Cooling towers size and cost as related to their location
by Layne Russell Zimmerman

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Mechanical Engineering
Montana State University

Abstract:
State of the art methods for sizing evaporative, dry, and hybrid (combination of evaporative and dry) cooling towers were examined. Where appropriate these methods were used to develop computer programs for sizing cooling towers. The well known Merkel theory was incorporated in programs to size wet cooling towers. Where methods had not been developed for sizing cooling towers, as for dry cooling towers, heat exchanger-theory was used to develop methods of sizing these towers. A program was developed to size the dry cooling towers. This program together with the programs for sizing evaporative cooling towers were used to size hybrid cooling towers.

The relationships between the size of the cooling towers and the total power plant cost were examined, and the important variables stressed.

It was shown that accurate methods of sizing the cooling system must be used in conjunction with all plant designs to do any cost optimizations. Due to the complex interaction at a proposed plant site of the weather, water availability, and construction costs, the methods provided herein are indispensable in determining the overall picture when planning a new site.

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Signature Layne Zimmerman

Date March 10, 1976

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ABSTRACT

State of the art methods for sizing evaporative, dry, and hybrid (combination of evaporative and dry) cooling towers were examined. Where appropriate these methods were used to develop computer programs for sizing cooling towers. The well known Merkel theory was incorporated in programs to size wet cooling towers. Where methods had not been developed for sizing cooling towers, as for dry cooling towers, heat exchanger theory was used to develop methods of sizing these towers. A program was developed to size the dry cooling towers. This program together with the programs for sizing evaporative cooling towers were used to size hybrid cooling towers.

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NOMENCLATURE

English Letter Symbols

a	Effective heat transfer area per unit volume in wet tower
A	Total heat transfer area
A_c	Heat exchanger minimum free flow area
A_f	Total fin area of one side of a heat exchanger
A_{fr}	Total frontal area of a heat exchanger
C	Flow-stream capacity rate ($\dot{m}\ C_p$)
C_c	Flow-stream capacity rate of cold-side fluid
C_h	Flow-stream capacity rate of hot-side fluid
C_{min}	Smaller of the two quantities C_c and C_h
C_{max}	Larger of the two quantities of C_c and C_h
C_p	Specific heat at constant pressure
D_h	Hydraulic diameter of internal passage
F_G	Connection factor to log-mean rate equation
f	Flow friction factor within heat exchanger
G	Mass flow rate of air
G_a	Mass flow rate of air per unit area
h	Enthalpy
h	Film conductance coefficient for convection heat transfer
K	Overall heat transfer coefficient from water to air
K_G	Contraction loss coefficient for flow at heat exchanger entrance

K_e	Expansion loss coefficient for flow at heat exchanger exit
K_g	Coefficient of sensible heat transfer per unit of effective heat transfer area
K_L	Coefficient of total heat transfer per unit of effective heat transfer area
K'	Coefficient of latent heat transfer per unit of effective heat transfer area
k	Thermal conductivity
L	Mass flow rate of water in evaporative tower
L_a	Mass flow rate per unit area in evaporative tower
L_e	Evaporation mass flow rate
l	Fin length from root to center
M	Molecular weight
$\dot{m}$	Mass flow rate
P	Pressure
Q_L	Rate of latent heat trnasfer
Q_s	Rate of sensible heat transfer
Q_w	Total heat transfer rate from water
q	Heat transfer rate
R	Gas constant
$\bar{R}$	Universal gas constant
r_h	Hydraulic radius
s	Air speed
T	Temperature of air

t	Temperature of water
U	Overall thermal conductance
V	Volume
v	Specific volume
v_m	Average specific volume

GREEK LETTER SYMBOLS

α	Ratio of total transfer area on one side of the exchanger to total volume
δ	Fin thickness
ε	Heat exchanger effectiveness
η_o	Total surface temperature effectiveness
ϕ	Relative humidity
σ	Ratio of free-flow area to frontal area (A_c/A_{fv})
μ	Viscosity
ρ	Density
ω, ω'	Humidity ratio or absolute humidity of air and air-water film respectively

DIMENSIONLESS GROUPINGS

N_{Nu}	Nusselt number ($h4r_h/k$)
N_{Re}	Reynolds number ($4r_h\dot{m}/\mu A_c$)
N_{st}	Stanton number ($hAc/\dot{m}C_p$)
N_{Pr}	Prandtl number ($\mu C_p/k$)

N_{tu}	Number of transfer units of a heat exchanger
NTU_L	Number of transfer units (KaV/L)
NTU_G	Number of transfer units (kaV/G)

All primes refer to water-air interface properties.

INTRODUCTION

Disposing of vast quantities of waste heat, due to the increasing demand for electrical power has become a major enterprise, and a major concern for groups of technically oriented people. Environmentalists are concerned about how power generating plants and cooling tower design will affect the site selection. Divisions within the state governments are given the job of regulating the power companies and satisfying the majority of concerned people. Because of these concerned people, the Montana Department of Natural Resources and Conservation funded a research assistantship in the area of cooling tower sizing. This thesis presents work done by the research assistant in the areas of evaporative, and dry, water to air cooling and combinations of these, all of which require cooling towers as the instruments of heat dissipation.

The evaporative or wet cooling towers are composed of a series of tower units each of which is independent and capable of functioning alone. The different types and methods of sizing each are discussed in Chapter 2. The methods presented enable a technical person to size evaporative cooling towers for any ambient temperature, barometric pressure, and relative humidity. The different designs of evaporative towers each have their own particular advantages and limitations. The counterflow tower is more efficient thermally, but the crossflow tower has less air resistance, and will develop higher air flow velocities than in the counterflow tower using equal fan horsepower.

Due to the availability of water and construction costs, dry cooling towers are presently not feasible in many areas. A larger dry cooling tower is required to do a job comparible to an evaporative cooling tower. This is expensive, but the cost of water is rising also. Large generating plants cannot be constructed in water short areas with evaporative cooling towers, because of the makeup water required. If water supplies become more limited, the difficulty of power plant site selection will intensify. A 1000 MW fossil-fuel fired generating plant will require around 4000 gpm of make-up water due to evaporation alone if evaporative cooling is employed. Construction of large dry cooled generating plants has been done only in England thus far. The knowledge gained from these show that it is possible to construct plants of almost any size using dry cooling. Chapter 3 presents methods of sizing dry cooling towers to meet year round ambient weather conditions and additional information on analyzing heat exchangers under off-design conditions.

Various chemical production plants in dryer sections of the country have used dry cooling for years. One reason for this is that it is easier to use air for cooling remote parts of the plant where piping of water can be inconvenient and costly.

A more modern answer to the cooling problem is the use of the hybrid or wet/dry cooling tower. If plume control or water availability are major concerns, they may be alleviated with the combination cooling. This idea is delt with in Chapter 4. The use of dry or wet/dry cooling becomes practical as the selection of construction sites becomes more difficult due to necessary environmental protection restrictions, and limited water availability.

Chapter 2

WET COOLING TOWERS

The general development of wet cooling tower theory is attributed to Merkel and is called the Merkel formulation. It is presented by Gurney and Cotter (1) in terms of water droplets with air flowing past them as shown in Figure 2.1.

It is assumed that the air in contact with the water is moving very slowly with respect to the droplet, and is saturated. The bulk air moving past the water always has a lower vapor pressure, and the vapor at the higher pressure in the water film attempts to equalize with the vapor pressure in the air. This results in a flow of water vapor, evaporation, and the water looses heat. This combined with direct conduction provides the necessary heat transfer.

To begin, assume the water droplet to be falling through a counterflow tower, with water fed into the top, and air into the bottom as shown in Figure 2.2. Wet cooling tower calculations are normally based on the pack plan area which contains the area around the free droplets as well as the contact area of the packing. Equations can be developed to find the sensible heat transfer, and the latent heat transfer. The sensible heat transfer is that due to conduction, and the latent heat transfer is that due to evaporation.

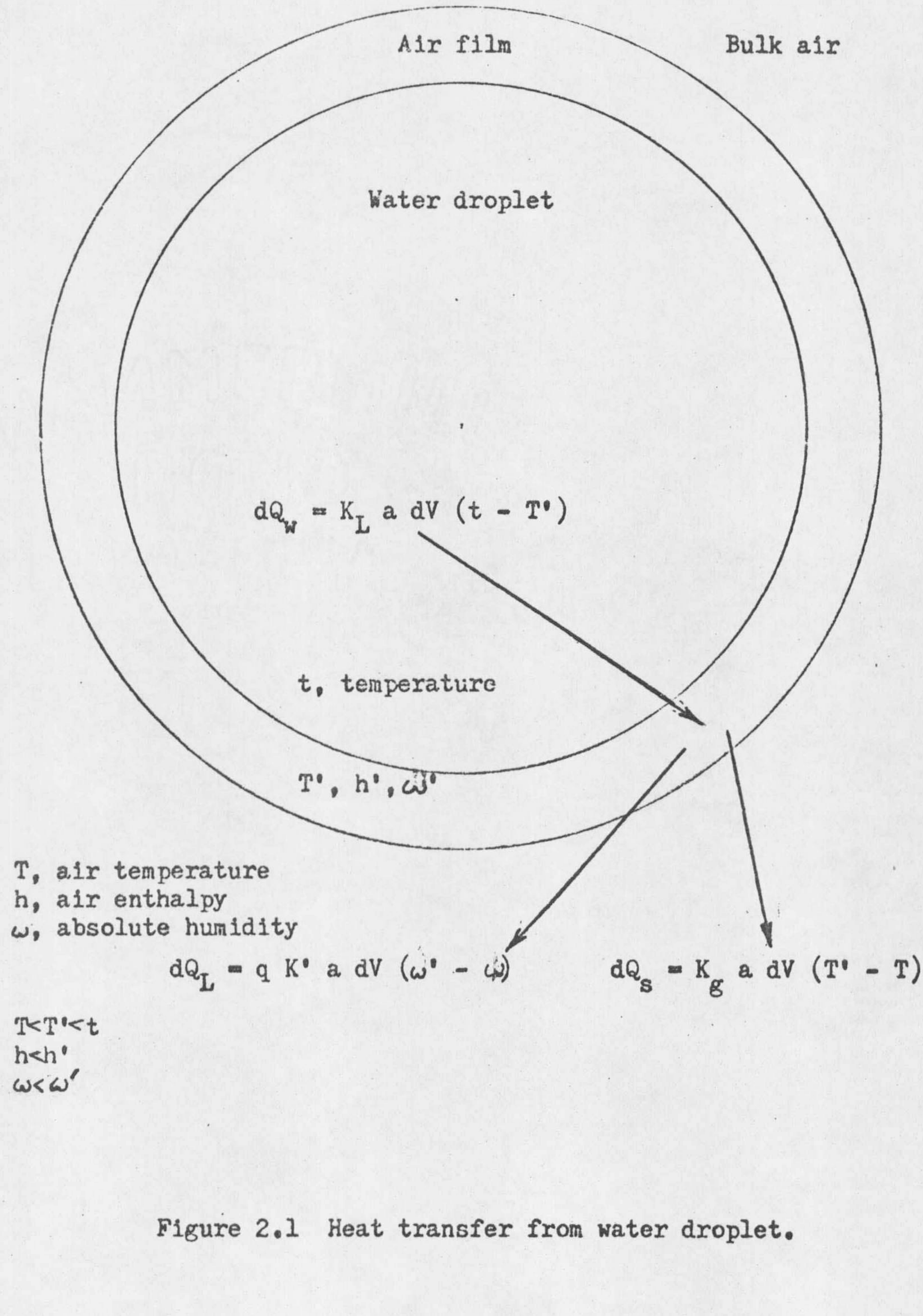

Figure 2.1 Heat transfer from water droplet.

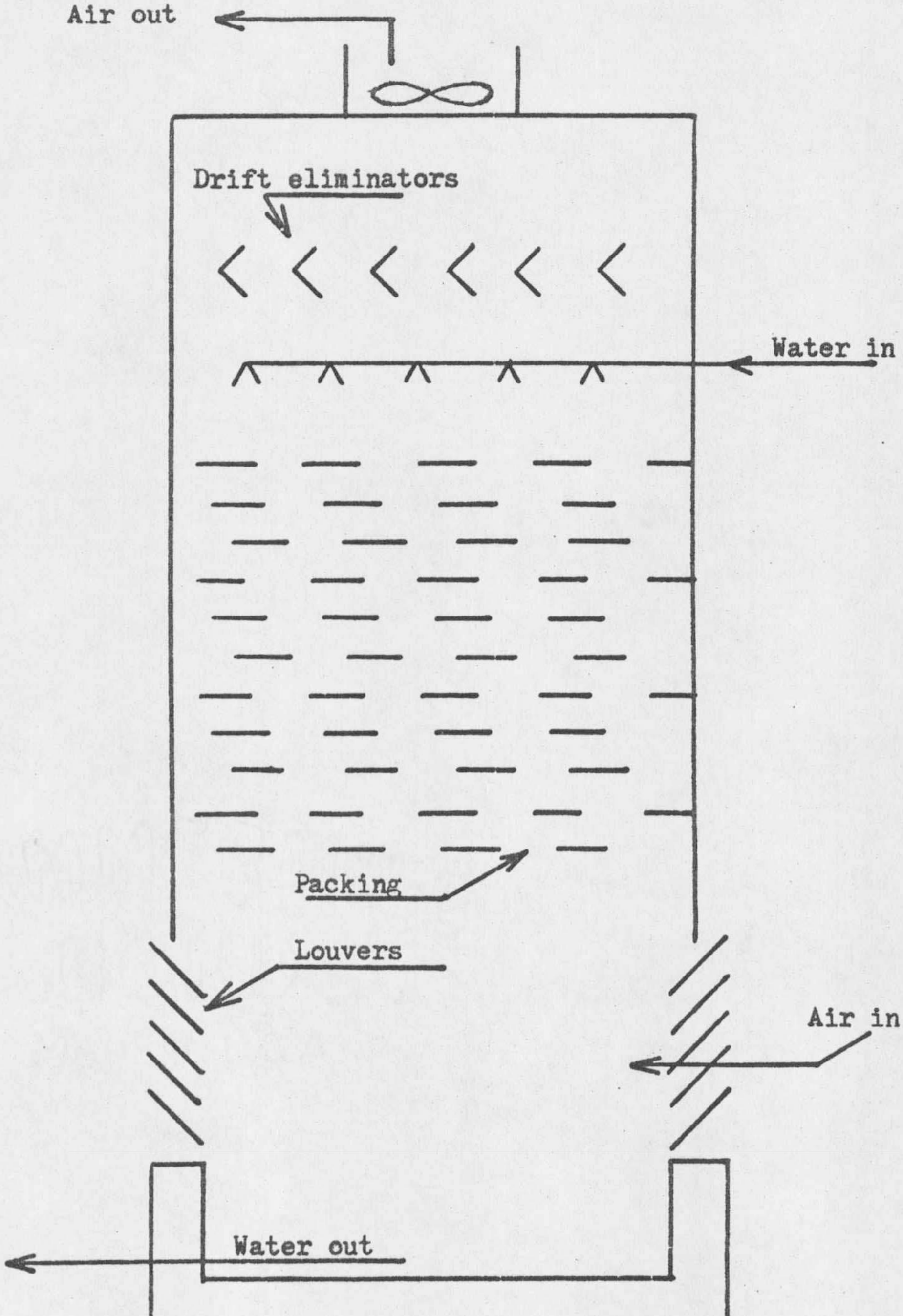

Figure 2.2 Counterflow induced-draft tower draws air directly counter to the water flow.

Rate Equations

The total heat transfer from the water to the interfacial film is

$$dQ_w = L\ dt = K_L\ a\ dV\ (t - T') \tag{2.1}$$

The rate equation for the sensible heat from the interfacial air to the main air stream is

$$dQ_s = K_g\ a\ dV\ (T' - T) \tag{2.2}$$

The mass transfer from the film to the air is of the form

$$dm = K'\ a\ dV\ (\omega' - \omega) \tag{2.3}$$

Let q = latent heat of evaporation, and the rate equation for the latent heat transfer becomes

$$dQ_L = q dm = q\ k'\ a\ dV\ (\omega' - \omega) \tag{2.4}$$

Mass and Energy Balances

The rate of mass leaving the water equals the rate of humidity increase in the air

$$dm = G\ d\omega \tag{2.5}$$

The heat lost by the water equals the heat gained by the air

$$G\ dh = L\ dt \tag{2.6}$$

The enthaply of moist air per pound mass of dry air is

$$h = C_{pa}(T-T_o) + \omega\,[q + C_{pv}(T-T_o)] \tag{2.7}$$