6].

Different mathematical models have been proposed but they do not work for all the cooling towers. For this reason, it is necessary to have a better comprehension of the relation of the volumetric heat and mass transfer coefficients.
In this work, a cooling tower was built on a laboratory scale with acrylic film type packing to study the relation of the volumetric heat and mass transfer coefficients.

The packing was sized according to the design parameters found in the work of Mohiuddin AKM et al., 1996 [7]. It was found two different zones of heating resistance. In the first zone, where the range of \( \frac{h_{a}}{k_{a}} = -m \) was [3 to 25], the gas phase and the liquid phase have the similar strength of heat resistance. In the second zone, the resistance to the heat flow was dominated by the gas phase, range of \(-m [25-\infty)\).

2. Methodology

It was designed a cooling tower with the dimensions shown in table 1. Liquid water at 48°C enters at the top of the tower while the cool air enters at the bottom.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of decks film type</td>
<td>3</td>
</tr>
<tr>
<td>Vertical deck spacing splash type</td>
<td>0,35 m</td>
</tr>
<tr>
<td>Total packing height</td>
<td>1,15 m</td>
</tr>
</tbody>
</table>

Table 1. Dimensions of the packed cooling tower

The material of the film type packing was acrylic which has a thermal conductivity of 0.20 W/m·K. The shape of the film type packing is shown in figure 1.
Figure 1. Film type packing designed according to the parameters given by A. K. M. Mohiuddin and K. Kant, 1996, a) picture of the packing b) Dimensions (in mm)

The operating conditions used in the experiments are shown in table 2.

Table 2. Operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Valor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet water Temperature ( T_{L2} )</td>
<td>48°C</td>
</tr>
<tr>
<td>Inlet air dry bulb temperature ( T_{BS1} )</td>
<td>26.2°C</td>
</tr>
<tr>
<td>Inlet air wet bulb temperature ( T_{BS2} )</td>
<td>22.4°C</td>
</tr>
<tr>
<td>Volumetric flow of water, gpm</td>
<td>1.7</td>
</tr>
<tr>
<td>Mass rate of dry air</td>
<td>205.23 Kg/h</td>
</tr>
<tr>
<td>Inlet enthalpy of the air, ( h_{y1} )</td>
<td>65.81 KJ/Kg</td>
</tr>
</tbody>
</table>

2.1 Equations

Figure 2 shows the scheme of the system with the variables used in the mass and energy equations. It was made a global energy balance (see Eq. 1) to build the operating line, where \( C_\ell \) is the specific heat of the liquid which is considered constant in the range of temperature of this system. The subscript 1 means the conditions at the bottom of the tower. \( T_{LO} \) is the reference temperature (0°C).

\[
\dot{L}C_\ell(T_L - T_{LO}) + G_S' h_{y1} = L'C_\ell(T_{L1} - T_{LO}) + G_S' h_y
\]  
(1)

To determine the height of the tower (Z), first it is employed a differential energy balance with the total energy gained by the air, which is the sum up of the latent heat and the sensible heat, see equation 2.

\[
G_S' dh_y = \lambda_o (H_i - H_o) k_i a_m M_d dz + h_o a_\ell (T_i - T_o) dz
\]  
(2)
Where $k_y\alpha$ is the volumetric mass transfer coefficient of the system, $\lambda_o$ is the latent heat of the water, $h_{oa}h$ is the volumetric heat transfer coefficient of the air, $H_i$ is the air humidity at the interface, $H_L$ is the air humidity in the bulk, $T_i$ is the air temperature at the interface, and $T_L$ is the air temperature in the bulk.

After some algebraic manipulations of equation 2, it is obtained the equation 3 to determine the size of the tower.

$$Z = \frac{G_S}{k_y\alpha} \int_{h_{y1}}^{h_{y2}} \frac{dh_y}{h_{y1} \left( h_{yi} - h_y \right)}$$

(3)

To solve the integral of equation 3 it is used the following relation

$$\frac{h_La}{k_ya} = \frac{h_{yi} - h_y}{T_i - T_L}$$

(4)

where $h_La$ is the volumetric heat transfer coefficient of the water.

3. Results and Analysis

The results were obtained running the experiments with the operating conditions shown in table 2.
Figures 3 shows the cooling tower with all the variables used and measured with special sensors. With the given inlet and outlet conditions of the air, the relative humidity obtained was 72.34% and 98% respectively. As can be seen, the air gets out almost saturated with water indicating that the tower has a good heat and mass transfer. It was used the relation \( L/G = 1.7 \). The volumetric mass transfer coefficient \((k_ya)\) was 724 Kg/h.m\(^3\) for a relation \(-m = h_ya/k_ya = 200\). The efficiency of the tower with these operating conditions was 25%. The air enthalpy at the top \(h_{y2}\) was obtained using the Eq. 1, and \(T_{G2}\) was obtained with the Mickley method.

\[
Z = (HTU)(NTU) = \frac{G_s}{k_y a} \int_{h_{y1}}^{h_{y2}} \frac{dh_y}{(h_{y1} - h_y)} = 1.41 m
\]  

Where \(HTU = \frac{G_s}{k_y a}\) and \(NTU = \int_{h_{y1}}^{h_{y2}} \frac{dh_y}{(h_{y1} - h_y)}\)

As can be seen

\[
HTU = f(k_ya)\text{ and } NTU = f\left(\frac{h_ya}{k_ya}\right) = f\left(\frac{h_{y1} - h_y}{T_i - T_L}\right) = f(-m)
\]  

Figure 3. Cooling tower parameters

Figure 4 shows the operating line of the cooling tower for the given operating conditions shown in figure 3. As can be seen, the size of the tower \((Z=1.41 m)\) is calculated with equation 3.
Given the experimental data and the height of the tower, it is obtained the operating line. Then, with the Mickley method, it was obtained the outlet air temperature. It has to match the experimental data.

For this special case, the conditions of the outlet air are almost saturated, it means that equation 3 is satisfied for multiples values of $k_ya$ depending on the value of $-m = \frac{h_ya}{k_ya}$. Figure 4 shows that the operating line remains constant for the different values of $-m$ [3, 25, 200], and the air outlet temperature remains constant as well for the condition of quasi-saturated.

![Figure 4. Behavior of the relation of the interface water-air with the operating line](image)

Considering the variation of $-m$ obtained in figure 4, it was obtained a direct relation between the volumetric mass transfer coefficient $k_ya$ and $m = -\frac{h_ya}{k_ya}$.

Figure 4 shows two zones, the blue zone, and the red zone. The red zone is the zone where $m$ can be considered infinite which means that the heat transfer coefficient is so much higher than the mass transfer coefficient. It means that resistance to the heat flow in the red zone is dominated by the gas phase.
Relation of the volumetric mass and heat transfer coefficients

Figure 5. Behavior of the volumetric mass transfer coefficient as a function of

\[-h_La / k_ya = (h_y - h_y) / (T_i - T_L)\]

In the blue zone corresponding to low values of \( m \) in the range [3-25], both the gas phase and the liquid phase have the similar strength of heat resistance. It can be said that this tower has the following relation:

\[ k_y a^{1.512} h_La^{-0.512} = 4217.8 \]  

(7)

4. Conclusions

In the present work, it was studied the performance of the volumetric mass transfer coefficient \( k_ya \) as a function of the relation \( m = -h_La / k_ya = (h_y - h_y) / (T_i - T_L) \) in a cooling tower with film type packing. Most of the cooling towers have a constant relation of \( -m = h_La / k_ya \). However, when the air outlet approximates to the conditions of saturation, the theoretical determination of the air outlet temperature remains constant letting to work with values of the volumetric mass transfer coefficient in a specific range depending which phase dominates the resistance to the heat flow. Two zones where found. The first zone, where the gas phase and the liquid phase have the similar strength of heat resistance, is in the range of \(-m\) values [3-25]. The second zone, where the resistance to the heat flow is dominated by the gas phase, has the range of \(-m\) [25-∞).

References


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