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Simulation of a Counter-Flow and Cross-Flow Cooling Tower by the Stepwise Integration Method

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ABSTRACT

The stepwise integration method is an approximation method for determining the water temperature in the fill layers for a counter-flow cooling tower and in the fill cells for a cross-flow cooling tower. Accordingly, it can be assumed that the mean driving force in each layer is a constant and the water temperature difference of each layer is equal to the cooling range divided by the required number of layers. Thus, the stepwise integration method can predict the volumetric heat transfer coefficient, the outlet temperatures of the water and air passing through the cooling tower and also determine the operating points of a cooling tower with a known value of *KaV* under a given approach. However, the stepwise integration method can also simulate and plot the approach curve by condition 1 (given the inlet and outlet temperatures of water), and the characteristic curve by condition 2 (given a value of *KaV* for the entire fill). In a cross-flow cooling tower, where the value of *KaV* for the entire fill, the flow rates of the entering air and water, the inlet dry bulb and inlet wet bulb temperatures and the hot water temperature are known, it is possible to predict the outlet water temperature by the stepwise integration method. In addition, the stepwise integration method can be used to simulate and plot the approach curve using condition 1 and the characteristic curve using condition 2.

Keywords: stepwise integration, counter-flow and cross-flow cooling tower

INTRODUCTION

A counter-flow cooling tower is widely used in air conditioning systems and industrial process. In a counter-flow tower, the air is induced from the bottom of the tower and is in contact with the falling water over the entire height of the tower. The warm water flows counter to the air, transferring sensible heat from the higher temperature of the water to the lower temperature of the air and becoming partly evaporative heat. By obtaining latent heat from the downward flowing thin water films, evaporative vapor is extracted from the water films. After that, the cooled water leaves the bottom of the tower and warm air with high moistures leaves the top of the cooling tower. Evaporation results from the difference in saturated pressure between the water films and the vapor pressure of moisture in the air passing through the fill. The vapor pressure depends on the water temperature and the degree of saturation of the air. Sensible heat is transferred from the high temperature of the water to the low temperature of the air. The latent heat is transferred from the water film to the moist air, due to the vapor pressure difference of the moisture in the air passing through the fill and air at the interface. Because simultaneous heat and mass transfers are

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present in the fill of a cooling tower, the coupled differential equations governing the conservation of mass and energy must be solved simultaneously.

For a constant value of L / G , the value of *KaV* depends on the dynamics of the airflow and the distribution of water droplets above the top of the fill. The value of *KaV* is used to characterize the cooling tower and as the basis for predicting its performance at a given cold water temperature and inlet wet bulb temperature.

The current study aimed to use the stepwise method to predict the volumetric heat transfer coefficient, the outlet temperatures of the water and air passing the fill of both counter-flow and cross-flow cooling towers, and the operating points of each cooling tower with a known value of *KaV* under a given approach.

MATERIALS AND METHODS

Objectives

This study aimed to use the stepwise method to predict the operating variables, namely, the temperatures of the water and air passing through each section of the fill of both counter-flow and cross-flow cooling towers under two conditions, described below.

Assumptions

If the fill of a tower is divided into a number of small layers for a counter-flow cooling tower and divided into a number of small cells for a cross-flow cooling tower, the stepwise integration method can be applied, based on the following assumptions (Stoecker and Jones, 1983):

1) For simplicity, the small quantity of water which evaporates is considered to be negligible.

2) Since the fill in the tower is to be divided into a number of small layers, it can be assumed that the mean driving force $(h_s - h_a)_m$ is the arithmetic mean enthalpy difference for each layer.

3) The temperature of the surface of water droplets is uniform and the internal conduction of a droplet is negligible.

4) The value of *KaV* for each layer $(KaV)_{layer}$ can be calculated from the mean driving force.

5) When the water temperatures in an arbitrary section (i) to (i+1) are known, the sensible heat transfer of air can be determined from the convective heat transfer on the fill surface and the temperature difference is assumed to be the mean temperature difference of the air and water.

Stepwise integration method

The stepwise integration method can be applied for two conditions of study, namely, given the inlet and outlet temperatures of water and given the value of KaV for the entire fill. It can be classified in more detail by the following two conditions.

Condition 1: Given the inlet and outlet temperatures of water.

When the inlet and outlet temperatures of the water, the flow rates of the entering water and air, and the inlet wet bulb temperature are known, it is possible to calculate the value of *KaV* for the cooling tower and the outlet dry bulb temperature of the air by the stepwise integration method.

The number of transfer units for the entire fill can be defined by Equation 1:

$$\frac{KaV}{L} = \int_{h_{W,out}}^{h_{W,in}} \frac{dh_s}{(h_s - h_a)} \qquad (1)$$

For a counter-flow cooling tower, stepwise integration can be used to determine the water temperature by dividing the fill into *n* layers as shown in Figure 1, with the water temperature decreasing in each layer, and $(T_1 - T_2)/n$. T_1 and T_2 are the hot water temperature and the cold water temperature, respectively. It can be assumed that the mean driving force in each layer is a constant

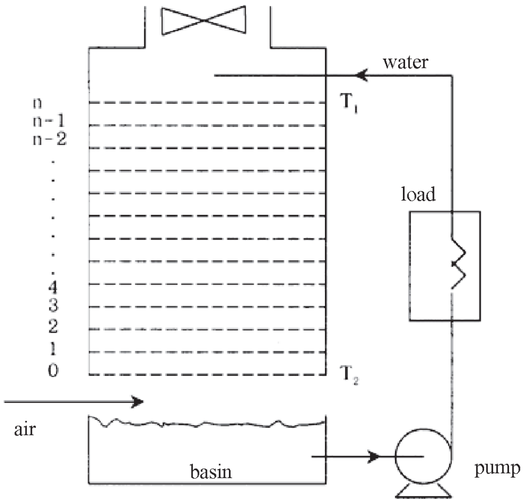

Figure 1 Division of the fill of n layers from section (0) to section (n) of a cooling tower (Stoecker and Jones, 1983).

(Mills, 1995). Thus, Equation 1 can be written as Equation 2:

$$\frac{KaV}{L}=\frac{C_W}{(h_s-h_a)_{0,1}}\int_0^1 dT+\frac{C_W}{(h_s-h_a)_{1,2}}\int_1^2 dT$$

$$+......+\frac{C_W}{(h_s-h_a)_{n-1,n}}\int_{n-1}^{n} dT \qquad (2)$$

Based on the mean driving force in each layer, it can be approximated as $(h_s - h_a)_{m,0-1}$ for the first layer, $(h_s - h_a)_{m,1-2}$ for the second layer,…, $(h_s - h_a)_{m,(n-1)-n}$ for the final layer, respectively.

Substituting the mean driving force in each layer into Equation 2, gives Equation 3:

$$\frac{KaV}{L}=\frac{C_W(T_1-T_2)}{n}\sum\frac{1}{(h_s-h_a)_m} \qquad (3)$$

In order to calculate the dry bulb temperature of the air at an arbitrary section (i+1) of a layer, $t_{db,i+1}$, the dry bulb temperature of the air entering the section (i), $t_{db,i}$ must be known (Stoecker and Jones, 1983).

The sensible heat balance can be written as:

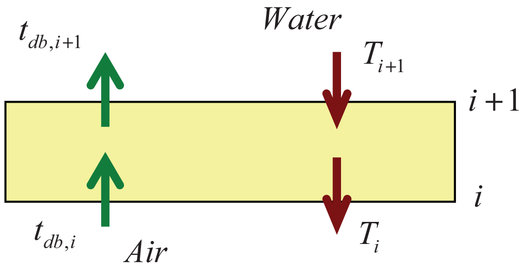

Figure 2 Water and air temperatures in an arbitrary layer between section (i) and section (i+1) of the fill for a counter-flow cooling tower.

$$GC_{pm}(t_{db,i}-t_{db,i+1})=h_{conv}\Delta A\left(\frac{t_{db,i}+t_{db,i+1}}{2}-\frac{T_i+T_{i+1}}{2}\right)$$

Solving for gives Equation 4:

$$t_{db,i+1}=\frac{t_{db,i}-\dfrac{(KaV)_{layer}}{2G}(t_{db,i}-T_i-T_{i+1})}{1+\dfrac{(KaV)_{layer}}{2G}} \qquad (4)$$

where $(KaV)_{layer}$ is the value of heat transfer coefficient for layer $(KaV)_{layer} = h_{conv}\Delta A/C_{pm}$ and it can be calculated using Equation 5:

$$(KaV)_{layer}=C_w L\frac{(T_1-T_2)}{n}\cdot\frac{1}{(h_s-h_a)_{m,i-(i+1)}} \qquad (5)$$

Condition 2: Given the value of *KaV* for the entire fill.

When the value is known for KaV for the entire fill, the flow rates of the entering air and water, the inlet dry bulb and inlet wet bulb temperatures and the hot water temperature are given, it is possible to predict the outlet water temperature and the outlet air temperature by the stepwise integration method.

However, the procedure for prediction of the outlet temperatures of the water and air requires an iterative calculation. The outlet water temperature must be assumed and the value of KaV can be calculated by the procedure of condition 1.

If the calculated value of KaV differs from the given value of KaV, the outlet water temperature must be assumed as the new value for the next iteration.

When the dry bulb temperature of the air entering section (i) is known, the dry bulb temperature of the air leaving section (i+1) can also be calculated from Equation 4.

A cross-flow cooling tower can be divided into n cells as shown in Figure 3. Water enters the top of the fill at an inlet temperature and flows through the nozzles, while air enters the left side of the fill with an inlet enthalpy $h_{a,inlet}$.

In the first cell, the water enters at a temperature T_1 and leaves at $T_{1,5}$ while the air enters at an enthalpy $h_{a,inlet}$ and leaves at $h_{1,2}$. Then, the air enters the second cell at an enthalpy $h_{1,2}$ and the water enters the fifth cell at a temperature $T_{1,5}$, respectively. Therefore, the enthalpies of air leaving the forth cell, eighth cell and twelfth cell at the right side of the fill are $h_{4,out}$, $h_{8,out}$, and $h_{12,out}$ and the temperatures of water leaving the ninth cell, tenth cell, eleventh cell and twelfth cell at the bottom of the fill are $T_{9,out}$, $T_{10,out}$, $T_{11,out}$, and $T_{12,out}$, respectively.

If the value of KaV is known for the entire fill of a cooling tower, the outlet water temperature T_2 can be calculated, based on the given values of the inlet water temperature, T_1, the inlet wet bulb temperature of the air (inlet air enthalpy), $t_{wb,inlet}$, the flow rate of the water, L and the flow rate of the air, G.

The fill can be divided into a number of small cells or increments. For example, there are 12 cells as shown in Figure 3 and each cell has a value of KaV per cell $(KaV)_{cell}$ and it can be calculated using Equation 6:

$$(KaV)_{cell} = \frac{KaV}{12} \tag{6}$$

If the divided air passages (m) and the divided water passages (n) are known, a value of KaV for each cell can be calculated using Equation 7:

$$(KaV)_{cell} = \frac{KaV}{m \cdot n} \tag{7}$$

In Figure 4, the energy balance in the first cell can be determined in the three forms of heat transfer by Equations 8-10:

Water side: $$\dot{Q} = L_{cell} C_w (T_1 - T_{1,5}) \tag{8}$$

Air side: $$\dot{Q} = G_{cell} (h_{1,2} - h_{a,inlet}) \tag{9}$$

Cell characteristics:

$$\dot{Q} = (KaV)_{cell} \left(\frac{h_{si} + h_{so}}{2} - \frac{h_{a,inlet} + h_{1,2}}{2} \right) \tag{10}$$

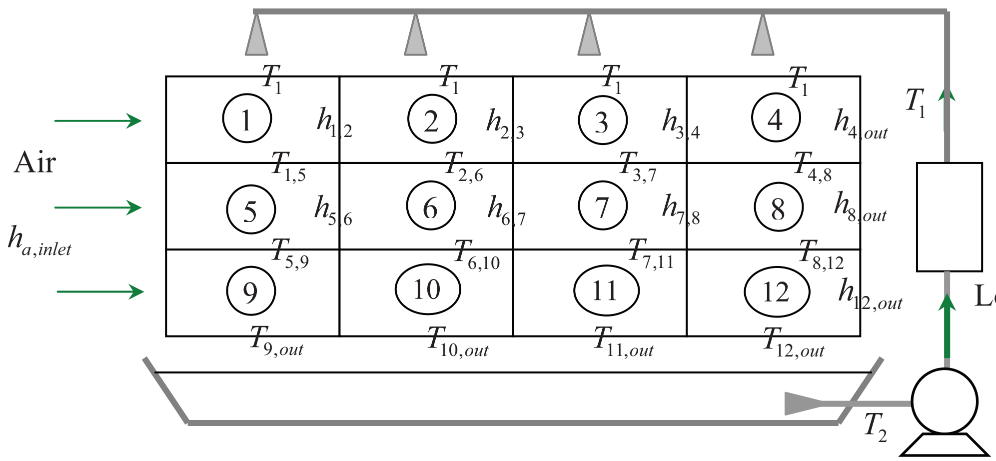

Figure 3 Division of the fill of a cross-flow cooling tower into 12 cells. (Stoecker and Johns, 1983)

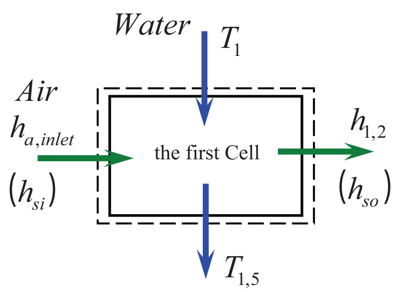

Figure 4 Energy balance between the air and water in the first cell of the fill.

The enthalpy of the saturated air can be calculated in a range of water temperatures from 11 to 40°C from Equation 11 (Stoecker and Jones, 1983):

$$h_s = 4.7926 + 2.568T - 0.029834T^2 + 0.0016657T^3 \quad (11)$$

For given values of $(KaV)_{cell}$, T_1 , $h_{a,inlet}$, L_{cell} , and G_{cell} , it is possible to calculate $T_{1,5}$, $h_{1,2}$, h_{so} , $\dot{Q}$ and from Equations 8, 9, 10 and 11. From Equations 9 and 10, the outlet air enthalpy of cell can be calculated.

$$h_{1,2} = \frac{Gh_{a,inlet} + \frac{1}{2}(KaV)_{cell}(h_{si} + h_{so} - h_{a,inlet})}{\frac{(KaV)_{cell}}{2} + G} \quad (12)$$

From Equations 8 and 9, the outlet water temperature of the first cell can be calculated.

$$T_{1,5} = T_1 - \frac{G(h_{1,2} - h_{a,inlet})}{LC_w} \quad (13)$$

The information flow diagram for the simulation of Equations 8, 11, 12 and 13 is illustrated in Figure 5. Assuming the trial value of $T_{1,5}$ as input in Equations 8 and 11, the outputs of Equations 8 and 11 are $\dot{Q}$ and h_{so} , respectively. The output of Equation 12 is then the input of Equation 13 and the output is $T_{1,5}$, which can be compared with the trial value. Therefore, the operating variables ($T_{1,5}$, $h_{1,2}$, h_{so} , and $\dot{Q}$) for each cell can be simulated by running a computer program (Rieder and Busby, 1986).

RESULTS AND DISCUSSION

Condition 1

A counter-flow cooling tower operates with the following conditions:

- Hot water temperature T_1 38 °C
- Cold water temperature T_2 30 °C
- Inlet wet bulb temperature $t_{wb,inlet}$ 27 °C
- Inlet dry bulb temperature $t_{db,inlet}$ 30 °C
- Water flow rate $\dot{V}_w$ 1200 L/min
- Air flow rate $\dot{V}_a$ 900 m^3/min
- Number of fill layers n 10 layers

The stepwise method can be used to predict the volumetric heat transfer coefficient and the outlet temperature of the air.

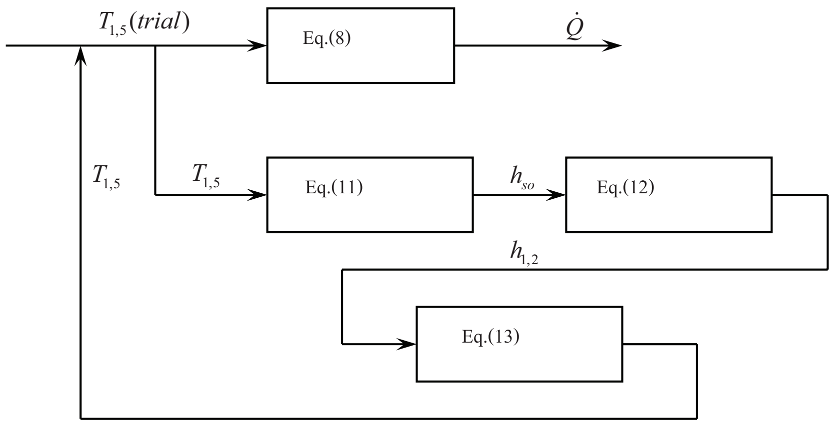

Figure 5 Information flow diagram for the simulation of the first cell in Figure 4.

The simulated results for condition 1 are presented in Table 1. For section zero to section ten of the fill (which must be divided into 10 layers), the water temperature decreases 0.8°C for each layer. In the first layer between section zero and section one, the temperature of the water entering and leaving the first layer was 30 and 30.8°C, respectively, and the mean water temperature for the first layer was 30.4°C, with the corresponding enthalpy of the saturated air in this layer being 101.7 kJ/kg. The enthalpy of air at section zero was the enthalpy of the saturated air at the inlet wet bulb temperature 27°C (kJ/kg). From the energy balance of the first layer, the enthalpy of air leaving the first layer can be determined as Equation 14 (Mills, 1995):

$$h_{a,1} = h_{a,0} + (L/G)C_w \frac{(T_1 - T_2)}{n} \qquad (14)$$

From Equation 14, the vale $h_{a,1}$ = 88.824 kJ/kg can be obtained. The average air enthalpy in the first layer was 86.85 kJ/kg. The value of $(h_s - h_a)_m$ in this layer was 101.7-86.85=14.853 kJ/kg.

The mean driving force of the second layer can be calculated using the same procedure. The enthalpy of air entering the second layer is equal to the enthalpy of air leaving the first layer (86.85 kJ/kg). Finally, the summation of $1/(h_s - h_a)_m$ for the entire fill can be calculated as shown in Table 1.

The value of KaV for the entire fill can be calculated from Equation 3 as:

$$KaV = C_w L \frac{T_1 - T_2}{n} \sum \frac{1}{(h_s - h_a)_m}$$

$$KaV = 4.175(19.959)(0.8)(0.5855)$$

= 39.03 kW/(kJ/kg of enthalpy difference)

The value of $(KaV)_{layer}$ and the temperature of the air leaving layer ($t_{db,i+1}$) can be calculated from Equations 5 and 4, as shown in the last column of Table 1. When air enters the bottom of the fill at 30°C, the air leaves the top of the fill at 34.4°C.

Condition 2

A cross-flow cooling tower operates under the following conditions:

- Hot water temperature T_1 38 °C
- Cold water temperature T_2 (unknown)
- Inlet wet bulb temperature $t_{wb,inlet}$ 27 °C

Table 1 Mean water temperature, average air enthalpy, average saturated air enthalpy, mean driving force and outlet dry bulb temperature of each layer for condition 1 by the stepwise integration method.

No. of layer (section)	Mean water temperature °C	Average h_a kJ/kg	Average h_s kJ/kg	$(h_s - h_a)_m$ kJ/kg	$\frac{1}{(h_s - h_a)_m}$	$t_{db,i+1}$ °C
1st layer (0-1)	30.4	86.85	101.7	14.853	0.0673	30.09
2nd layer (1-2)	31.2	90.80	106.08	15.288	0.0654	30.35
3rd layer (2-3)	32.0	94.74	110.62	15.882	0.0630	30.71
4th layer (3-4)	32.8	98.69	115.32	16.637	0.0601	31.15
5th layer (4-5)	33.6	102.63	120.18	17.552	0.0570	31.65
6th layer (5-6)	34.4	106.58	125.2	18.626	0.0537	32.18
7th layer (6-7)	35.2	110.52	130.38	19.861	0.0503	32.72
8th layer (7-8)	36.0	114.47	135.72	21.257	0.0470	33.28
9th layer (8-9)	36.8	118.41	141.22	22.812	0.0438	33.84
10th layer (9-10)	37.6	122.36	146.88	24.527	0.0408	34.40

- Inlet dry bulb temperature $t_{db,inlet}$ 30 °C
- Water flow rate $\dot{V}_w$ 1200 L/min
- Air flow rate $\dot{V}_a$ 900 m^3/min
- KaV for the entire fill KaV 39.03 kW/kJ/kg of enthalpy difference

The stepwise method can be used to predict the outlet temperatures of the air and water by dividing the entire fill of the tower into 12 cells (three passages for the air and four passages for the water) as shown in Figure 3.

The simulation of Equations 8, 11, 12 and 13 can be applied to each divided cell of the cross-flow cooling tower as illustrated in Figure 5, using the operating parameters of the cooling tower illustrated by condition 2. The results of the simulation can be presented as the temperature of the water and air leaving each cell and the enthalpy of the air leaving each cell, as shown in Figure 6. It was found that the outlet water temperature for each passage was not uniform and the outlet water temperatures of the passages near the air inlet were less than for those in the passages far from the air. In addition, the outlet air temperatures for each passage were not uniform and the outlet temperatures of the passages near the top of the fill were higher than those of the passages near the bottom of fill. Accordingly, the mean temperature of water at the bottom of fill was 30.38°C.

Performance comparison of the counter-flow cooling tower and the cross-flow cooling tower determined from condition 2

The conditions of tower operation are:

- Hot water temperature T_1 38 °C
- Unknown cold water temperature T_2
- Inlet wet bulb temperatures ($t_{wb,inlet}$) are kept constant at 23, 24, 25, 26, 27 and 28°C.
- Inlet dry bulb temperature $t_{db,inlet}$ 32 °C
- Water flow rate $\dot{V}_w$ 1200 L/min
- Air flow rate $\dot{V}_a$ 900 m^3/min
- Heat coefficients (KaV) are kept constants of 25, 30, 35, and 40 kW/(kJ/kg)
- Number of layers for the counter-flow cooling tower 10 layers
- Number of cells for the cross-flow cooling tower 12 cells

The stepwise integration method can be used to predict the volumetric heat transfer coefficient and the outlet temperatures of the air and water for the given six values of inlet wet bulb temperatures (23, 24, 25, 26, 27 and 28°C), respectively. The effect of the inlet wet bulb temperature is clearly apparent on the outlet water temperature at a constant value of KaV under the given values of hot water temperature (38°C), inlet dry bulb temperature (32°C), water flow rate (1200 L/min) and air flow rate (900 m^3/min). The counter-flow cooling tower and the cross-flow

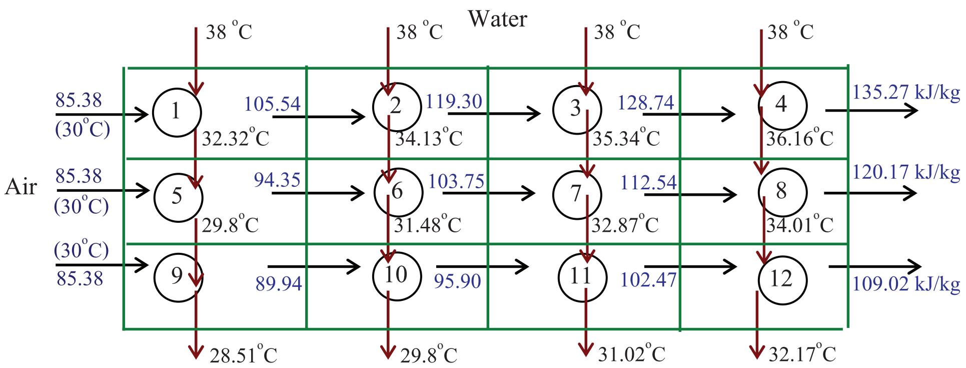

Figure 6 Results of the simulation of a cross-flow cooling tower using the case study values from condition 2.

cooling tower are divided into 10 layers and 12 cells, respectively.

The procedure for predicting the outlet temperatures of the water and air requires an iterative calculation. The outlet water temperature must be assumed and the value of KaV can be calculated using the procedure of condition 1. If the calculated value of KaV differs from the given value of KaV, the outlet water temperature should assume the new value for the next iteration. The iterative calculation is completed when the calculated value of KaV approaches the given value of KaV.

When the dry bulb temperature of the air entering section (i) is known, the dry bulb temperature of air leaving the section (i+1) can be calculated from Equation 4 and the dry bulb temperature of air leaving the final section (the outlet temperature of the air) can be calculated.

Accordingly, it is possible to predict the outlet water temperatures and the outlet air temperatures by the stepwise integration method. Under the given values of hot water temperature (38°C), inlet dry bulb temperature (32°C), water flow rate (1,200 L/min), air flow rate (900 m^3/min), with the fill divided into 10 layers by setting four values of at 25, 30, 35 and 40 kW/ kJ/kg of enthalpy difference. Accordingly, curves can be plotted, as shown in Figure 7, namely the outlet water temperatures of the counter-flow cooling tower (solid lines) and the cross-flow cooling tower (dashed lines). At a constant value of KaV, the outlet water temperature increased with the inlet wet bulb temperature. At a constant inlet wet bulb temperature, the outlet water temperature for a high value of KaV was lower than that for a low value of KaV. For a given value of KaV, the performance of a counter-flow cooling tower was higher than that of a cross-flow cooling tower, because a counter-flow cooling tower produced a low outlet water temperature.

Operating point of approach curve and characteristic curve can be determined by the stepwise integration method

Cooling tower performance is often specified in terms of the cooling tower's range, approach, inlet wet bulb temperature and water

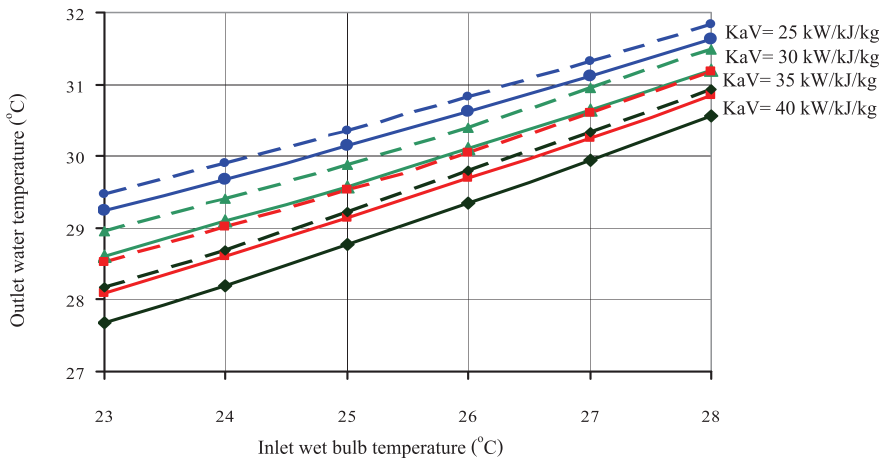

Figure 7 Effect of the inlet wet bulb temperature on the outlet water temperature at various values of KaV under given values of hot water temperature (38°C), inlet dry bulb temperature (32°C), water flow rate (1,200 L/min) and air flow rate (900 m^3/min) for the counter-flow cooling tower (solid lines) and the cross-flow cooling tower (dashed lines), using the parameters for condition 2.

flow rate. The operating point can be determined from the intersection of the approach curve and the characteristic curve of the given fill. The KaV / L values can be obtained from fill testing under the given hot water temperature and wet bulb temperature and by varying the water to air flow ratio (L / G). These cooling tower data are plotted most often in the form of KaV / L versus L / G. Accordingly, the characteristic curve of each type of fill can be obtained in the form of $KaV / L = C (L / G)^{-n}$ (Cooling Tower Institute, 1982). The stepwise integration method can also be used to simulate and plot the approach curve using the parameters of condition 1 (for given the inlet and outlet temperatures of the water) and the characteristic curves using condition 2 (for given the value of KaV for the entire fill).

Accordingly, the operating points of two characteristic curves and an approach curve (HWT=38°C, CWT= 30°C, and inlet WBT=25°C) can be determined as at L / G =1.335 (KaV / L =1.4276) for fill with KaV = 30 kW/(kJ/kg) , and at L / G =1.660 (KaV / L =1.8953) for fill with KaV = 40 kW/(kJ/kg), as shown in Figure 8.

CONCLUSIONS

The value of KaV depended on the dynamics of the airflow and the distribution of water droplets above the top of the fill in the cooling tower. A given cooling tower can maintain a constant air flow rate and water flow rate. Accordingly, the magnitude of KaV for the fill also remains constant. The value of KaV can characterize the cooling tower and can be the basis for predicting the cooling tower performance under a given inlet wet bulb temperature. The effect of the inlet wet bulb temperature on the outlet water temperature and outlet dry bulb temperature at various values of KaV can be predicted by computer.

When the inlet and outlet temperatures of the water, the flow rates of the entering water and air, and the inlet wet bulb temperature are known, it is possible to calculate the value of KaV by the stepwise integration method in accordance with condition 1 (given the inlet and outlet temperatures of water). When the value of KaV for the entire fill, the flow rates of the entering air

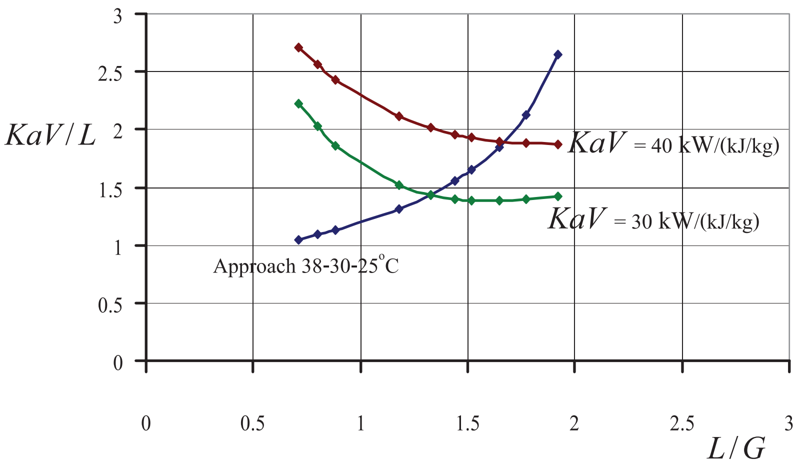

Figure 8 Operating points of two characteristic curves (at KaV = 30 kW/(kJ/kg) and KaV = 40 kW/(kJ/kg) and an approach curve (HWT=38°C, CWT=30°C, and inlet WBT=25°C) of a counter flow cooling tower determined by the stepwise integration method.

and water, the inlet dry bulb and inlet wet bulb temperatures and the hot water temperature are known, it is possible to predict the outlet water temperature by the stepwise integration method in accordance with condition 2 (given the value of KaV for the entire fill). In addition, the stepwise integration method can be used to simulate and plot the approach curve using condition 1, and the characteristic curves can be determined using condition 2.

LIST OF SYMBOLS

C_{pm} Specific heat capacity of moist air ($kJ / kg \cdot K$)
C_w Specific heat capacity of water ($kJ / kg \cdot K$)
T Water temperature ($°C$)
T_1 Hot water temperature ($°C$)
T_2 Cold water temperature ($°C$)
G Total air mass flow rate (kg / s)
L Total water mass flow rate (kg / s)
G_{cell} Air mass flow rate of a fill cell (kg / s)
L_{cell} Water mass flow rate of a fill cell (kg / s)
L / G Water to air flow ratio ($kg - water / kg - dryair$)
h_s Enthalpy of saturated air at the same water temperature (kJ / kg)
h_a Enthalpy of the moist air (kJ / kg)
$h_{a,\text{inlet}}$ Enthalpy of the air at the inlet wet bulb temperature (kJ / kg)
h_{conv} convective coefficient on area in section (i) to section (i+1) ($kW / m^2 \cdot K$)
KaV / L Volumetric heat transfer coefficient of the entire fill (dimensionless)
$(KaV)_{layer}$ Heat transfer coefficient of fill layer in a counter-flow tower ($kW / kJ / kg$ *of enthalpy difference*)
m Number of the divided air passage for a cross-flow cooling tower
n Number of the divided water passage for a cross-flow cooling tower
n Number of fill layer for a counter-flow cooling tower
$(h_s - h_a)_m$ Mean driving force in each layer (kJ / kg)
$(h_s - h_a)_{m,n-(n+1)}$ Mean driving force in layer from section (n)and section (n+1) (kJ / kg)
t_{db} Dry bulb temperature of the air ($°C$)
$t_{db,inlet}$ Dry bulb temperature of the air entering fill ($°C$)
$t_{db,i}$ Dry bulb temperature of the air entering layer at the section (i) ($°C$)
$t_{db,i+1}$ Dry bulb temperature of the air leaving layer at the section (i+1) ($°C$)
$t_{wb,inlet}$ Wet bulb temperature of the entering air fill ($°C$)
$\dot{V}_w$ Volume water flow rate (L / min)
$\dot{V}_a$ Volume air flow rate (m^3 / min)
ΔA Heat transfer area in the section (i) to section (i+1) (m^2)

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