A comparison between the counter and cross flow cooling tower for thermal power plants

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Abstract:

In this paper the counter flow cooling tower in Al-Nassiriah thermal power station was studied. Design of new cross flow cooling tower is made and tested instead of existing counter flow cooling tower. The analysis of cross flow cooling tower is made by using finite difference method. The design parameters of the cooling tower are evaluated at different operating conditions such as variations of weather, different water to air flow ratio. Then comparison between the results of two tower types shows that the cross flow cooling tower has high performance in heat transfer process. A computer program is developed to make the necessary design computations for both types of towers to evaluate the variation with the different conditions.

المتخصّص:

تم في هذا البحث دراسة برج التبريد ذو الحريان المتعاكسة الموجود في محطة الناصرية الحرارية. ويجاد موافقته. بعد ذلك تم تصميم برج تبريد متقاطع جديد وتم اختباره. يبادل التفاعل المتعاكسة الموجود تحليلاً. البرج المتقاطع تم استخدام طريقة الفروقات المحددة. العوامل التصميمية الأساسية لبرج التبريد من كل النوعين حسب ضد اعتبارات مختلفة مثل تغيرات طبيعة الجو أو تغير نسبة الماء إلى الهواء في برج التبريد، وتم مقارنة النتائج لكل النوعين حيث وجد أن البرج المتقاطع له أداء أعلى في عملية التبادل الحراري. تم إعداد برنامج حاسوبي لإجراء الحسابات التصميمية المختلفة لكل النوعين من الأبراج وتبسيط حساب التباين مع الظروف المختلفة.
List of symbols:-

\( a \) : contact surface area per unit volume of packing (\( m^2/m^3 \))
\( CR \) : cooling range (\( ^\circ C \))

\( C_{pw} \) : specific heat for water (\( J/kg.\circ C \))

\( dq \) : Rate of heat transfer
\( G \) : mass flow rate of air (\( kg/s \))
\( G_a \) : Air loading (air mass flux) (\( kg/s.m^2 \))
\( h \) : heat transfer coefficient at the interface (\( W/m^2.C \))
\( H_{ae} \) : air enthalpy at the tower exit (\( kJ/kg \))
\( H_{ae} \) : air enthalpy at the tower entrance (\( kJ/kg \))
\( h_w \) : Latent heat of water (\( kJ/kg \))
\( H_s \) : enthalpy of saturated air at the water temperature (\( kJ/kg \))
\( K \) : mass transfer coefficient at the interface (\( kg/s.m^2 \))
\( L \) : mass flow rate of water (\( kg/s \))
\( L_w \) : water loading (water mass flux) (\( kg/s.m^2 \))
\( T_w \) : water temperature (\( ^\circ C \))
\( W_a \) : Humidity ratio of moist air at the air stream Temp.
\( W_w \) : Humidity ratio of saturated air at the water Temp.

Introduction :-

A cooling tower cools water by contacting it with air and evaporating some of the water. In most cooling tower serving refrigeration, air conditioning systems and in power plant. One or more propeller or centrifugal fans move air vertically up or horizontally through the tower. A large surface area of water is provided by spraying the water through nozzles or splashing the water down the tower from one baffle to another. A cooling tower configuration used for large capacity power plant applications is the hyperbolic shape, which resembles a chimney 50 to 100 m high. In the cooling tower a heat transfer takes place from the water to the unsaturated air, there are two driving forces for the transfer: the difference in dry bulb temperatures and the difference in vapor pressures between the water surface and the air. These two driving forces combine to form the enthalpy potential [1][2]. There are many researches made to study and develop the cooling towers: Egalilichoff [3] studied the counter flow cooling tower based on Merkel theory and introduced a performance chart. Stanford [4] used Lewis relation in his work to combine the coefficient of sensible heat and mass transfer into a single overall heat transfer coefficient. Lin et al. [5] studied the counter and cross flow cooling tower fill made of redwood material and correlated a method to evaluate the number of transfer unit. Fujita et al. [6] Studied the thermal performance of a mechanical draft counter and cross flow cooling tower on the basis of the enthalpy potential theory. Patras [7] studied a cross flow cooling tower with straight path asbestos plate pack the work consists of developing the exiting cooling tower test plant by introducing new parts. M.P.Maiya [8] modified a counter flow cooling tower by introducing a heat exchanger.
Analysis of existing counter flow cooling tower:

One design of cooling tower is the counter flow type in which air passes upward through a falling spray of water. Fig. (1) shows differential volume of a counter flow cooling tower with L kg/s of water entering from the top and G kg/s of air entering from bottom. For simplicity the small quantity of water which evaporates is neglected [1][9].

The rate of heat removed from the water dq is equal to the rate gained by the air:

\[ dq = G dT_a = L C_p dT_w \]  \[ \text{(1)} \]

Applying the principles of heat and mass transfer to the interface between the water and air gives

\[ L C_p dT_w = -h_a dV(T_w - T_a) + k a dV(W_a - W_g) h_g \]  \[ \text{(2)} \]

![Diagram of a cooling tower](image)

Fig.(1) A differential control volume of cooling tower.

At the interface the following Lewis approximation generally holds:

\[ K = h/c_p \]  \[ \text{(3)} \]

Combining Eqs (2) and (3) gives:

\[ L C_p dT_w = k a dV(W_a - W_g) \]  \[ \text{(4)} \]

Where

\[ W_a = C_p T_w + W_g h_g \] and \[ W_a = C_p T_a + W_g h_g \]  \[ \text{(5)} \]

To determine the overall performance of the cooling tower, an integration over the entire packing volume is required.
The final result, which is the Merkel's equation, can be expressed as:

$$\int_0^L \frac{K_{adv}}{L} \, dL = \int_0^\gamma \frac{C_p \, d\theta_w}{\theta_w - H_w}$$

----------(6)

$$\frac{K_{adv}}{L} = \int_0^\gamma \frac{C_p \, d\theta_w}{\theta_w - H_w}$$

----------(7)

The term $K_{adv}/L$ is frequently referred to as the tower characteristics. The meaning of this term is similar to that of NTU (number of transfer units) in heat exchangers.

Equation (7) has no closed-form solution. This is mainly because the enthalpy of saturated air does not vary linearly with the water temperature.

The straight line relationship is suggested by eq.(1). In a finite form, eq.(1) becomes:

$$H_{aw} - H_{aw} = \frac{L}{G} (CR)$$

----------(8)

**Analysis of designed cross flow cooling tower**:

Another configuration of cooling tower is the cross flow tower, in which the air passes horizontally through the falling water sprays[4][5].

Fig.(2) indicates a typical cross section of cross flow tower. A heat balance on the differential volume as shown by fig.(2) yields

$$-(dx) (1) (L) (C_{pw}) (d\theta_w) = (dy) (1) (G) (dH_a)$$

----------(9)

Rearranging it yields

$$-L C_{pw} \left( \frac{\partial T_w}{\partial y} \right) = G \left( \frac{\partial H_a}{\partial x} \right)$$

----------(10)

Examining the differential volume again and equating the heat lost by water to the heat transfer rate at the water-air interface, gives:

Fig. (2) cross flow tower section
With incremental volume.
\[-(\text{dx})(\text{d}T) \cdot (C_{pw}) = (\text{dy})(\text{d}T) \cdot (H_v - H_w)\]

OR

\[-L \cdot C_{pw} \left( \frac{\partial T}{\partial y} \right) = k(T_v - T_w)\]

\[\text{equation (11)}\]

Combining equation (11) with equation (10) gives:

\[G \left( \frac{\partial H_v}{\partial x} \right) = k(H_v - H_w)\]

\[\text{equation (12)}\]

The cooling tower process requires two boundary conditions and property relationship. These are:

Air enthalpy of the first column. \[H_v(0, y) = C_1\]

Water temperature of first row. \[T_w(x, 0) = C_2\]

The mathematical model for a cross flow cooling tower is non linear and therefore has no exact solution. The numerical method frequently used is the finite difference. The algebraic equations for water temperature and air enthalpy calculations are derived as follows:

Consider a two-dimensional body that is to be divided into equal increments in both the X and Y directions, as show in fig. (3). The m locations indicates the x increment and the n locations indicating the Y increment. It is required to establish the water temperature and air enthalpy at any of these nodal points.

Applying equation (12) to any point gives:

\[G[H_v(m, n) - H_v(m-1, n)] = k \Delta x[H_v(m, n) - H_v(m-1, n)]\]

\[\text{equation (13)}\]

Using the central finite difference at the interior points [5].

Fig. (3) Tower grid for mathematical nodal

\[H_v(m, n) = \frac{H_v(m, n) + H_v(m, n)}{2}\]

\[\text{equation (14)}\]

\[H_v(m, n) = \frac{H_v(m, n) + H_v(m, n)}{2}\]

\[\text{equation (15)}\]

Substituting equations (15) and (14) into equation (13) gives:

\[H_v(m, n) - H_v(m-1, n) = \frac{k \Delta x}{2G}[H_v(m, n) - H_v(m, n) - H_v(m, n) + H_v(m, n) - H_v(m, n)]\]

\[\text{equation (16)}\]

Let \[M_v = \frac{k \Delta x}{G}\]
This equation gives the air enthalpy at the interior points. To evaluate the water temperature at the interior nodal, applying eq.(11) yields:

$$L \rho C_w [T_s(m,n) - T_s(m,n-1)] = k a \delta y [H_s(m,n) - H_s(m,n)]$$

Using central finite difference at these points and substituting into eq.(18) gives:

$$T_s(m,n) = T_s(m,n-1) - \frac{M_s}{2C_p} [-H_s(m,n-1) - H_s(m,n-1) + H_s(m,n) - H_s(m,n)]$$

Where $M_s$ is the mesh size. The value of $M_s$ must be calculated with the equation:

$$M_s = \frac{Q_s}{Q_c}.$$

To evaluate the air enthalpy at the top of the tower put $H_s(m-1,n)=H_s(m,0)$ in equation (17) and calculate the value of $H_s(m,0)$. The water temperature at the air entrance is found by setting $m=0$ and $H_s(0,n-1)=H_s(0,0)$ in eq.(19) and calculate the value of $T_s(0,0)$.

The cross flow tower characteristics (or tower NTU) is then the sum of the $M_s$ mesh values needed to obtain the tower grid size that gives the desired exit water temperature.

**Case study:**
To verify the presented mathematical models of existing and designed cooling towers. The data of Al-Nassiriah power station has been a case study. This station was designed to produce 210 MW. The maximum design data of cooling tower are as in following [10]:-

- Hot water temperature =42 (°C)
- Cold water temperature =25 (°C)
- Ambient wet-bulb temperature = 25 (°C)
- Air flow rate =750 (m³/sec.)
- Water flow rate =27500 (m³/hr.)

**Results and discussion:**

Fig.(4) shows the relation between the tower approach AP (The difference between exit water temperature and air wet-bulb temperature ) and NTU. From the figure the tower approach decreases when NTU increases. A low values of tower approach is desirable to obtain low water temperature exit from the tower.

Fig.(5) Shows the variation of NTU with different values of wet-bulb temperature for two towers. The comparison is made at flow ratio=1. From the figure the cross flow tower provides higher NTU values which means that it effective to reduce water temperature exit from the tower to the smaller values compared with counter flow tower.
Fig. (6) Shows the relation between NTU values and water-air flow ratio. From the figure it seen that the values of NTU are reduced when the flow ratio is reduced. The comparison is made at WBT=25°C.

Fig. (4) Comparison between thermal Performance of two tower types

Fig. (5) Relation between NTU and wet-bulb temperature for two towers

Fig. (6) Variation of NTU with water-air flow ratio for two towers

Fig. (7) Variation of NTU with inlet water temperature for two towers
Fig.(7) Shows the influence of inlet water temperature to the tower on thermal performance of the tower .The calculations are made at flow ratio =1 and WBT=25 (C) .From the figure it seen that the NTU values are increase when the inlet water temperature is increased and the inlet water temperature is an effective parameter which must be taken into account in designing the cooling tower .

Conclusions :
In this paper the counter flow cooling tower used in AL-Nassiriah power station is analyzed . Then designing a new cross flow cooling tower for this station and a comparison is made for the results of two towers types .

From the results
1-The cross flow cooling tower is provide higher thermal performance through providing higher NTU values comparing with the used counter flow cooling tower , therefore it reducing exit water temperature to the smaller values .
2- It is require large size compared with counter flow tower.

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