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\documentclass[a4paper,12pt]{article}
\usepackage[left=2cm, right=2cm, top=2cm, bottom=
2cm]{geometry}
\usepackage{float}
\usepackage{color}
\definecolor{lightgray}{gray}{0.5}
\usepackage{subcaption}
\usepackage{tabularx}
\usepackage{amsmath}
\usepackage{siunitx}
\usepackage{graphicx}
\usepackage{paralist}
\usepackage{calc}
\title{Cooling Tower Design for Water Cooled Generator}
\author{Zarif Ahmad Razin Bhuiyan\\ ID: 1610137, Dept.
of ME}
\date{November,2020}
\begin{document}
\maketitle
\begin{abstract}
    This article is an example of cooling tower
    design. Well known Merkel Method is used. A brief theory
    of cooling tower has been derived first. MATLAB
    programming code has been used to do numerical
    integration. Theory and MATLAB code have been lead to
    completion of the design.
\end{abstract}
\section{Introduction}
    Cooling tower design is based on the principle of
    \textit{evaporative cooling}. There are several types of
    cooling tower. Based on water and air flow direction,
    Counter flow, Parallel flow, Cross flow cooling tower
    are available. Air and water flow opposite direction in
    counter flow cooling tower. In Mechanical draft cooling
    tower, a fan is used to flow the air. Fan is positioned
    at the exit of air in induced draft cooling tower. A
    schematic diagram of \textit{counter flow induced draft
    cooling tower} is shown in figure (\ref{fig1}). Water
    and air are in close contact during evaporative
    cooling. Heat and mass transfer are happened between air
    and water. The phenomenon is very complex to model
    mathematically. Well known model for cooling tower
    design is \textbf{Merkel Method} which is used in this
    article. To increase heat transfer fill material is
    used. There are two types of fill: Splash fill, Film
    fill. Film fill has been used for this design.
    Geographical location is very important as thermal

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properties of air depend on it. Dhaka is selected as
geographical location for this design. Cooling tower is
designed for \SI{3}{MW} generator having heat load about
\SI{1}{MW}.
\section{Cooling Tower
Theory\textsuperscript{\cite{cengel,design,paper1,handbo
ok,paper2}}}
\begin{figure}
    \centering
    \includegraphics[scale=0.8]{fig_cooling_tower.pdf}
}
    \caption{Schematic diagram of counter flow
    induced draft cooling tower}
    \label{fig1}
\end{figure}
A \textit{counter flow induced draft} cooling tower is
shown in figure (\ref{fig1}).\\
Mass Balance:\\
\begin{align}
    L+L_1+G+\omega_1 G &= L+G+\omega_2 G \quad \text{notag} \\
    L_1 &= (\omega_2-\omega_1)G \quad \textbf{eq1}
\end{align}
\end{align}
Energy Balance:
\begin{align}
    0 &= LC_{pT_2} + Gh_2 - L_1C_{pT_3} - LC_{pT_1} - Gh_1 \\
    \text{notag} \\
    LC_p(T_1- T_2) &= G(h_2-h_1) - L_1C_{pT_3} \quad \text{notag} \\
    \\
    h_2 - h_1 &= \frac{L}{G} C_p (T_1 -T_2) \\
    \textbf{eq2}
\end{align}
\end{align}
As,  $L_1C_{pT_3} \approx 0$  \\
The most generally accepted theory of cooling tower heat
transfer process is that developed by \textbf{Merkel}.
This analysis is based upon \textbf{enthalpy potential
difference} as driving force. Each particle of the water
is assumed to be surrounded by a film of air, and the
enthalpy difference between the film and surrounding air
provides the driving force for the cooling process. From
figure \ref{fig2},
\begin{figure}
    \centering
    \includegraphics[scale=0.8]{fig_merkel_eq}
    \caption{Heat transfer form water to air due to
    enthalpy potential difference.}
    \label{fig2}
\end{figure}
\end{figure}

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\begin{align}
& -LC_p \, dT = k \, dA (h_w - h) \quad \text{notag} \\
& \Rightarrow -C_p \frac{d}{dA} (h_w - h) = \frac{k}{L} \quad \text{notag} \\
& \Rightarrow -C_p \frac{d}{dA} (h_w - h) = \frac{k a}{L} \quad \text{notag} \\
& \quad \text{NTU} = \frac{k a V}{L} = C_p \int_{T_2}^{T_1} \frac{1}{h_w - h} \, dT \quad \text{label{eq3}}
\end{align}

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Equation (\ref{eq3}) is known as **Merkel** Equation. Right hand side of equation (\ref{eq3}) only depends on air and water properties. \\

From Equation (\ref{eq2}), enthalpy of air-water-vapour mixture (h) can be expressed as a function of water temperature (T).

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\begin{align}
h = h_1 + \frac{L}{G} C_p (T - T_2) \quad \text{label{eq4}}
\end{align}

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Enthalpy of the saturated air (\$h_w\$) can be express as,

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\begin{align}
h_w = 1.005T + \frac{0.622 P_g}{(2500.9 + 1.82 T)} \quad \text{(KJ/Kg \text{-} Dry air)}
\end{align}
\quad \text{label{eq5}}

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Corresponding value of saturated air pressure (\$P_g\$) at water temperature is given in steam table. \\

In above equations, \\

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\begin{tabular}{cl}
NTU & = Number of Transfer Unit \\
L & = Water flow rate (\si{kg/s}) \\
G & = Air flow rate (\si{kg/s}) \\
C_p & = Specific heat of water. (\si{kJ/kg.K}) \\
L_1 & = \text{Evaporative loss of water.} (\si{kg/s}) \\
T_1 & = \text{Entering (hot) water temperature.} (\si{\degreeCelsius}) \\
T_2 & = \text{Exit (cold) water temperature.} (\si{\degreeCelsius}) \\
h_1 & = \text{Enthalpy of air-water-vapour mixture at inlet} (\si{kJ/kg-dry air}) \\
h_2 & = \text{Enthalpy of air-water-vapour mixture at exit} (\si{kJ/kg-dry air}) \\
k & = \text{Mass transfer co-efficient} (\si{kg/s.m^2}) \\
a & = \text{Contact area per unit tower volume} (\si{m^2/m^3}) \\
V & = \text{Active cooling volume} (\si{m^3})
\end{tabular}

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h & = Enthalpy of air-water-vapour mixture at water temperature (\si{kJ/kg-dry air}) \\

\$h_w\$ & = Enthalpy of saturated air at water temperature (\si{kJ/kg-dry air}) \\

T & = Water temperature (\si{\degreeCelsius}) \\

\$P_g\$ & = Saturated vapour pressure at water temperature (\si{kPa}) \\

\$P\$ & = Total pressure of air-water-vapour mixture (\SI{100}{kPa}) \\

\$\omega_1\$ & = Absolute humidity of inlet air-water-vapour mixture (kg/kg - dry air) \\

\$\omega_2\$ & = Absolute humidity of exit air-water-vapour mixture (kg/kg-dry air)

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\end{tabular}
\section{Design Parameter}

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The required tower size is a function of the following \cite{handbook}:

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\begin{compactenum}[a.]
\item Cooling range
\item Approach to wet-bulb temperature
\item Quantity of water to be cooled
\item Wet- bulb temperature
\item Air velocity through the cell
\item Tower height
\end{compactenum}

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\vspace{0.5cm}

In Dhaka, maximum humidity is about 75\% during July-August. During this time, temperature is about \SI{32}{\degreeCelsius} \cite{website}. Corresponding wet-bulb temperature and enthalpy are respectively \SI{28}{\degreeCelsius} and \SI{90}{kJ/kg-dry air} \cite{cengel}. Power of water cooled generator is \SI{3}{MW}. Applying rule of thumb, heat load is about one third of power generation. Cooling tower has Long range (14-36 \si{\degreeCelsius}) and wide approach (8-11 \si{\degreeCelsius}). Value of \$\frac{L}{G}\$ ranges from 0.75 to 1.5. \cite{paper1,handbook}. \\[0.25cm]

Design Data: \\[0.1cm]

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\begin{tabular}{ll}
Heat Load & : \SI{1}{MW} \\
Wet bulb temperature, $T_{wet}$ & : \SI{28}{\degreeCelsius} \\
Inlet water temperature, $T_1$ & : \SI{70}{\degreeCelsius} \\
Exit water temperature, $T_2$ & : \SI{38}{\degreeCelsius} \\
Range, ($T_1 - T_2$) & : \SI{32}{\degreeCelsius}
\end{tabular}

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        Approach, ( $T_2 - T_{\text{wet}}$ ) &:
\SI{10}{\degreeCelsius} \\
        Enthalpy of inlet air,  $h_1$  &: \SI{90}{kJ/kg} - dry
air \\
         $\frac{L}{G}$  Ratio &: 1.5
\end{tabular}
\begin{figure}
\centering
\includegraphics[scale=0.6]{fig NTU LG}
\caption{Upto  $\frac{L}{G}=2$ , value of NTU
remains constant (above specified condition)}
\label{fig3}
\end{figure}
\section{Calculation}
\paragraph{Water and Air Flow Rate:}
\begin{align*}
\text{Heat Load} &= LC_p(T_1 - T_2) \\
\rightarrow 10^3 &= L \times 4.183 \times (70 - 38) \\
L &= \SI{7.47}{kg/s}
\end{align*}
\end{align*}
Again,  $\frac{L}{G}=1.5$  \quad  $G = \SI{4.98}{Kg}$  \text{-dry air}/s$
\paragraph{Numerical Integration:}
From equation (\ref{eq3}),
\begin{align}
NTU &= 4.18 \int_{38}^{70} \frac{1}{h_w - h} dT
\end{align}
\end{align}
where,  $h$  and  $h_w$  are evaluated by equation
(\ref{eq4}) and (\ref{eq5}) respectively. Numerical
Integration (Equation \ref{eq7}) was performed in MATLAB
using Simpson  $\frac{1}{3}$  Rule.
\begin{align}
NTU &= 4.18 \sum_{k=1}^n \left[ \frac{\Delta T}{3} \left( f\left(T_2 + (2k-2)\Delta T\right) + 4f\left(T_2 + (2k-1)\Delta T\right) + f\left(T_2 + 2k\Delta T\right) \right) \right] \quad \text{\textbf{eq7}}
\end{align}
\end{align}
where,  $f(T) = \frac{1}{h_w(T) - h(T)}$ ;
\hspace{0.5cm} Number of division,  $n=20$ ;
\\
and Step size,  $\Delta T = \frac{T_1 - T_2}{n} = \frac{32}{20} = 1.6$  [0.2cm]
Determined NTU=1.018
\begin{figure}
\centering

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\includegraphics[scale=1,trim=2.5cm 0cm 3cm
0cm,angle=90]{fig cooling char}
\caption{Cooling Tower Process Heat Balance.
*Cold water,  $T_2=38^\circ\text{C}$ }
\label{fig4}
\end{figure}
\paragraph{MATLAB Code:}
\begin{verbatim}
%Cooling Tower NTU
% Using Merkel Equation
function NTU = Cooling_Tower()
    T_w = 28; % wet bulb temperature (degreeCelsius)
    T_1 = 70; % Water Inlet Temperature (degreeCelcius)
    T_2 = 38; % Water Outlet Temperature (degreeCelcius)
    L_G = 1.5; %L/G Ratio
    C_p = 4.18; % Specific Heat of water (kJ/kg.K)
    h_1 = 90; %Enthalpy of air at water outlet
temperature (kJ/kg dry air)
    function y = h(T) %Enthalpy of air at water
temperature (kJ/kg)
        y = h_1 + L_G*C_p*(T-T_2);
    end
    function y = h_w(T) %Enthalpy of saturated air at
water temperature (kJ/kg)
        y = 1.005.*T +
(0.622.*P_g(T).*(2500.9+1.82.*T))./(100-P_g(T));
    end
    function y = P_g(T) %Saturated vapour pressure
        T_sat = 5:5:100;
        P_sat
=[0.8725;1.2281;1.7057;2.3392;3.1698;4.2469;5.6291;
7.3851;9.5953;12.352; 15.763; 19.947;
25.043;31.202;
38.597; 47.416; 57.868;70.183; 84.609;101.42];
        y= interp1(T_sat,P_sat,T);
    end
    function y=f(T)
        y = 1/(h_w(T)-h(T));
    end
    n = 20;
    a = (T_1-T_2)/n;
    sum = 0;
    for k=1:(n/2)
        sum = sum + a/3*(f(T_2+(2*k-2)*a)+4*f(T_2+(2*k-1)*a)+f(T_2+(2*k)*a));
    end
    NTU = C_p*sum;

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%Plotting Graph
x = T 2:0.5:T 1;
x_1 = (T 2-15):0.5:(T 1+2);
plot(x,h(x),'k-',x_1,h_w(x_1),'k-','Linewidth',1);
axis([20,75,0,1000])
xlabel('Temperature (^{\circ} C)');
ylabel('Enthalpy of air,h_w or h (kJ/kg dry air)');
hold on;
grid on;
plot([1,1]*T 2,ylim,'k--');
plot([1,1]*T 1,ylim,'k--');
plot([20,38],[1,1]*90,'k--');
plot([20,70],[1,1]*h(70),'k--');
plot([1,1]*T_w,ylim,'k--');
hold off
end
\end{verbatim}
\color{lightgray}
\textbf{ans =1.0177}
\color{black}
\paragraph{Floor Sizing\textsuperscript{\cite{paper3}}:}
The balance between the capital cost and fan power cost usually limits the fan power for packed towers. Hence the maximum air flowrate is about  $\text{SI}\{8800\}\{\text{kg/h.m}^2\}$ . A poor water flow distribution over the packing is commonly experienced at water flowrates in excess of around  $\text{SI}\{15000\}\{\text{kg/h.m}^2\}$ . If the flowrate is increased beyond this value, the water cascades in thick streams instead of falling as a spray, so that the effective surface area is reduced. This condition is called \textit{flooding}. On the other hand, if the water flowrates drops to about  $\text{SI}\{3000\}\{\text{kg/h.m}^2\}$  or less, surface tension causes the water flow to channel. This gives a poor water distribution, and hence a marked drop in performance.
\begin{align*}
L' &= L/A \quad G'=G/A
\end{align*}
where,  $L'$  is water flow rate per unit floor area ( $\text{SI}\{\text{kg/h.m}^2\}$ );  $G'$  is air flow rate per unit floor area ( $\text{SI}\{\text{kg/h.m}^2\}$ );  $A$  is area of cooling tower floor ( $\text{SI}\{\text{m}^2\}$ ).
\begin{align*}
L &= \text{SI}\{7.47\}\{\text{kg/s}\} = \text{SI}\{26892\}\{\text{kg/h}\} \\
G &= \text{SI}\{4.98\}\{\text{kg/s}\} = \text{SI}\{17928\}\{\text{kg/h}\}
\end{align*}
\end{align*}
Assume, floor area,  $A = \text{SI}\{2.3\}\{\text{m}^2\}$ 
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\begin{align*}
L' &= \frac{L}{A} = \frac{\text{SI}\{26892\}\{\text{kg/h}\}}{\text{SI}\{2.3\}\{\text{m}^2\}} \\
&= \text{SI}\{11692.17\}\{\text{kg/h.m}^2\} < \text{SI}\{15000\}\{\text{kg/h.m}^2\} \\
G' &= \frac{G}{A} = \frac{\text{SI}\{17928\}\{\text{kg/h}\}}{\text{SI}\{2.3\}\{\text{m}^2\}} \\
&= \text{SI}\{7794.78\}\{\text{kg/h.m}^2\} < \text{SI}\{8000\}\{\text{kg/h.m}^2\}
\end{align*}
Assumption of floor area is okay.
\begin{figure}[h]
\begin{subfigure}{0.6\textwidth}
\includegraphics[scale=1]{fig_acs}
\end{subfigure}
\begin{subfigure}{0.4\textwidth}
\begin{tabular}{ll}
$h_a$ &= 27 mm \\
$h_b$ &= 27 mm \\
$v_a$ &= 73 mm \\
$v_b$ &= 73 mm \\
$\lambda$ &= 1.1010 \\
$m$ &= 0.80
\end{tabular}
\end{subfigure}
\caption{Corrugated asbestos sheets (CAS) size and transfer characteristics \cite{paper3}}
\label{fig5}
\end{figure}
\paragraph{Sizing of Packing/Fill Material\textsuperscript{\cite{paper3}}:}
Empirical co-relation are available for different type of packaging in literature. \textit{Corrugated asbestos sheets (CAS)} are selected as packing material. \textit{Volume heat transfer co-efficient ( $ka/L'$ )} is represented by an equation of the form,
\begin{align}
\frac{ka}{L'} &= \lambda \left( \frac{L}{G} \right)^{-m} \quad \text{\textbf{eq8}}
\end{align}
where,  $\lambda$  and  $m$  define the transfer characteristics of this type of packing. The values of  $\lambda$  and  $m$  for CAS are given in figure \ref{fig5}.
\begin{align}
NTU &= \frac{kaV}{L} = \frac{ka}{L} \frac{V}{A} \quad \text{\textbf{eq9}}
\end{align}
```

$NTU = \frac{kaH}{L}$ \label{eq9}

where, H is packing height (m). From equation (\ref{eq8}),

$$\frac{ka}{L/G} = 1.1010 (1.5)^{-0.80} \quad \text{quad} \quad [L/G = 1.5]$$

$$ka = 0.796 \text{ per meter}$$

Putting this value is equation (\ref{eq9}),

$$1.018 ka = (0.796)H \quad \text{quad} \quad [NTU = 1.018]$$

$$H = 1.28 \text{ m}$$

Paragraph Fan Design \textsuperscript{\cite{paper3}}:

The horsepower (hp) required to drive the fans is empirically calculated using rule of thumb that each $226.5 \text{ m}^3/\text{min}$ of air discharged by the fan requires 1 hp .

$$P = \frac{G \times 60}{226.5} \times \frac{1}{\rho} \times \rho$$

$$\rho = \frac{101.325 - \phi P_g}{R_a T}$$
 Where, P is power requirement of ID fan (hp); G is air flowrate (kg/s); ρ is density of saturated air at exit temperature (kg/m^3); ϕ is relative humidity; R_a is gas constant (kJ/kg.k); T is air exit temperature (K); P_g is saturated vapour pressure at exit air temperature (kPa)

$$\rho = \frac{101.325 - 1 \times 31.202}{0.2870 \times (273 + 70)}$$

$$\rho = 0.712 \text{ kg/m}^3$$
 Then,

$$P = \frac{4.98 \times 60}{0.712} \times \frac{1}{226.5}$$

$$P = 1.85 \text{ hp}$$

Paragraph Blowdown & Make-up Water \textsuperscript{\cite{paper3}}:

$$\pi_c = \frac{\text{Concentration of dissolve solid in the cooling tower water}}{\text{Concentration of dissolve solid in cooling tower make-up water}}$$
 Where, π_c is cycles of concentration. Usually, the circulating water salt

content is limited to 3-7 times the concentration of the salts in the make-up water. Assume, $\pi_c = 5$

The make-up water and blow down rate are given by,

$$M = \frac{\pi_c \times E}{\pi_c - 1}$$
 \label{eq10}
$$B = \frac{E}{\pi_c - 1} - W$$
 \label{eq11}
 Where, M is make up water rate as percentage of the circulation rate; B is blowdown rate as percentage of the circulation rate; E is evaporative water loss as a percentage of circulation rate; W is windage loss as a percentage of circulation rate. Windage loss is about 0.1-0.3% of circulation rate. Assume, $W = 0.3\%$

Form equation (\ref{eq1}),

$$L_1 = G \left(\omega_2 (T_{db}, T_{wb}) - \omega_1 (T_{db}, T_{wb}) \right)$$
 Where, T_{db} is dry bulb temperature ($^{\circ}\text{C}$); T_{wb} is wet bulb temperature ($^{\circ}\text{C}$)

$$L_1 = 4.98 \left(\omega_2 (70, 52) - \omega_1 (32, 28) \right)$$

$$= 4.98 \times (0.0869 - 0.0224) = 0.321 \text{ kg/s}$$

$$E = \frac{L_1}{L} = \frac{0.321}{7.47}$$

$$= 4.30 \%$$
 From equation (\ref{eq10}) and (\ref{eq11}),

$$M = \frac{5 \times 4.30}{5 - 1}$$

$$= 5.38 \%$$

$$B = \frac{4.30}{5 - 1} - 0.3$$

$$= 0.78 \%$$

Section Result

Fill Material &: Corrugated Asbestos Sheets (CAS), film fill

Packing Height &: 1.28 m

Floor Area &: 2.3 m^2

L/G &: 1.5

Water circulation rate &: 7.47 kg/s or 26.89 Ton/h

Air flow rate &: 4.98 kg/s or 17.93 Ton/h

Blowdown & Make-up Water rate &: 0.78% & 5.38% of water circulation rate

Fan Power &: 1.85 hp\\
 Range &: \SI{32}{\degreeCelsius} [wide range]\\
 Approach &: \SI{10}{\degreeCelsius} [large
 approach]\\
 Location &: Dhaka, Bangladesh
\end{tabular}
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