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NOMENECLATURE

Symbol	Description
A	Body surface area, m^2
$\vec{A}_j$	The j face area vector, m^2
c_p	Specific heat of fluid, kJ/kgK
$D_{i,m}$	Diffusion coefficient for species i, m^2/s
D_t	Turbulent diffusivity, m^2/s
G_b	Generation of turbulence kinetic energy due to buoyancy, kg/m s^3
g_i	The component of the gravitational vector in the i^{th} direction, m/ s^2
I	Intensity of fluctuation
J_i	The diffusion flux of species, kg/m s
K	Kinetic energy of turbulence, m^2/s^2
K_t	Turbulent thermal conductivity
l	Length scale of Turbulence, m
M_t	Turbulent Mach number
Pr_t	Turbulent Prandtl number for energy
R_i	Net rate of production of species *i* by chemical reaction, kg/m^3s
S_i	Rate of creation of species
Sc	Molecular Schmidt number
Sc_t	Turbulent Schmidt number
$S\varphi$	Source term of the general form of conservation equation
$\boldsymbol{u}_i$	Fluctuating velocity component, m/s
$\boldsymbol{u}_i$	Mean velocity component, m/s
$\vec{u}$	Flow velocity vector, m/s

GREEK LETTERS

ρ	Density of the fluid, kg/m^3
τ_{ij}	The stress tensor, N/ m^2
τ_{ij}	The strain tensor , N/ m^2
ε_{ij}	Kronecker delta
μ_{eff}	Effective turbulent viscosity
$\Gamma\varphi$	The diffusion coefficient
μ_t	Turbulent viscosity, kg.m/s
ϵ	Turbulence dissipation rate, m^2/s^3
β	Coefficient of thermal expansion, K^{-1}
δV_j	The volume swept out by the control volume face j, m^3
Φ_f	Value of Φ convected through face *f*
$\nabla\Phi$	Gradient of Φ
λ	Molecular mean free path factor
σ_ϵ	Turbulent Prandtl numbers for ϵ
σ_K	Turbulent Prandtl numbers for k
$-\rho\overline{u_i u_j}$	Reynolds stresses term
ψ	Gaussian random number

ABBREVIATIONS

ACC	Air Cooled Condenser
ACHE	Air Cooled Heat Exchanger
CFD	Computational Fluid Dynamics
CT	Cooling Tower
CV	Control volume
DCP	District Cooling Plant
ERR	Exhaust Recirculation Ratio
FDCT	Forced Draft Cooling Tower
FDDCT	Forced Draft Dry Cooling Tower
FDWCT	Forced Draft Wet Cooling Tower
H_2O	Water Vapor
HVAC	Heating Ventilation and Air Conditioning
IDAC	Indirect Air Cooled
LES	Large Eddy Simulation
MDCT	Mechanical Draft Cooling Tower
NDCT	Natural Draft Cooling Tower
NDCWCT	Natural Draft Counter Flow Cooling Tower
NDDCT	Natural Draft Dry Cooling Tower
NDWCT	Natural Draft Wet Cooling Tower
NTU	Number of Transfer Units
Pa	Pascals
PISO	Pressure-Implicit with Splitting of Operators
PIV	Particle Image Velocimetry
PPS	Power Plant Structure
RANS	Reynolds-Averaged Navier-Stokes
RH	Relative Humidity
RNG	Re-Normalization Group
RSM	Reynolds Stress Model
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
W	Watt

ABSTRACT

Cooling Towers are one of the main components utilized in numerous major processes applications; any decrease in the cooling tower performance highly affects the main process. One of the major causes of deficiency is the recirculation of hot humid air from the cooling tower outlet back into the cooling tower air intake.

As recirculation occurs, the average entering wet bulb temperature at the intake of cooling tower increases and results in efficiency loss at the cooling towers and accordingly the associated process equipment up to the limit that it might causes malfunction of the equipment.

This study utilized computational fluid dynamics (CFD) to investigate numerically the effect of wind direction, wind velocity, intake louver location and cooling towers roof arrangement on cooling towers recirculation.

The numerical modeling was performed using computational fluid dynamics (CFD) simulations using CFD software ANSYS 16.0.

A geometry of a district cooling plant where large number of cooling towers utilized, was constructed and enclosed in a larger domain through which wind was introduced. Two rows of cooling towers were considered in the model.

The CFD modeling solved the continuity, species, energy and momentum equations in addition to Large Eddy Simulations (LES) equations for turbulence model, which was selected based on previous findings.

The wind profile was introduced into software via a user defined function to provide more realistic wind simulation.

It is observed during the study that the recirculation rate initially increases as the wind speed increases and then tends to decrease as wind speed increases further.

This study represents a parametric study on recirculation at different winds speeds, direction, architectural enclosure louvers location, fan stack heights and exit velocities. The numerical simulations have been carried out and the output results have been compared and analyzed. It was concluded that the recirculation is minimized when the wind direction is parallel to the towers configuration. The rate is also reduced by locating the architectural enclosure louvers higher than cooling towers intake. It was also concluded that increasing the exit fan velocity slightly decreases the recirculation rate.

CHAPTER 1

INTRODUCTION

1.1 Background

Cooling towers have been widely used, being a low cost and efficient equipment which delivers the required cooling with low consumed energy. They operate by the principle of evaporative cooling, to remove the undesirable heat from a running process.

After installation, cooling tower should be well maintained and operated efficiently. Performance should be monitored especially recirculation which has a major effect on cooling tower performance. Prevailing wind is considered a major factor from the factors that affects cooling towers recirculation.

Recently computational Fluid Dynamics (CFD) has become a powerful tool in predicting the performance of cooling towers at difference arrangements and wind conditions.

1.2 Types of Cooling Towers

Cooling towers have various designs, among which cooling towers type, materials and size is selected to reject the heat from the served process. The selection process is based on the best performance according to the operating conditions for a specific industrial process.

1.2.1 Classification according to air flow driving force

According to the air flow driving force, the cooling towers are classified as follows:

1.2.1.1 Atmospheric/ Natural draft towers

Atmospheric towers utilize natural induction produced by pressurized spray of water distribution system. These types are used in processes having small heat loads and not requiring precise or reliable cold water temperature as they are very susceptible to performance degradation due to wind conditions.

On the contrary, the hyperbolic natural draft tower thermal performance is very precise and reliable. These towers operation rely on the air flow movement produced by density difference due to the difference between warm air inside that stack and the relatively cooler ambient air outside the tower. This type of towers has a remarkably large size and sometimes exceed 150 m of height.

1.2.1.2 Mechanical draft towers

Mechanical draft towers utilize fans to produce the required air volume movement through the tower, hence they have the ability of changing the air flow rate to cater for different operating conditions either by changing the fans rotation speed or even turning it off in part load conditions. As the performance is affected by fewer psychrometric variables, it has better stability compared to atmospheric towers.

Mechanical draft towers are categorized as follows:

Forced draft Towers:

This is the type of towers where the air stream is forced to enter the tower by a fan installed at the entrance of the cooling tower which blows the air through it.

Forced draft towers have high inlet velocities and low exhaust velocities, consequently it is tremendously vulnerable to recirculation, and thus it has more stability issues compared to induced draft. Also, in very cold regions it is susceptible to icing problems as the fan is facing the cold entering air stream.

Usually, forced draft towers use centrifugal blowers, which has the advantage of high static pressures compared to propeller type, allowing towers to be installed indoors having ducted exhaust providing more separation between the intake and exhaust air streams minimizing recirculation.

Induced Draft towers

This is the type of towers where the air stream is induced through the tower due to the negative pressure inside the tower produced by a fan installed at the cooling tower air stream exit.

Exit air velocity ranges from 3 to 4 times higher than air entrance velocity, which provides a very small potential for self-initiated recirculation, and thus recirculation can be quantified on the basis of wind conditions. As the fan is located at the cooling tower warm air stream exit, it is less prone to ice formation problems. [1]

Hybrid draft towers

Hybrid draft towers are referred to as fan assisted natural draft towers. They are similar to natural draft towers but having shorter stacks and internally installed fans to enhance the air flow.

Their design is based on a compromise between fans required horse power and stack cost impact. When properly designed, fan will be required to operate only during high ambient and peak conditions.

This type is also a good choice in locations where low discharge level of tower plume is not permitted.

1.2.2 Classification according to Air Flow

According to relative air and water flow relationship inside the tower, cooling towers are classified as follows:

1.2.2.1 Counterflow towers:

In counterflow towers, air movement direction is vertically upward which counters the direction of downwards water flow. In small sizes, towers are typically higher and require more pumping head and larger fan power compared to crossflow towers. However, in larger towers the use of low pressure gravity distributions systems the comparison tends to equalize or even reverse.

1.2.2.2 Crossflow towers:

In crossflow towers air movement direction is horizontally which is across the downwards flow of water. It utilizes gravity low pressure water distribution is system, which has the advantage of easy maintenance.

1.2.2.3 Spray-fill towers

Spray-fill towers, are towers with no fill and hence it relies only upon the water atomization to maximize the water to air contact. It is used in applications where excessive contaminants or solids would affect the heat transfer surface.

1.2.3 Classification by Construction

1.2.3.1 Field-erected towers

The towers are constructed at the site. Usually, large towers are field erected.

1.2.3.2 Factory assembled towers

The towers are completely assembled at the factory and might be divided into sections according to shipping requirements. Usually, small towers cells or modules are assembled at the factory and installation and connections are performed at the site.

1.3 Factors Affecting Cooling Towers Performance

The following are main factors which affects cooling towers performance.

1.3.1 Wet-Bulb Temperature

The entering air wet bulb temperature is the basis of design of evaporative cooling towers. Proper determination of cooling towers entering wet bulb temperature is crucial to select the cooling towers which provides the required performance.

During cooling towers operation, the entering air wet bulb temperature is increased over the ambient due to mixture of the recirculation of the hot humid air from the cooling tower discharge with the ambient air entering the cooling tower. The amount of wet bulb increase is directly proportional the amount of recirculation.

Special care must be taken when providing the installation location ambient wet bulb temperature to the cooling tower manufacturer, as it might be higher than the values indicated in the location weather database due to recirculation effect. An increase of 1°C (1.8°F) would increase the cold water temperature by 1°C (1.8°F) as indicated in Figure 1.1, which shows the relationship between wet bulb and cooling tower supply temperature.

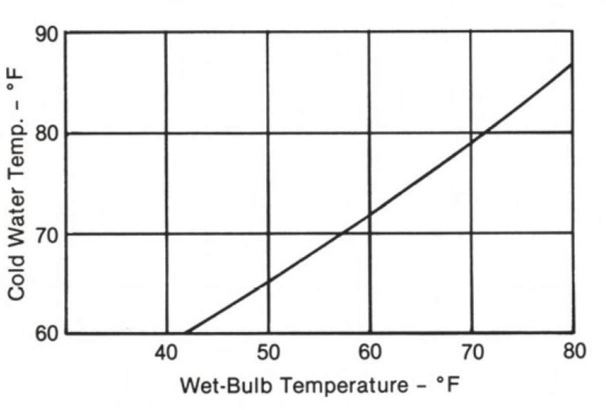

Figure 1.1: Relation between wet bulb and cooling tower supply temperatures. [1]

1.3.2 Recirculation

As illustrated in Figure 1.2, recirculation is the mixture of air flowing into the cooling tower with a percentage of moist air which is exhausted from the cooling tower. The mixing leads to an increase in the wet bulb temperature of the air entering the cooling tower, resulting in a reduction to cooling tower performance. An increase of a two degree Fahrenheit (1.1°C), results in capacity reduction up to 16%. Further elevation of the wet bulb temperature entering the tower up to 3°C can lead to capacity reduction of more than 50%. [2]

A recirculation allowance up to 1.1°C is recommended for cooling towers design wet bulb temperature. [3]

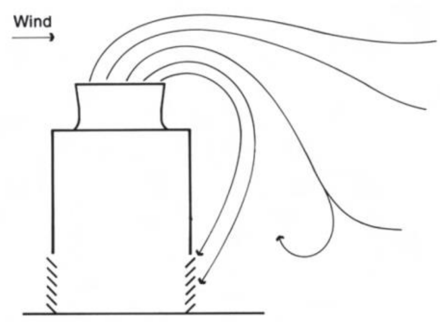

Figure 1.2: Cooling Tower recirculation

1.3.3 Interference

Interference phenomena is the elevation of cooling tower entering air wet bulb temperature due to other local heat sources upwind of the cooling towers. If cooling tower will be installed such that other existing cooling towers installations are located upwind the new towers, a portion of saturated discharge of the upwind tower mix with ambient air of the downwind tower. Figure 1.3 illustrates the interference phenomena.