OPTIMAL DESIGN OF FORCED DRAFT COUNTER FLOW COOLING TOWERS

By

Leena Omar Mohamed El Sayed Abd El Salam

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE
In
MECHANICAL POWER ENGINEERING

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Title of Thesis: OPTIMAL DESIGN OF FORCED DRAFT COUNTER FLOW COOLING TOWERS

Key Words: Counter flow cooling towers **,** Forced Draft ,Parametric analysis **,**Minimization, Operating cost

Summary:
The study aims at analytically determining the optimum conditions for a counter flow forced draft cooling tower taking the minimization of the operating cost as an objective. First a mathematical model that effectively describes the counter flow cooling tower was selected and the programming was carried out with MATLAB software. Then a parametric analysis was conducted in which the effect of parameters: air and water mass flow rate(s), inlet water temperature was investigated on performance parameters. Finally different case studies were examined in order to select optimum conditions which resulted in minimizing the operating cost .

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Nomenclature

Symbol	Quantity
a	Fill density (m^2/m^3)
A	Cross-sectional area (m^2)
Ce	Price of electricity (LE/kW.hr)
Cop	Operating cost (LE/month)
CopF	Operating cost due to fan (LE/month)
CopMw	Operating cost due to make-up water (LE/m^3)
CopP	Operating cost due to pump (LE/month)
Cw	Price of water (LE/m^3)
c_{pv}	Specific heat of vapour (J/kg.K)
c_{pw}	Specific heat of water (J/kg.K)
c_{pa}	Specific heat of air (J/kg.K)
Ga	Air Loading (kg/m^2.s)
Gw	Water Loading (kg/m^2.s)
h	Enthalpy (J/kg)
hc	Volumetric convective heat transfer coefficient(W/K.m^3)
H	Number of operating hours
K	Surface mass transfer coefficient (kg/s.m^2)
Ka	Volumetric mass transfer coefficient (kg/s.m^3)
K_{annu}	Annualization factor
Kf	Fill loss coefficient
L	Length or Height (m)
L/G	Liquid to Gas or water to air mass flow rate (kgw/kga)
Le	Lewis factor
Me	Merkel number
mw	Mass flow rate of water (kg/s)
n	Number of cycles of concentration
Pf	Power required by the fan (Watt)
Pt	Total pressure (Pa)
Pv	Vapour pressure (Pa)
ΔPd	Dynamic pressure drop (Pa)
ΔPt or deltaP	Total pressure drop (Pa)
Q	Heat load (MWatt)
T	Temperature (^oC)
Tdb	Air dry bulb temperature (^oC)
Twb	Air wet bulb temperature (^oC)
Twi	Inlet water temperature (^oC)
Two	Outlet water temperature (^oC)
w	Humidity ratio ($kg_{w.v}/kg_{d.a}$)
ws	Saturation humidity ratio ($kg_{w.v}/kg_{d.a}$)
z	Height (m)

Greek symbols

μ	Dynamic viscosity (kg/s.m)

η_f	Efficiency of the fan
η_p	Efficiency of the pump
$\boldsymbol{\rho}$	Density (kg/m^3)

Subscripts

bd	Blow down
d	Drift
d.a	Dry air
ev	Evaporated water
i	Inlet
ma	Moist air
mw	Make-up water
o	Outlet
s	Saturation
w.v	Water vapour

Superscripts

a	air
w	water

Abbreviations

CT	Cooling Tower
CTI	Cooling Tower Institute
E-NTU	Effectivness-Number of Transfer Units
HCP	Horizontally Corrugated Packing
LCCA	Life Cycle Cost Analysis
TAC	Total Annual Cost
VCP	Vertically Corrugated Packing
1D -ODE	One Dimensional Ordinary Differential Equation
4-ODEs	Four Ordinary Differential Equation

Abstract

Cooling towers are used in many applications such as refrigeration, power generation, chemical and petrochemical plants which use water to remove heat generated from different processes. The main function of the cooling tower is to cool down a certain amount of hot water into a lower temperature, in order to reuse the water.

The current thesis focuses on a certain type "Counter flow forced draft" cooling towers. The present study aims at achieving the most optimum design and operating conditions of counter flow cooling tower to enhance the performance and hence reduce the costs. First, a mathematical model that effectively describes the counter flow cooling tower was selected and modified and programmed with MATLAB software. Second, a parametric study was carried out to examine the effect of some operating parameters such as: inlet water temperature, inlet air and water mass flow rates on performance parameters. The performance parameters studied included the Effectiveness, Range, outlet water temperature. Third, different case studies were examined to determine the optimum design conditions (Case study 1, Case study 2) of the counter flow cooling tower in order to reduce the operating cost. "Case study 3" examined the effect of varying inlet wet bulb temperature on the operating costs of the cooling tower.

The results from the parametric study showed that as the air mass flow rate increased both Effectiveness and Range increased while outlet water temperature decreased. On the contrary, as the water flow rate increased both Effectiveness and Range decreased while outlet water temperature increased. The Effectiveness, Range and outlet water temperature varied directly with inlet water temperature. Increasing the inlet water temperature by 20%, increased the Effectiveness by 14%, the Range by 58.82% and the outlet water temperature 7.6%.

Considering the case studies, the results from "Case study 1" showed that at outlet water temperature 30^{o}C, operating on a cross sectional area of 8.5m^2 would reduce the operating cost by 11.3 % than when operating on a cross sectional area of 5.5m^2. For "Case study 3" at outlet water temperature 30^{o}C, as the wet bulb temperature increased from 20^{o}C to 26 ^{o}C the operating cost increased by 34.8 %. The results from "Case study 2"showed that the optimum design condition was defined by outlet water temperature and inlet water temperature. The condition having the highest inlet and outlet (Twi=46^{o}C, Two=34^{o}C) water temperature resulted in the minimum operating cost. The percentage change in the highest operating cost from the least operating cost corresponded to~ (25%).

Chapter 1 : Introduction

1.1 Introduction

Different applications such as refrigeration, power generation, chemical and petrochemical plants use water to remove heat generated from different processes. In order to get rid of the heat generated, the hot water can be discharged (dumped) directly into large water reservoirs (sinks) such as rivers, lakes, seas and oceans. However, these large reservoirs are not always available near the industries. Also, the water coming out from different processes can have a high temperature so discharging it directly into the water reservoirs can cause death of living creatures. Hence, the federal and local governments have established strict regulations concerning the direct discharge of water.

In order to get rid of the heat generated another alternative exists. The hot water could be cooled by means of air and then reused. This could be achieved by means of “Cooling Tower”. Cooling towers are mechanical equipment that dissipate waste thermal energy into the atmosphere.

If the air and water are in direct contact then the cooling tower is termed as an evaporative/wet type cooling tower .However if the water flows in tubes and the air flows at the outside of the tubes then the cooling tower is termed as a dry type cooling tower .This study is concerned with the wet/evaporative type. The term evaporative refers to the main type of heat rejection method. The heat rejection occurs mainly by means of evaporation of a small amount of the water , thus lowering its temperature while increasing the air temperature and the amount of water vapor in air.

There are many advantages of evaporative over dry type cooling towers . First the water could be cooled to a low temperature. Second they require smaller surface area to reject/remove the same heat load. Thus the evaporative cooling tower is a suitable choice when the desired water temperature is low or when the amount of heat rejected is high (lowering the surface area is an objective).

On the other side the main disadvantage include water mass flow rate reduction due to the evaporation process. This could be a problem especially in countries where the price of water is high or the availability of the water is low.

Another specification for the cooling tower is the relative direction between water and air. There exist two types of flow counter and cross flows. The advantage of the counter flow type is that it gives better distribution of the water with the air hence increasing the performance of the tower.

Finally the method by which the air moves through the tower could be either using a fan (mechanical draft) or depending on the buoyancy effect (natural draft). The disadvantage of the natural draft that it requires a large height thus a high capital cost. On the other side, the mechanical draft requires smaller volume but higher operating cost due to the dependence on the fan (s).The present study is concerned with the Counter flow mechanical draft evaporative cooling tower type. The working principle of an evaporative counter flow mechanical draft cooling tower could be demonstrated as in Figure 1-1.

1.2 Method of operation of the cooling tower

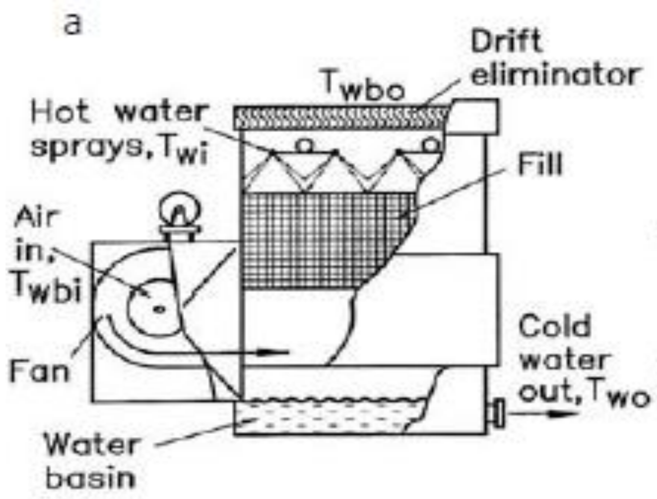

Figure 1-1: Counter flow evaporative mechanical draft cooling tower[1].

The cooling tower shown in Figure 1-1 consists of: water distribution system, packing, collection/water basin, drift eliminator and the surrounding structure (i.e casing).

The hot water enters the tower through a water distribution system where it is sprayed in form of small droplets. Then the droplets undergo breaking as in splash fill type , flow as a thin film as in film fill type or undergo both breaking and film forming as in tickle type fills. Inside the fill most of the heat rejection occurs about 90% [2].The air is drawn into the cooling tower by means of a fan installed at the exit of the tower. Because the fan is at the exit then the cooling tower is classified as induced type mechanical draft type. If the fan is located at the entrance then its function is to push the air into the tower and then the cooling tower is classified as forced type mechanical draft type Both the water and air flow vertically in opposite directions, the water flows downwards while the air flows upwards which would imply counter flow type. Below the fill the water droplets are also cooled. Finally the cooled water is collected in the water or collecting basin and returned to the process.

Considering the air which enters from below the fill and cools the water as it rises upward .It exits the tower containing more amount of water vapor than when entering the tower. At the exit of the tower before the fan drift eliminators exists to prevent the entrainment of water droplets with air.

1.3 Mechanism of water cooling or heat rejection

The cooling of the water occurs due to both mass and heat transfer. The cooling process occurs due to mass transfer (diffusion) mainly and convection .Mass transfer of water into air occurs because the partial pressure of water vapor in air is lower than the partial pressure of the saturated air surrounding the water. The convection occurs due to the temperature difference between ambient air and hot water. The rates of mass and heat transfer are increased mainly by