MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY (MIST)

EXPERIMENTAL INVESTIGATION ON COUNTER-FLOW INDUCED DRAFT COOLING TOWER AND PERFORMANCE ANALYSIS

A thesis submitted to the Department of Mechanical Engineering, Military Institute of Science and technology, Dhaka, in January, 2017 in partial fulfillment of the requirements for the degree of Bachelor of Science in Mechanical Engineering.

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STUDENT DECLARATION

This is to certify that the thesis entitled, **"EXPERIMENTAL INVESTIGATION ON COUNTER-FLOW INDUCED DRAFT COOLING TOWER AND PERFORMANCE ANALYSIS"** is an outcome of the investigation carried out by the author under the supervision of **Maj. Md Altab Hossain, PhD,** Department of Nuclear Science & Engineering, MIST. This thesis or any part of it has not been submitted to elsewhere for the award of any other degree or diploma or other similar title or prize.

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I wish their ever success in life.

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ABSTRACT

Cooled water is necessary for air conditioners, manufacturing processes, power generation and many other purposes. Cooling tower is an equipment used to reduce the temperature of water by extracting heat from water and emitting it to the atmosphere. Cooling towers are able to lower the water temperatures more than other devices that use only air to reject heat, like the radiator in a car and are therefore more cost-effective and energy efficient. In the past most of the processes requiring cooling used piped town water through the equipment. After cooling the equipment the water was drained to the gutter. So, the water was totally wasted after using it once. Cooling towers were introduced so that the wastage of water can be reduced by recycling the water. Cooling towers make use of evaporation. Some of the water is evaporated into a moving air stream and subsequently discharged into the atmosphere. The evaporation process only takes place on the surface of a liquid and needs latent heat of vaporization to happen. Sensible heat is drawn from the body of the water to the surface to supply the energy needed for the latent heat. It can be seen that for a little evaporation a lot of sensible heat will be needed therefore the main body of the circulating water is cooled for very little loss of water.

The main purpose of this study is to work on developing mathematical model for cooling tower and examine methodically the performance of a model of closed loop 10 RT counter flow induced draft bottle type cooling tower which has been developed only for this project purpose.

A detailed mathematical model for a counter flow induced draft cooling tower has been developed using Merkel Theory. Dr. Merkel developed a cooling tower theory for the mass and sensible heat transfer between the air and water in counter flow cooling tower. Several experiments has been conducted by changing the L/G (L= water flow rate; G= air mass flow rate) ratio with the help of changing the flow rate (L) of water to observe the behavior of different characteristics, represented in graphical form. Tower characteristics graph has been plotted at 90%, 100% and 110% water flow rate. The performance prediction of cooling tower related with the performance curves by means of the simple method is made by a few design parameters as well as water flow rate, L/G, KaV/L (Tower Demand), range, cold water temperature, wet bulb temperature, and fan BHP. The performance prediction by the detail method is requiring all the actual cooling tower dimensions, thermal rating conditions, and all the mechanical rating conditions. Calculation of pump selection for the circuit has been shown.

The efficiency obtained from the experiment we have conducted varies from 35% to 45% which indicates the good performance of the system we have developed.

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Nomenclature:

Symbol	Meaning
T_1	Inlet dry bulb temperature
T_2	Inlet wet bulb temperature
T_3	Outlet dry bulb temperature
T_4	Outlet wet bulb temperature
T_5	Inlet water temperature
T_6	Outlet water temperature
L	water flow rate
G	air flow rate
NTU	Tower demand
H_{a1}	Air enthalpy at inlet
H_{a2}	Air enthalpy at outlet

Chapter 01

Introduction

1.1 Background of study

A cooling tower is a device used to reduce the temperature of water. The water is then recycled back into many process and industries that use it. Common applications include cooling the circulating water used in oil refineries, petrochemical and other chemical plants, thermal power stations and HVAC(heating, ventilation and air conditioning) systems for cooling buildings.

Industries use numerous machines and instruments that produce a lot of heat. The heat must be removed otherwise the system will collapse due to overheating. Production will be hampered and machineries will face an irreparable damaged causing the industry a great amount of loss. So, cooling tower is an extremely vital part of any industry. The smallest cooling towers are designed to handle water streams of only a few gallons of water per minute supplied in small pipes like those might be seen in a residence, while the largest cool hundreds of thousands of gallons per minute. Power plants use larger cooling towers. Thermoelectric power plants boil water to create steam, which then spins turbines to generate electricity. The heat used to boil water can come from burning of a fuel, from nuclear reactions, or directly from the sun or geothermal heat sources underground. Once steam has passed through a turbine, it must be cooled back into water before it can be reused to produce more electricity. Colder water cools the steam more effectively and allows more efficient electricity generation. In power plants wet-recirculating or closed-loop systems reuse cooling water in a second cycle rather than immediately discharging it back to the original water source. Most commonly, wet-recirculating systems use cooling towers to expose water to ambient air. Some of the water evaporates; the rest is then sent back to the condenser in the power plant. An HVAC (heating, ventilating, and air conditioning) cooling tower is used to dispose of ("reject") unwanted heat from a chiller. Water-cooled chillers are normally more energy efficient than air-cooled chillers due to heat rejection to tower water at or near wet-bulb temperatures. Air-cooled chillers must reject heat at the higher dry-bulb temperature, and thus obtain lower average reverse-Carnot cycle effectiveness. In areas with a hot climate, large office buildings, hospitals, and schools typically use one or more cooling towers as part of their air conditioning systems. Generally, industrial cooling towers are much larger than HVAC towers.

Cooling towers are designed and manufactured in several types, with numerous sizes available in each type. Not all types are suitable for application to every heat load configuration. There are atmospheric towers which utilize no mechanical device to create airflow through the tower. There are also mechanical draft towers which use either single or multiple fans to provide flow of known volume of air through the tower. Mechanical draft towers are categorized as either forced draft on which the fan is located in the ambient air stream entering the tower and the air is blown through or induced draft where a fan is located in the exiting air stream that draws air through the tower. In a counter-flow cooling tower air travels upward through the fill or tube bundles, opposite to the downward motion of the water. In case of cross-flow cooling tower air moves horizontally through the fill as the water moves downward.

If cooled water is returned from the cooling tower to be reused, some water must be added to replace, or make-up, the portion of the flow that evaporates. Because evaporation consists of pure water, the concentration of dissolved minerals and other solids in circulating water will tend to increase unless some means of dissolved-solids control, such as blow-down, is provided. Some water is also lost by droplets being carried out with the exhaust air (drift), but this is typically reduced to a very small amount by installing baffle-like devices, called drift eliminators, to collect the droplets. The make-up amount must equal the total of the evaporation, blow-down, drift, and other water losses such as wind blowout and leakage, to maintain a steady water level.

Evaporation of the circulating water cools the majority of water in cooling tower. A cooling tower takes the heat transfer law 'the greater the exposed surface area, the greater will be the rate of heat transfer. The evaporation process only takes place on the surface of a liquid and needs latent heat of vaporization to happen (2256 kJ/kg). Sensible heat (4.19 kJ/kg K), is drawn from the body of the water to the surface to supply the energy needed for the latent heat. It can be seen that for a little evaporation a lot of sensible heat will be needed therefore the main body of the circulating water is cooled for very little loss of water. Warm to hot water from the cooling process is pumped to the top of the cooling tower and into the sprays where the water is broken up into droplets and distributed over the Fill. The water droplet spreads out as it slides down the Fill creating the surface area necessary for evaporation. The evaporation rate of the water is restricted by the amount of moisture already in the air around it. To maintain evaporation the moistened air must be replaced with dry air, usually by fans blowing air through the tower.

The early investigators of cooling tower theory grappled with the problem presented by the dual transfer of heat and mass. The Merkel theory overcomes this by combining the two into single process based on enthalpy potential. Dr. Merkel developed a cooling tower theory for the mass (evaporation of a small portion of water) and sensible heat transfer between the air and water in a counter flow cooling tower. The theory considers the flow of mass and energy from the bulk water to an interface, and then from the interface to the surrounding air mass. The flow crosses these two boundaries, each offering resistance resulting in gradients in temperature, enthalpy, and humidity ratio. Merkel demonstrated that the total heat transfer is directly proportional to the difference between the enthalpy of saturated air at the water temperature and the enthalpy of air at the point of contact with water.

1.2 Problem statement:

The machines and processes of industry, as well as those devoted to human comfort generate tremendous amount of heat. This heat must be continuously dissipated for effective working. This heat is usually transferred to a cool flowing volume of water but final rejection is always to the atmosphere which is accomplished by some form of heat exchanger. Many of those terminal heat exchangers are not recognized easily as they are known as creeks, rivers, lakes etc. the natural process of evaporation makes them very effective but they are insufficient for their limited surface area and dependence upon random wind. At some point in distant past people began to manipulate artificial breeze and basic concept of cooling tower was unknowingly founded.

1.3 Objectives of thesis:

The main objective of this project was get acquainted with the design, development and parameters of a cooling tower. However, the specific objectives of the study are:

1. To develop mathematical model and design parameter optimization.
2. To develop the induced draft counter flow cooling tower.
3. To investigate the performance of the developed setup experimentally.

1.4 Organization of the thesis:

Chapter one: In this chapter background of study, problem statement, objectives of thesis are discussed.

Chapter two: literature review gives an overview of history, present condition and types of cooling tower

Chapter three: Materials and methodology are described in this chapter. Experimental setup, procedure, mathematical modeling are included in this chapter

Chapter four: Graphical presentation and their result and discussion are shown in this chapter.

Chapter five: Conclusion, limitations of study, and further recommendation are discussed in the chapter.

Chapter 02

Literature Review

2.1 History

Starting in the 1800s, cooling equipment became essential in developing countries; the Industrial revolution affected everything from transportation (steam engines!) to retail manufacturing, and all of this heavy equipment would overheat unless a cooling agent could remove the excess heat.

It started to become really expensive for industrial businesses to use water cooling towers during the 1900s unless they were positioned near a large body of water, like the Atlantic Ocean. The biggest problem simply was that, in the middle of a prairie with no formal irrigation or water systems, factories never knew if they'd have enough clean water to use. Condensers used cool water to condense the steam that was produced by the steam engine's pistons or turbines. This reduced the back pressure of the engine which lead to a reduction in steal and fuel consumption. The water is also re used which increased the power of the steam engines. The downside is that while costs are saved on fuel, the costs to obtain a sufficient amount of water exceeded that. It was more of a problem for land based machines as sea machines did not face this issue.

After further development, other systems began to form by adapting to the environment. Areas with more land used cooling ponds; Areas with a limited supply of water took advantage of municipal water sources while urban areas which lacked space used cooling towers.

The cooling towers were usually placed on building or rooftops that were either utilizing natural airflow or supplied with air through fans. The larger sized cooling towers were built in around the 1920s for usage in a coal fired electrical power station.

2.2 Types of cooling tower:

Cooling towers are designed and manufactured in several types, with numerous sizes (models) available in each type. Not all types are suitable for application to every heat load configuration. Understanding the various types, along with their advantages and limitations, can be of vital importance to the prospective user, and is essential to the full understanding of this text.

2.2.1 Atmospheric towers utilize no mechanical device (fan) to create air flow through the tower. The small atmospheric tower depicted in Figure 2 derives its airflow from the natural induction (aspiration) provided by a pressure-spray type water distribution system. Although relatively inexpensive, they are usually applied only in very small sizes, and are far more affected by adverse wind conditions than are adverse wind conditions than are other types. Their use on process requiring accurate, dependable cold water temperatures is not recommended and as such has become rarely used.

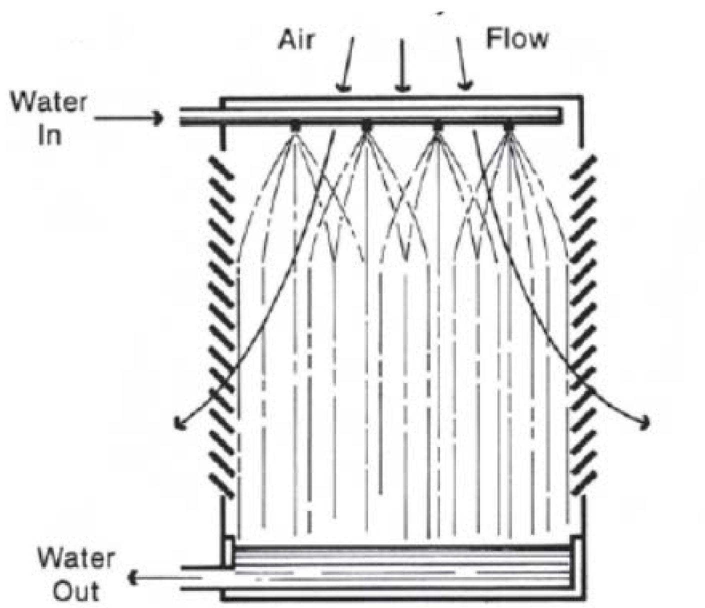


Figure 2.1 – Atmospheric spray tower [1]

Conversely, the atmospheric type known as the hyperbolic natural draft tower is extremely dependable and predictable in its thermal performance. Air flow through this tower is produced by the density differential that exists between the heated (less dense) air inside the stack and the relatively cool (more dense) ambient air outside the tower. Typically, these towers tend to be quite large (250,000 gpm and greater), and occasionally in excess of 500 feet in height. Their name, of course, derives from the geometric shape of the shell.

Although hyperbolic towers are more expensive than other normal types, they are used extensively in the field of electric power generation, where large unified heat loads exist, and where long amortization periods allow sufficient time for the absence of fan power (and mechanical equipment maintenance costs) to recoup the differential cost of the tower. The syn fuels industry also potentially generates heat

Loads warranting consideration of the use of hyperbolic towers. However, because natural draft towers operate most effectively in areas of higher relative e humidity, many such plants located

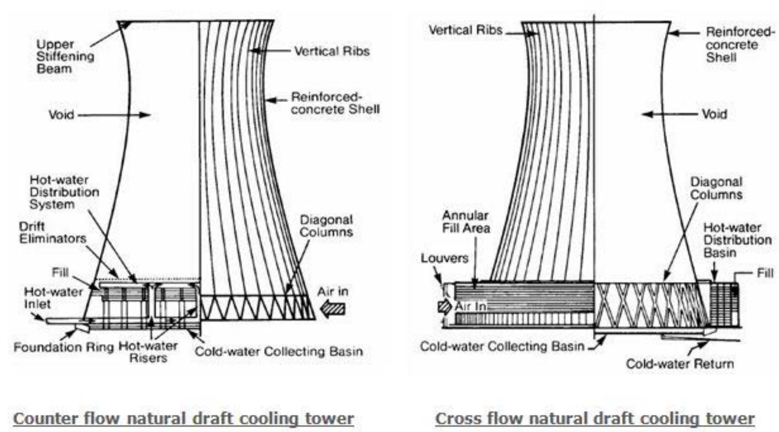


Figure 2.2– Cross flow & counter flow natural draft tower [2]

in arid and/or higher altitude regions find mechanical draft towers more applicable.

2.2.2 Mechanical draft towers use either single or multiple fans to provide flow of a known volume of air through the tower. Thus, their thermal performance tends toward greater stability, and is affected by fewer psychometric variables, than that of the atmospheric towers. The presence of fans also provides a means of regulating air flow, to compensate for changing atmospheric and load conditions, by fan capacity manipulation and/or cycling.

Mechanical draft towers are categorized as either forced draft on which the fan is located in the ambient air stream entering the tower, or the air is blown through; or **induced draft** wherein a fan located in the exiting air stream draws air through the tower.

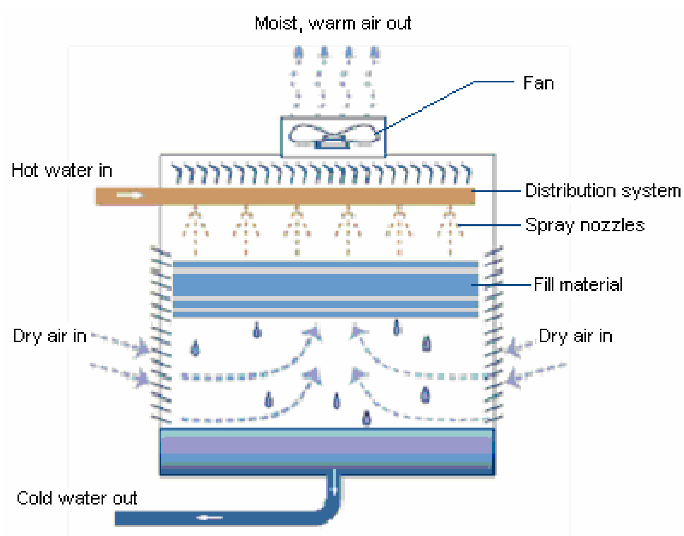


Figure 2.3– Induced draft, counter flow, blower fan tower. [3]

Forced draft towers are characterized by high air entrance velocities and low exit velocities. Accordingly, they are extremely susceptible to recirculation and are therefore considered to have less performance stability than the induced draft. Furthermore, located in the cold entering ambient air stream, forced draft fans can become subject to serve icing (with resultant imbalance) when moving air laden with either natural or recalculated moisture.

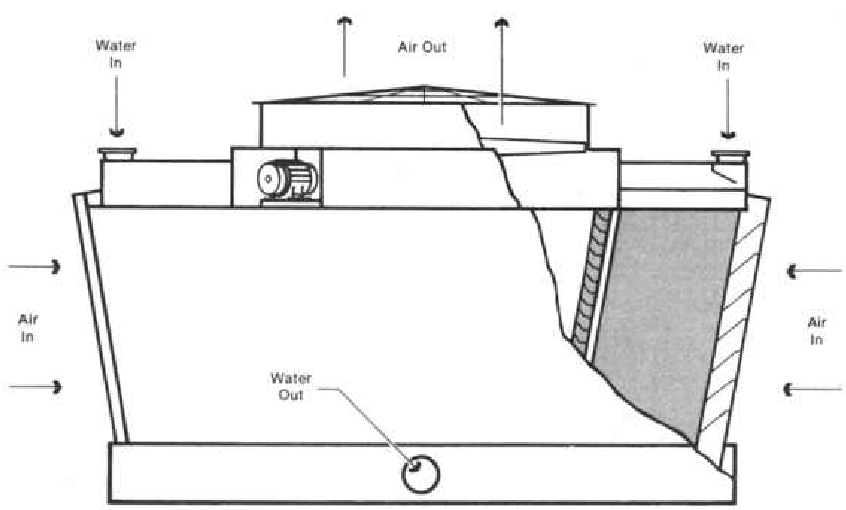


Figure 2.4– Induced draft, cross flow, blower fan tower [4]

Usually, forced draft towers are equipped with centrifugal blower type fans which, although requiring considerably more horsepower than propeller type fans, have the advantage of being able to operate against the high static pressures associated with ductwork. Therefore, they can either be installed indoors (space permitting), or within a specially designed enclosure that provides significant separation between intake and discharge locations to minimize recirculation

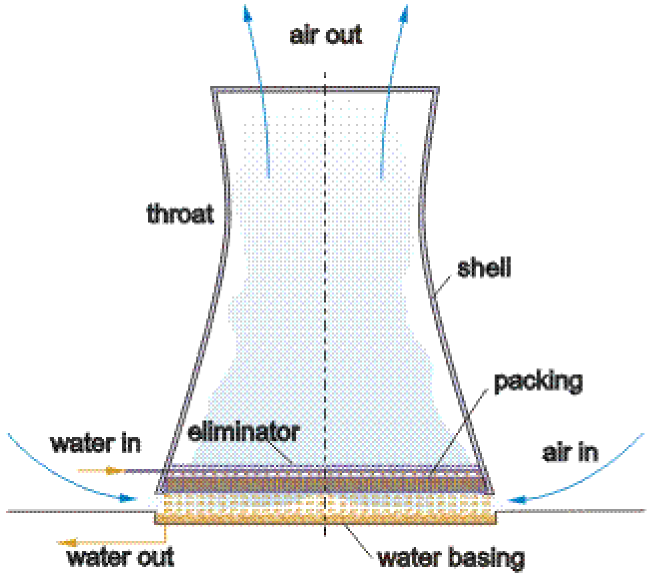


Figure 2.5 – Fan-assisted natural draft tower [5]

Induced draft towers have an air discharge velocity of 3 to 4 times higher than their air entrance velocity, with the entrance velocity approximating that of a 5mph wind. Therefore, there is little or no tendency for a reduced pressure zone to be created at the air inlets by the action of the fan alone. The potential for recirculation on an induced draft tower is not self-initiating and therefore, can be more easily quantified purely on the basis of ambient wind conditions. Location of the fan within the warm air stream provides excellent protection against the formation of ice on the mechanical components. Widespread acceptance of induced draft towers is evidenced by their existence on installations as small as 15 rpm and as large as 700,000 rpm.

Hybrid draft towers can give the outward appearance of being natural draft towers with relatively short stacks. Internal inspection, however, reveals that they are also equipped with mechanical draft fans to augment air flow. Consequently, they are also referred to as fan-assisted natural draft towers. The intent of their design is to minimize the horsepower required for air movement, but to do so with the least possible stack cost impact. Properly designed, the fans may need to be operated of only during periods of high ambient and peak loads. In localities where a low-level discharge of the tower plume may prove to be unacceptable, the elevated discharge of a fan-assisted natural draft tower can become sufficient justification for its use

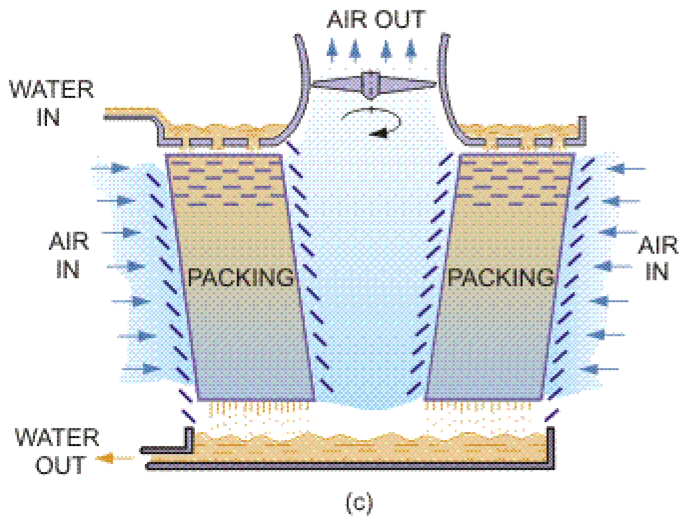


Figure 2.6- Forced draft, counter flow, cooling tower [6]

2.2.3 Characterization by air flow:

Cooling towers are also "typed" by the relative flow relationship of air and water within the tower, as follows:

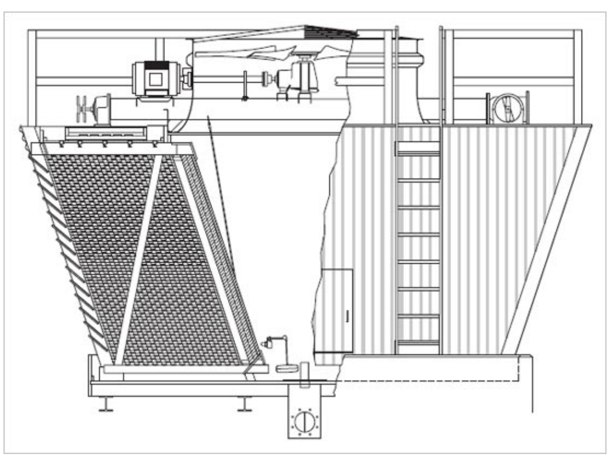


Figure 2.7- induced draft, double flow, counter flow tower [7]

Counter flow: Here, air moves vertically upward through the fill, counter to the downward fall of water. Because of the need for extended intake and discharge plenums, the use of high pressure spray systems; and the typically higher air pressure losses, some of the smaller counter flow towers are physically higher; require more pump head; and utilize more fan power than their cross flow counterparts. In larger counter flow towers, however the use of low-pressure gravity-related distribution systems, plus the availability of generous intake areas and plenum spaces for air management, is tending to equalize, or even reverse, this situation. The enclosed nature of a counter flow tower also restricts exposure of the water to direct sunlight, thereby retarding the growth of algae.

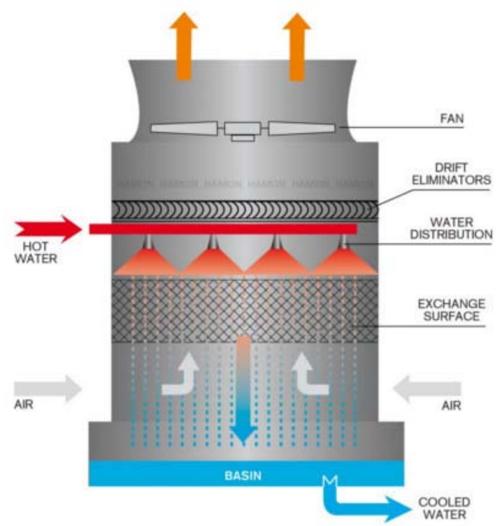


Figure 2.8-induced draft, single flow, counter flow tower [8]

Cross flow towers have a fill configuration through which the air flows horizontally, across the downward fall of water. Water to be cooled is delivered to hot water inlet basins located atop the fill areas, and is distributed to the fill by gravity through metering orifices in the floor of those basins. This obviates the need for a pressure-spray distribution system, and places the resultant gravity system in full view of ease of maintenance. By the proper utilization of flow-control valves (Sect. III-E-2), routine cleaning and maintenance of a cross flow tower's distribution system can be accomplished sectional, while the tower continues to operate.

Figure 2.9- small factory assembled cooling tower [9]

Cross flow towers are also sub-classified by the number of fill "banks" and air inlets that are served by each fan. The tower indicated in figure is a double-flow tower because the fan is inducing air through two inlets and across two banks of fill. Figure 7 depicts a single single-flow tower having only one air inlet and one fill bank, the remaining g three sides of the tower being cased. Single-flow towers are customarily used in locations where an unrestricted air path to the tower is available from only one direction. They are also useful in areas having a dependable prevailing wind direction, where consistent process temperatures are critical. The tower can be sited with the air inlet facing the prevailing wind, and any potential for recirculation is negated by the downside side of the tower being cased face.

Spray-fill towers have no heat transfer (fill) surface, depending only upon the water brake-up afforded by the distribution system to promote maximum water-to-air contact. The atmospheric tower is seen some of the times. Removing the fill from the tower in Figure would also make it “spray-fill”. The use of such towers is normally limited to those processes where higher water temperature is permissible. They are also utilized in those situations where excessive contaminants or solids in the circulating water would jeopardize a normal heat transfer surface.

2.2.4 Characterization by construction

Field-erected towers are those on which the primary construction activity takes place at the site of ultimate use. All large towers, and many of the smaller towers, are prefabricated, piece-marked, and shipped to the site for final assembly. Labour and/or supervision for final assembly is usually provided by the cooling tower manufacturer.

Figure 2.10-multi factory assembled cooling tower [10]

Factory-assembled towers undergo virtually complete assembly at their point of manufacture, whereupon they are shipped to the site in as few sections as the mode of transportation will permit. The relatively small tower is essentially intact. Larger, multi cell towers are assembled as “cells” or “modules” (see Nomenclature) at the factory, and are shipped with appropriate hardware for ultimate joining by the user. Factory-assembled towers are also known as “packaged” or “unitary” tower.

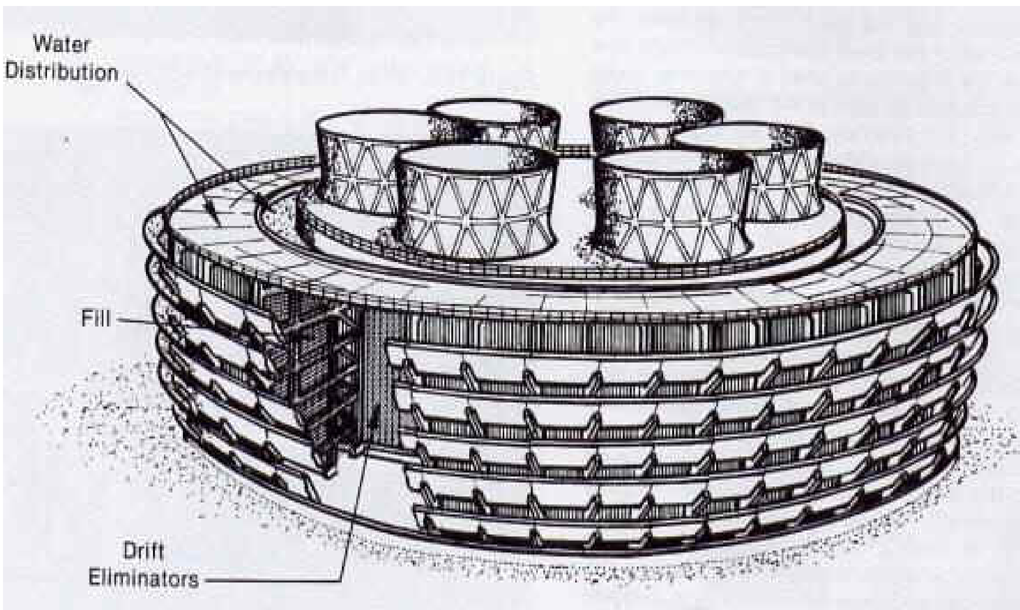


Figure 2.11- round mechanical draft, cross flow cooling tower [11]

2.2.5 Characterization by shape

Rectilinear towers are constructed in cellular fashion, increasing linearly to the length and number of cells necessary to accomplish a specified thermal performance.

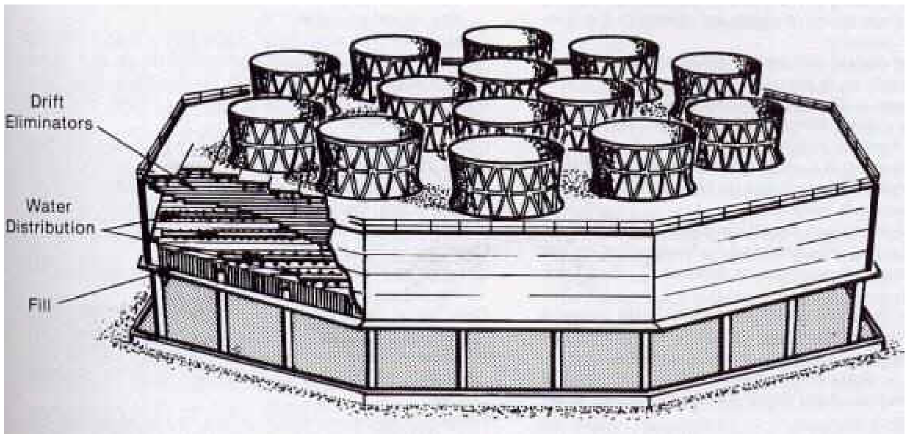


Figure 2.12- octagonal mechanical draft, cross flow cooling tower [12]

Round mechanical Draft ("RMD") towers, as the name implies are essentially round in plan configuration, with fans clustered as close as practicable around the counterpoint of the tower. Multi-faceted towers, such as the Octagonal Mechanical Draft ("OMD") depicted in figure 15, also fall into the general classification of "round" towers. Such towers can handle enormous heat loads with considerably less site area impact than that required by multiple rectilinear towers. In addition to which, they are significantly less affected by recirculation.

2.2.6 Characterization by Method of Heat Transfer

All of the cooling towers heretofore described are evaporative type towers, in that they derive their primary cooling effect from the evaporation that takes place when air and water are brought into direct contact. At the other end of the spectrum is the Dry tower where, by full utilization of dry surface coil sections, no direct contact (and no evaporation) occurs between air and water. Hence the water is cooled totally by sensible heat transfer.

In between these extremes are the Plume Abatement and Water Conservation towers, wherein progressively greater portions of dry surface coil sections are introduced into overall heat transfer system to alleviate specific problems, or to accomplish specific requirements. Dry towers, Plume Abatement, and Water Conservation towers will be discussed in greater depth in Section V of this manual. [13]

Chapter 03

Materials and Methodology

3.1 Experimental Setup and design:

In this section developed experimental setup and parameters will be described.

3.1.1 Design parameters optimization

Dry-bulb temperature (DBT):

The dry-bulb temperature is the temperature indicated by a thermometer exposed to the air in a place sheltered from direct solar radiation.

Wet-bulb temperature (WBT):

The wet-bulb temperature is the temperature a parcel of air would have if it were cooled to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel.

Relative humidity:

The ratio of the vapour pressure of moisture in the sample to the saturation pressure at the dry bulb temperature of the sample is called relative humidity.

Dew point temperature:

The saturation temperature of the moisture present in the sample of air, it can also be defined as the temperature at which the vapor changes into liquid (condensation).

Specific Humidity:

Specific humidity is defined as the proportion of the mass of water vapor per unit mass of the moist air sample (dry air plus the water vapour); it is closely related to humidity ratio and always lower in value.

Absolute humidity:

The mass of water vapour per unit volume of air containing the water vapour is called absolute humidity. This quantity is also known as the water vapour density.

Specific enthalpy:

Specific enthalpy - h - (J/kg, Btu/lb) of moist air is defined as the total enthalpy (J, Btu) of the dry air and the water vapor mixture - per unit mass (kg, lb) of dry air.

Specific volume:

Specific volume indicates the space occupied by air. It is the increase of density and is expressed as a volume per unit weight.

3.1.2 CONSIDERATIONS:

Approach:

For evaporative processes, the difference between the cold water temperature and entering wet bulb temperatures is the approach.

Range:

The temperature difference between inlet and outlet water of cooling tower is normally in the range.

Drift:

Drift is water lost from cooling towers as liquid droplets are entrained in the exhaust air. The drift loss is independent of the water lost by evaporation. Drift eliminators are used to control this drift loss from the tower.

Bleed-off/ blow down:

Cooling tower bleed-off/blow down is the flushing of a portion of high mineral concentration cooling tower system water down the drain, while simultaneously replacing it with fresh water. This process dilutes the system water mineral concentrations that steadily increase due to water evaporation.

Windage:

The water lost from the tower because of the wind is called windage. Sometimes it is called blowout.

Makeup water:

Water added to the circulating water system to replace water lost by evaporation, drift, windage, blow down and leakage.

3.1.3 Circuit design

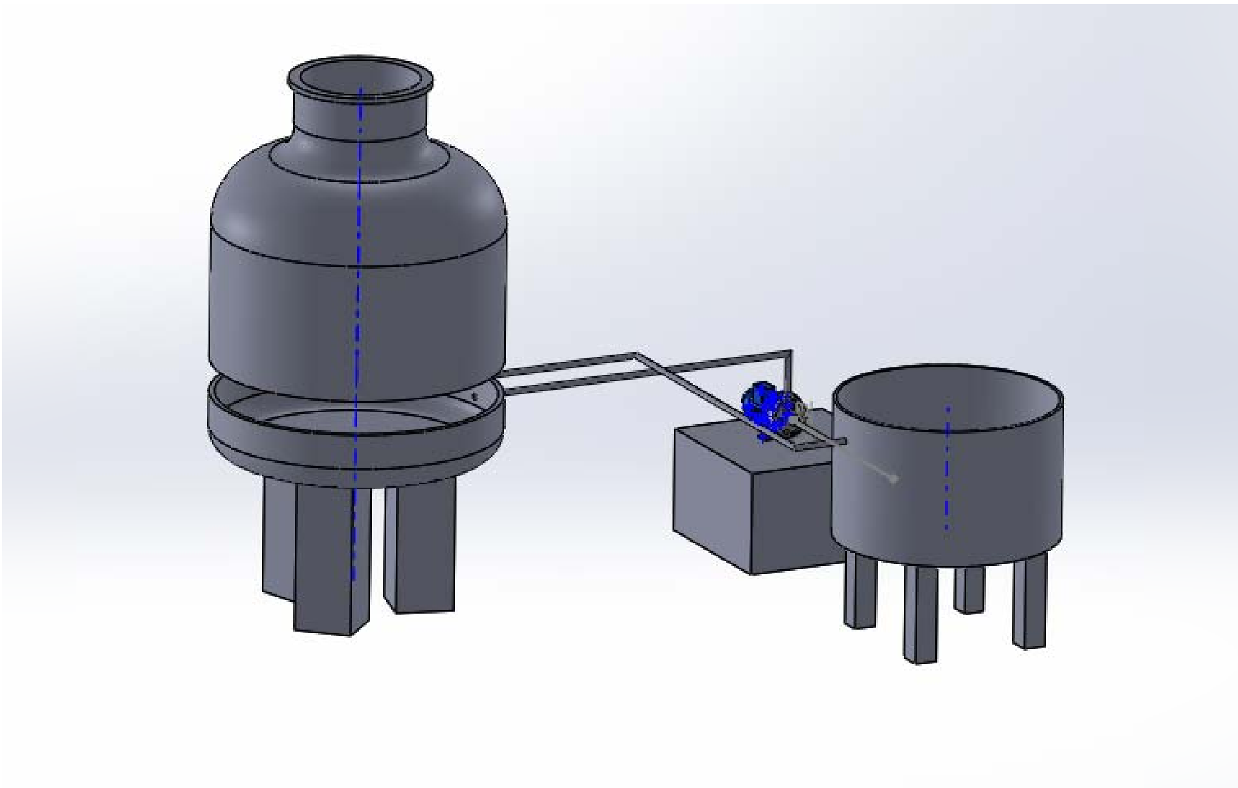


Fig 3.1 : Developed experimental Setup design in solid work

The cooling tower circuit has been designed for performance analysis of counter flow induced draft cooling tower experimentally.

It can also be used lab apparatus. For water supply a reservoir tank is used. It is a closed circuit setup, so water circulates again and again through the setup with some evaporation loss. 01 inch PVC pipe has been used for circuit connection. A pump of 0.5 hp has been used for lifting water, a flow meter with a ball valve has been used for controlling and measuring water flow rate.

Fig 3.2: Developed Experimental setup

3.1.4 Components

COOLING TOWER:

Fig 3.3: Bottled induced draft cooling tower

Manufacturer: Artisan Craft (BD) Ltd

Type: Mechanical Induced Draft Counter Flow Bottle Type Cooling Tower

Model: ART-10

Design and parameters:

- Heat rejection: 44kw
- Water flow rate: 7m3/hr
- Water inlet temperature: 37 ˚C
- Water outlet temperature: 32 ˚C
- Wet bulb temperature: 29 ˚C
- Range temperature: 5 ˚C
- Approach:
- Evaporation loss: 0.83%
- Drift loss: <0.01%
- Make-up water: <1.5%
- Noise level: 70.5 dB (A)
- Inlet water pressure head: 20KPa

Material of construction:

- Basin: FRP
- Casing: FRP
- Access door: NIL
- Fan stack: NIL
- Distribution basin: NIL
- Louver: Al net
- In-fill: PVC
- Eliminator: FRP
- Hardware: H.D.G.S.
- Ladder: H.D.G.S.
- Safety cage: NIL
- Safety guard rail: NIL
- Bolts and nuts: H.D.G.S.

Fan assembly and motor:

- Type of fan: Axial
- Fan diameter: 482mm
- Fan speed: 1440rpm
- No of fan blade: 4
- MOC fan blade: Nylon
- Air flow rate: 5100 m^3/hr
- Motor type: TEFC
- Motor rating: 0.18KW
- Pole no: 4
- Motor rpm: 1440
- Voltage/ Phase/ Hz: 38 V / 3phase / 50Hz
- Ingress protection rating: IP55
- Insulation: Class F

Water distribution system:

- Sprinkler distribution system
- Inlet pipe: DN40
- Outlet pipe: DN40
- Float valve: DN15
- Make up: DN25

- Overflow: DN25
- Drain: DN15

Physical data:

- Diameter: 1050mm
- Height: 1605mm
- Dry weight: 55kg
- Operating weight: 137kg

Pump:

A pump is a device that moves fluids by mechanical action. Centrifugal pumps are used to transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The rotational energy typically comes from an engine or electric motor. The fluid enters the pump impeller along or near to the rotating axis and is accelerated by the impeller, flowing radially outward into a diffuser or volute chamber (casing), from where it exits.

Common uses include water, sewage, petroleum and petrochemical pumping. Centrifugal pumps are the most preferred hydraulic pumps used in domestic and industrial world.

Fig 3.4: Centrifugal pump.

Specifications:

Power : 0 .5 hp

Total head : 30 meter

Static head : 6 meter

Voltage : 220 v

Frequency : 50 hz

Reservoir:

A drum of 24 inch length and 22 inch diameter is used as heating tank.

Pipe:

In this experiment about 20 ft of PVC pipe has been used. The pipes diameter is 1 in.

Ball valve:

A ball valve is a form of quarter-turn valve which uses a hollow, perforated and pivoting ball to control flow through it. It is open when the ball's hole is in line with the flow and closed when it is pivoted 90-degrees by the valve handle.[1] The handle lies flat in alignment with the flow when open, and is perpendicular to it when closed, making for easy visual confirmation of the valve's status.

Ball valves are durable, performing well after many cycles, and reliable, closing securely even after long periods of disuse. These qualities make them an excellent choice for shutoff and control applications, where they are often preferred to gates and globe valves, but they lack their fine control in throttling applications.

The ball valve's ease of operation, repair, and versatility lend it to extensive industrial use, supporting pressures up to 1000 bar and temperatures up to 752 °F (400 °C), depending on design and materials used. Sizes typically range from 0.2 to 48 inches (0.5 cm to 121 cm). Valve bodies are made of metal, plastic, or metal with a ceramic; floating balls are often chrome plated for durability.

Fig 3.5: Ball Valve.

Elbow joint:

3 mild steel elbows have been used

Fig 3.6: Elbow joint.

T joint:

One T joint has been used for the pressure gauge to be set.

Fig 3.7: T joint.

3.1.5 Measuring Devices

Flow meter:

A flow meter is a device used to measure the flow rate or quantity of a gas or liquid moving through a pipe. Flow measurement applications are very diverse and each situation has its own constraints and engineering requirements. Flow meters are referred to by many names, such as flow gauge, flow indicator, liquid meter, etc. depending on the particular industry; however the function, to measure flow, remains the same.

Fig 3.8: Flow meter

Thermocouple:

A Thermocouple is a sensor used to measure temperature. Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where the temperature is measured. When the junction experiences a change in temperature, a voltage is created. The voltage can then be interpreted using thermocouple reference tables to calculate the temperature.

There are many types of thermocouples, each with its own unique characteristics in terms of temperature range, durability, vibration resistance, chemical resistance, and application compatibility. Type J, K, T, & E are “Base Metal” thermocouples, the most common types of thermocouples. Type R, S, and B thermocouples are “Noble Metal” thermocouples, which are used in high temperature applications

Fig 3.9: Thermocouple sensor

Thermocouple controller:

As the name implies, a temperature controller is an instrument used to control temperatures, mainly without extensive operator involvement. A controller in a temperature control system will accept a temperature sensor such as a thermocouple or RTD as input and compare the actual temperature to the desired control temperature, or set point. It will then provide an output to a control element.

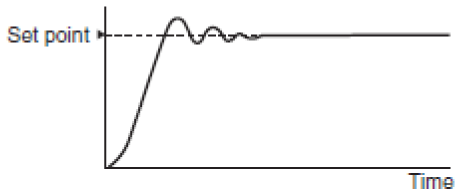
A good example would be an application where the controller takes an input from a temperature sensor and has an output that is connected to a control element such as a heater or fan. The controller is usually just one part of a temperature control system, and the whole system should be analyzed and considered in selecting the proper controller.

Fig 3.10: Temperature Controller.

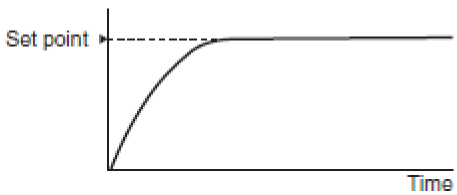
Temperature Control:

Temperature Controllers control temperature so that the process value will be the same as the set point, but the response will differ due to the characteristics of the controlled object and the control method of the Temperature Controller. Typically, a response shown in Figure (2), where the set point is reached as quick as possible without overshooting, is required in a Temperature Controller. There are also cases such as the one shown in Figure (1), where a response quickly increases the temperature even if it overshoots is required, and the one shown in Figure (3), where a response slowly increases the temperature is required.

(1) Response where the process value settles on the set point while repeatedly overshooting and undershooting



(2) Proper response



(3) Response where the process value slowly reaches the set point

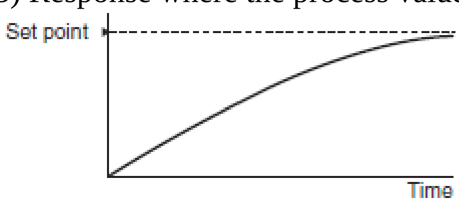


Fig 3.11: Different response in controller

Temperature Control Configuration Example

The following example describes the basic configuration for temperature control.

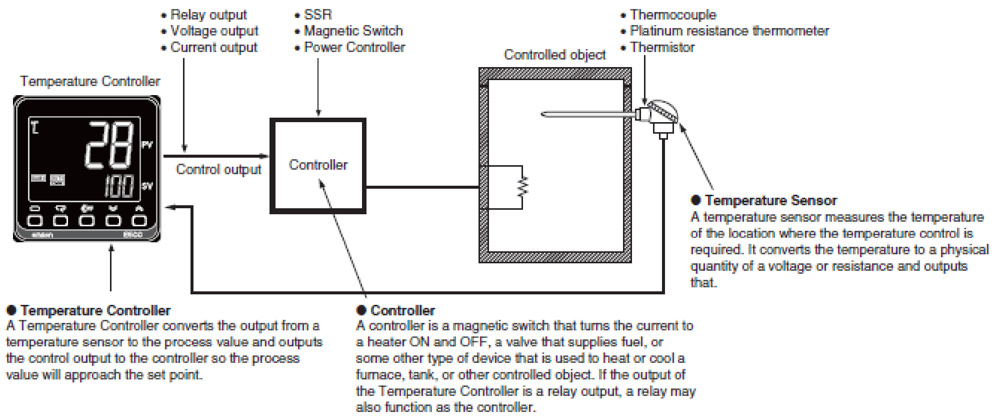


Fig 3.12: Temperature control

Rotary thermocouple selector switch:

Thermocouple selector switch is used for isothermal, low resistance switching of temperature measurement circuits. The selector switches have either silver plated contacts or gold plated contacts. Each style offers 2 to 34 positions in a break-resistant Noryl case. The isothermal design of these rotary switches minimizes temperature gradients between the input and output thermocouple wiring. This in turn minimizes errors in transmitting thermocouple signals due to the generation of a thermal emf at the wire junctions. The low resistance of the silver or gold plated contacts also enables switching of temperature sensitive resistance devices, such as RTDs and thermostats. Two pole SW and OSW series switches have a convenient off position. The off position may be left as an open circuit or shorted to keep spurious signals from registering on thermocouple instruments. Each pole is fully isolated. For quick and easy wiring, the terminals located at the rear of the switch are clearly marked.

Fig 3.13: Rotary thermocouple selector switch.

Anemometer:

An Anemometer or often known as a Wind Speed Meter, measures the wind velocity, which simply means the speed of which the wind travels. The word Anemos means wind and derives from the Greek language. A gentleman named Leon Battista Alberti introduced the first Anemometer as early as 1450, back then Leon most likely used it for his impressive buildings and architectural projects. There are different types of Anemometer and they all measure different features of the wind. The most common Anemometers today measure the wind speed and wind pressure.

A typical Anemometer will look something like a small and compact hand-held device. Some have different fans, which will act as the sensor and some operates using cups. The simplest version is the Cup Anemometer, which is simply operated by three or four cups as a sensor. The cups spin horizontally and the sensor picks up the amount of spins on a set time period to give an accurate reading on the wind speed.

Fig 3.14: Digital Anemometer.

Thermometer:

A thermometer is a device that measures temperature or a temperature gradient. A thermometer has two important elements: (1) a temperature sensor (e.g. the bulb of a mercury-in-glass thermometer) in which some physical change occurs with temperature, and (2) some means of converting this physical change into a numerical value (e.g. the visible scale that is marked on a mercury-in-glass thermometer). Thermometers are widely used in industry to control and regulate processes, in the study of weather, in medicine, and in scientific research.

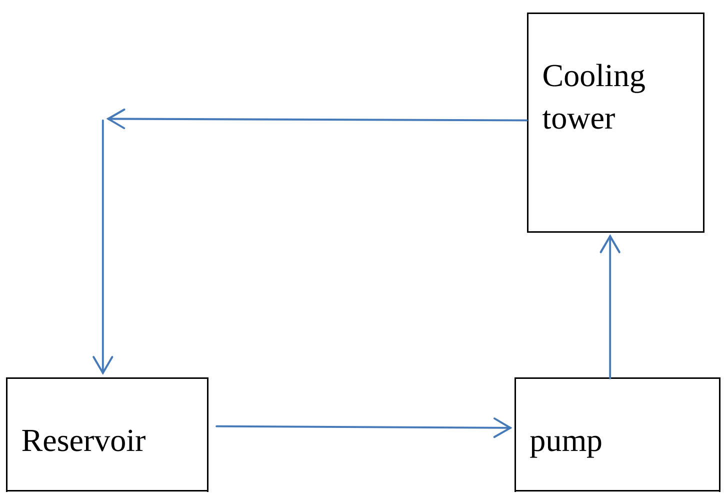
In the study dry bulb temperature and wet bulb temperature of the environment has been measured by thermometer.

Fig 3.15: Thermometer.

3.2 Experimental procedure:

The experimental setup is mainly developed for analyzing the performance of cooling tower. In the setup a reservoir has been used for hot water source. Water has been heated by external heat source. A 0.5 hp pump has been used to suck water from reservoir to cooling tower. Water flow meter has been used to measure the water flow rate and a ball valve has been used to control the flow rate of water. After evaporation the cooled water reserved in the basin flowed through the outlet pipe to the reservoir again. Air velocity has been measured by anemometer. As the cooling tower is a counter flow induced draft bottle type, at inlet air flows through the infill and makes it way to the outlet by a 1 hp fan. Air dry bulb temperature and wet bulb temperature at inlet and outlet has been measured by thermometer. Inlet and outlet temperature of water has been measured by two thermocouples controlled by electric controller. A switch has been used in the controller to measure temperature of inlet and outlet water at a time. When hot water enters into the cooling tower water is sprayed to the infill. Infill transforms the water in small droplets and that's why evaporation takes place easily by inlet air. Inlet air absorbs heat from small droplets of water. Evaporation rate or cooling efficiency depends on relative humidity (RH) of inlet air.

Block Diagram:



3.3 Mathematical Modeling:

Total heat transfer,

$$Q = K \times S \times (h_w - h_a) \tag{3.1}$$

Here, Q = total heat transfer Btu/h, K = overall enthalpy transfer coefficient lb/hr.ft^2, S = heat transfer surface ft^2. S equals to $a \times V$, which "a" means area of transfer surface per unit tower volume. (ft^2/ft^3), and V means an effective tower volume (ft^3), h_w = enthalpy of air-water vapor mixture at the bulk water temperature, Btu/lb dry air, h_a = enthalpy of air water vapor mixture at the wet bulb temperature, Btu/lb dry air

$$dQ = [K \times S \times (h_w - h_a)]$$

$$= K \times (h_w - h_a) \times dS \tag{3.2}$$

Heat transfer rate from water side,

$$Q = c_w \times L \times \text{Range} \tag{3.3}$$

C_w = Specific heat of water [Normally C_w = 1], L = Water flow rate

$$dQ = c_w \times L \times dt_w \tag{3.4}$$

Heat transfer rate from air side,

$$Q = G \times (h_{a_2} - h_{a_1}) \tag{3.5}$$

$$dQ = d[G \times (h_{a_2} - h_{a_1})]$$

$$= G \times dh_a \tag{3.6}$$

Here, G = air mass flow rate

From (2) and (6)

$$K \times (h_w - h_a) \times dS = G \times dh_a$$

$$K \times dS = \frac{G}{h_w - h_a} \times dh_a \tag{3.7}$$

By integration,

$$\frac{KS}{L} = \frac{KaV}{L} = \frac{G}{L}\int_{ha_1}^{ha_2} \frac{dh}{h_w - h_a}$$

$$\frac{KS}{L} = \frac{KaV}{L} = C_w \int_{tw_1}^{tw_2} \frac{dt_w}{h_w - h_a} \tag{3.8}$$

$$\int_a^b ydx = (b-a) \times \frac{(y_1 + y_2 + y_3 + y_4)}{4}$$

Where, y_1 = value of y at $x = a + 0.1 \times (b-a) = CWT + 0.1 \times Range$,

y_2 = value of y at $x = a + 0.4 \times (b-a) = CWT + 0.4 \times Range$

y_3 = value of y at $x = b - 0.4 \times (b-a) or\ x = a + 0.6 \times (b-a) = CWT + 0.6 \times Range$

y_4 = value of y at $x = b - 0.1 \times (b-a)\ or\ x = a + 0.9 \times (b-a) = CWT + 0.9 \times Range$

For the evaporation of $\frac{KaV}{L}$,

$$\frac{KaV}{L} = C_w \int_{tw_1}^{tw_2} \frac{dt_w}{h_w - h_a} = (tw_2 - tw_1) \times \frac{[\left(\frac{1}{Dh_1}\right) + \left(\frac{1}{Dh_2}\right) + \left(\frac{1}{Dh_3}\right) + (\frac{1}{Dh_4})]}{4}$$

Where,

Dh_1 = value of $(h_w - h_a)$ at a temperature of $CWT + 0.1 \times Range$

Dh_2 = value of $(h_w - h_a)$ at a temperature of $CWT + 0.4 \times Range$

Dh_3 = value of $(h_w - h_a)$ at a temperature of $CWT + 0.6 \times Range$

Dh_4 = value of $(h_w - h_a)$ at a temperature of $CWT + 0.9 \times Range$

$HEAT_{in} = HEAT_{out}$

WATER $HEAT_{in}$ + AIR $HEAT_{in}$ = WATER $HEAT_{out}$ + AIR $HEAT_{out}$

$$C_w L_2 tw_2 + Gha_1 = C_w L_1 tw_1 + Gha_2 \qquad (3.9)$$

(The difference between L_2 (entering water flow rate) and L_1 (leaving water flow rate) is aloss of water due to the evaporation in the direct contact of water and air. This evaporation loss is a result of difference in the water vapor content between the inlet air and exit air of cooling tower. Evaporation Loss is expressed in G x (w_2 –w_1) and is equal to $L_2 - L_1$.

Therefore,
$L_1 = L_2 - G(w_2 - w_1)$ (3.10)
Is established.

Finally, the relationship of C_w x L_2x (tw_2– tw_1) = G x (ha_2– ha_1) is established and this canbe expressed to C_w x L x (tw_2– tw_1) = G x (ha_2– ha_1) again. Therefore, the enthalpy of exitair, ha2 = ha1 + C_w x L / G x (tw_2– tw_1) is obtained. The value of specific heat of water isEq. 9 and the term of tw_2 (entering water temperature) – tw_1 (leaving water temperature) is called the cooling range. Simply,

$$ha_2 = ha_1 + \frac{L}{G} \times Range$$

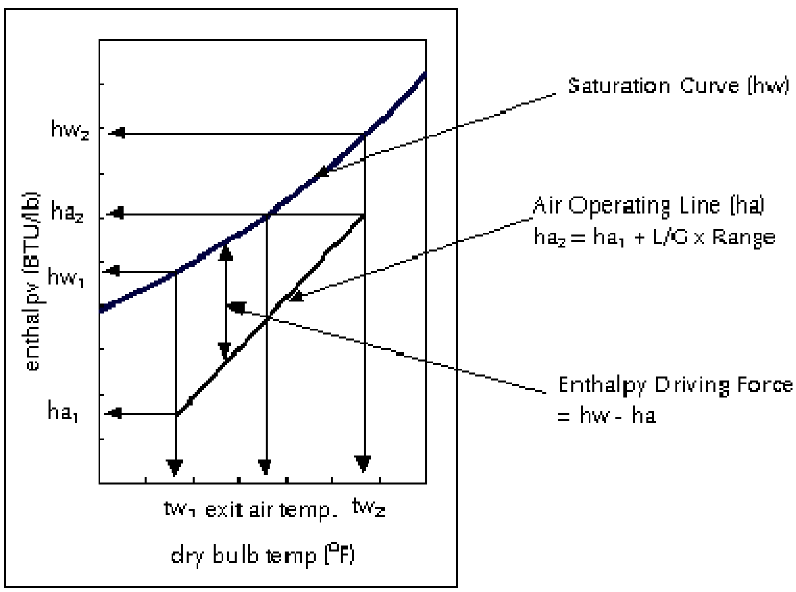


Fig 3.16: Enthalpy Vs DBT graph

NTU (Number if Transfer Unit) Calculation:

$$NTU = \frac{KaV}{L} = C_w \int_{T_2}^{T_1} \frac{dT}{h_w - h_a}$$

$$or \;\; = \frac{G}{L} \int_{ha_1}^{ha_2} \frac{dh_a}{h_w - h_a} \qquad (3.11)$$

The right side of the above equations is obviously dimensionless factor. This can be calculated using only the temperature and flows entering the cooling tower. It is totally independent from the tower size and fill configuration and is often called, for lack of another name, NTU. Plotting several values of NTU as a function of L/G gives what is known as the "Demand" curve. So, NTU is called Tower Demand too.

$$NTU \; or \; \frac{\mathrm{KaV}}{\mathrm{L}} = \text{Cooling Range} \times sum\; of \; \frac{\frac{1}{h_w - h_a}}{4} \qquad (3.12)$$

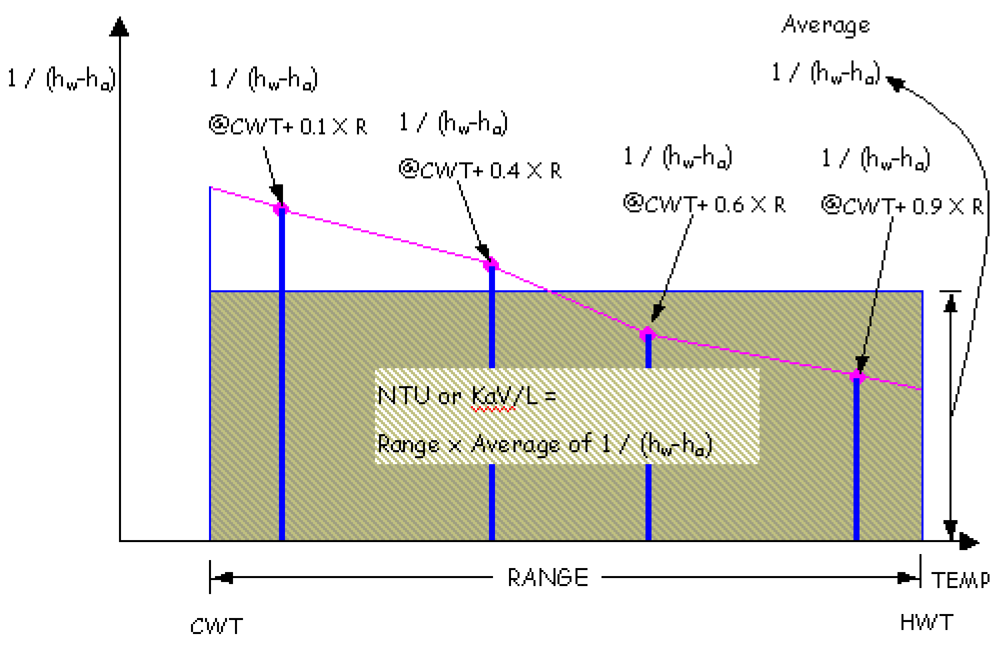


Fig 3.17: The average of 1/ (h w – h a) variation with the cooling range [14].

TOWER DEMAND CURVE:

The Merkel equation is used to calculate the thermal demand based on the design temperature and selected liquid-to-gas ratios (L/G). The value of KaV/L becomes a measure of the order of difficulty for the liquid cooling requirements. The design temperature and L/G relate the thermal demand to the MTD (Mean Temperature Difference) used in any heat transfer problem. The so-called "Brown Book" presented a change in format to a multi-cycle log plot. This format allows the cooling tower characteristic curves to be plotted as straight lines.

With the advent of the computer age the Cooling Tower Institute published the "Blue Book" entitled "Cooling Tower Performance Curves" in 1967. The availability and use of the computer allowed the Performance and Technology Committee to investigate several methods of numerical integration to solve the basic equation. The curves are plotted with the thermal demand, KaV/L as a function of the liquid-to-gas ratio, L/G. The approach lines (t_{w_1}- WBT) are shown as parameters.
The curves contain a set of 821 curves, giving the values of KaV/L for 40 wet bulb temperature, 21 cooling ranges and 35 approaches.

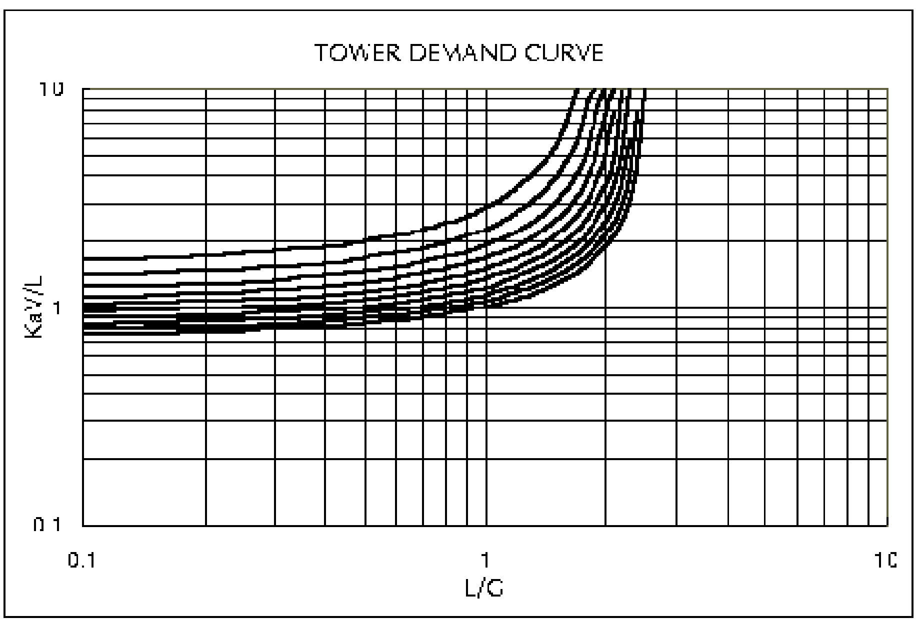


Fig 3.18: NTU Vs L/G

TOWER CHARACTERISTICS CURVE:

An equation form used to analyze the thermal performance capability of a specified cooling tower was required. Currently, the following equation is widely accepted and is a very useful to be able to superimpose on each demand curve, since $\frac{KaV}{L}$ vs. $\frac{L}{G}$ relationship is a linear function on log-log demand curve.

$$\frac{KaV}{L} = C\left(\frac{L}{G}\right)^{-m} \tag{3.13}$$

Where,

$\frac{KaV}{L}$= Tower Characteristic, as determined by Merkel equation

C = Constant related to the cooling tower design, or the intercept of the characteristic curve at $\frac{L}{G}$ = 1.0

m = Exponent related to the cooling tower design (called slope), determined from the test data

The characteristic curve may be determined in one of the following three ways;

(1) If still applicable and available, the vendor supplied characteristic curve may be used. In all cases the slope of this curve can be taken as the slope of the operating curve.

(2) Determine by field testing one characteristic point and draw the characteristic curve through this point parallel to the original characteristic curve, or a line through this point with the proper slope (- 0.5 to - 0.8).

(3) Determine by field testing at least two characteristic points at different L/G ratios. The line through these two points is the characteristic curve. The slope of this line should fall within the expected range, and serves as a check on the accuracy of the measurement.

A characteristic point is experimentally determined by first measuring the wet bulb temperature, air discharge temperature, and cooling water inlet and outlet temperature. The L/G ratio is then calculated as follows;

(1) It may be safely assumed that the air discharge is saturated. Therefore, the air discharge is at its wet bulb. Knowing wet bulb temperature at the inlet of tower, the enthalpy

increase of the air stream can be obtained from a psychometric chart. Air and water flow rates have to be in the proper range for uniform flow distribution. In case of recirculation of the air discharge, the inlet wet bulb may be 1 or 2°F above the atmospheric wet bulb temperature.

(2) From a heat and mass balance the dry air rate and the prevailing L/G ratio in the tower can be calculated [$L/G = D\ ha\ /\ (Cw\ x\ (tw_2 - tw_1))$] Next, the corresponding KaV/L value has to be established. This is simply done by plotting the calculated L/G and approach on the demand curve for the proper wet bulb and range.

Chapter 04

Result and Discussion

Different Characteristics analysis at different temperatures

Obs.	Inlet air					Outlet air					Water		
	Dry bulb temp , ˚C	Wet bulb temp , ˚C	RH %	Specific volume m^3/kg	Specific humidity kg/kg	Dry bulb temp, ˚C	Wet bulb temp, ˚C	RH %	Specific volume m^3/kg	Specific humidity kg/kg	Inlet temp ˚C	Outlet temp ˚C	Water flow rate , L m^3/h
1	23	18	61.8191	.85276	.01085	24.1	22.1	84.2559	.862787	.01593	28	24.5	1.73
2	25	21	70.2486	.86274	.01397	25.9	24.2	87.047939	.871358	.018393	27.9	24.8	1.73
3	22.5	19	72.21637	.853302	.01232	23.7	21.8	84.882313	.861263	.015661	30	26.1	1.73
4	24	22	84.22130	.862356	.015826	24.8	23.1	86.744423	.866450	.017135	28	25.3	1.73
5	26	21.5	67.53306	.866034	.014621	27.1	25.9	90.992112	.878016	.020710	29	26.1	1.73
6	23.5	20.5	76.508598	.858321	.013908	24.5	22.8	86.658578	.865132	.016805	29	25.9	1.73

Table 4.1

CALCULATION:

Theoretical cooling range,

$$R_{th} = T_1 - T_3 \text{ ˚C} \qquad (4.1)$$

Actual cooling range,

$$R_a = T_1 - T_2 \text{ ˚C} \qquad (4.2)$$

Cooling efficiency,

$$\eta = \frac{R_a}{R_{th}} \% \qquad (4.3)$$

Change in specific humidity,

$$\Delta w = w_{a_i} - w_{w_o} \text{ m}^3\text{/kg} \qquad (4.4)$$

$$\text{Make up water} = \Delta w \times \dot{m}_a \text{ m}^3\text{/sec} \qquad (4.5)$$

$$\text{\% of makeup water} = \frac{\Delta w \times \dot{m}_a}{m_w} \times 100 \qquad (4.6)$$

Obs.	Theoretical cooling range R_{th} (˚C)	Actual cooling range R_a (˚C)	Cooling efficiency η %	Change in sp. Humidity Δw (kg/kg)	Make up water (m^3/hr)	% make up water
1	10	3.5	35	5.08×10^{-3}	0.09189	15.896
2	6.9	3.1	44	4.42×10^{-3}	0.07995	13.831
3	11	3.9	35	3.34×10^{-3}	0.06042	10.452
4	6	2.7	45	1.31×10^{-3}	0.02369	4.098
5	7.5	2.9	39	6.09×10^{-3}	0.110168	19.059
6	8.5	3.1	36	2.9×10^{-3}	0.05246	9.075

4.1 Graphical Analysis

4.1.1 Tower performance observation with varying inlet wet bulb temperature

Tower performance curve has been observed with varying inlet wet bulb temperature. Cold water temperature has been increased with the increase in inlet wet bulb temperature.

Tower performance curve:

Cold water temp.	Entering wet bulb
24.5	18
26.1	19
25.9	20.5
24.8	21
26.1	21.5
25.3	22

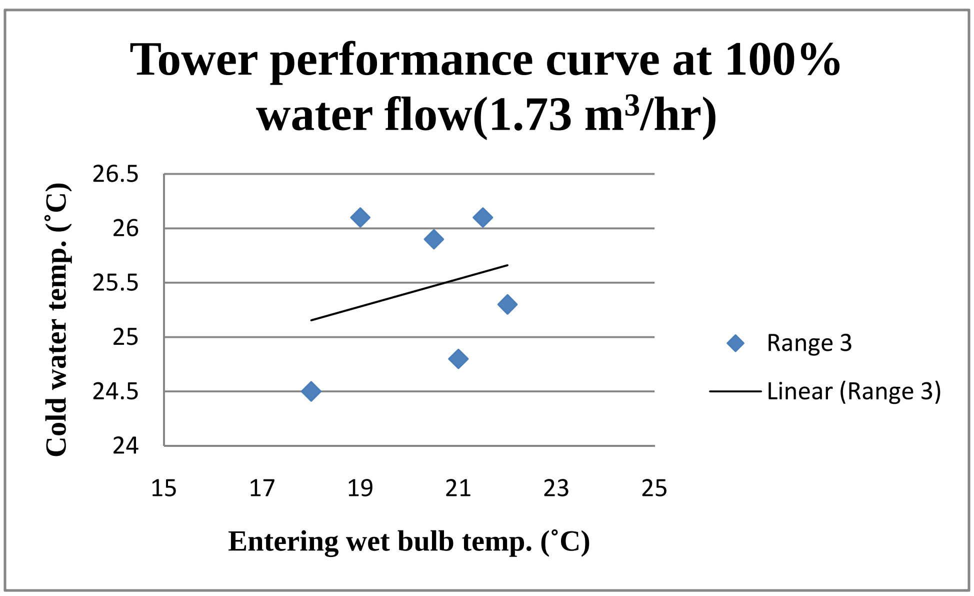


Fig 4.1: Cold water temp. (˚C) vs Inlet wet bulb temp. (˚C) at 1.73 m^3 /hr

Outlet water temp. (˚C)	Entering wet bulb temp. (˚C)
23.6	18
25.3	19
25.2	20.5
24	21
25.5	21.5
24.8	22

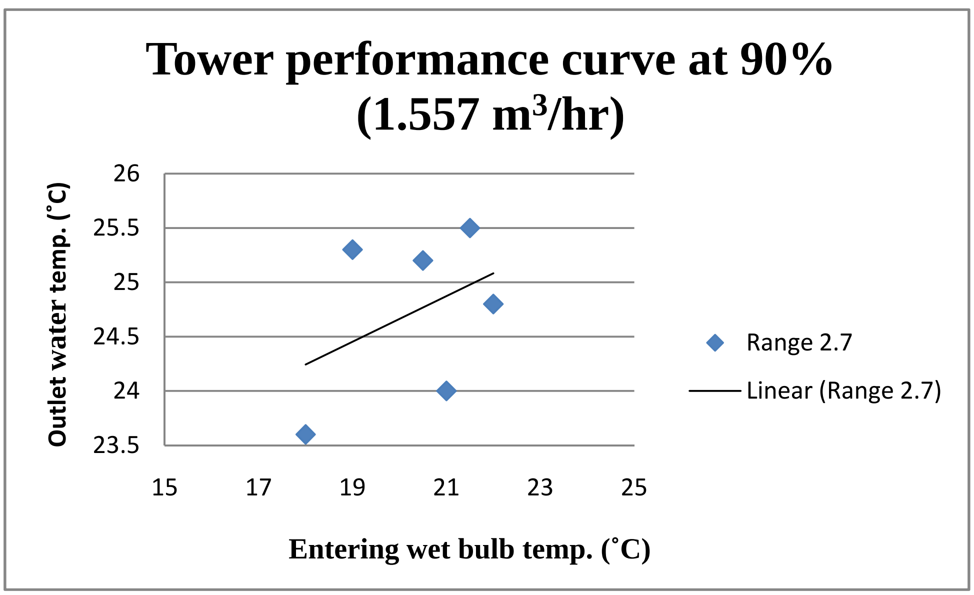


Fig 4.2: Cold water temp. (˚C) vs Inlet wet bulb temp. (˚C) at 1.557 m^3/hr

Cold water temp. (˚C)	Entering wet bulb temp. (˚C)
25.4	18
26.9	19
26.6	20.5
25.4	21
26.7	21.5
26	22

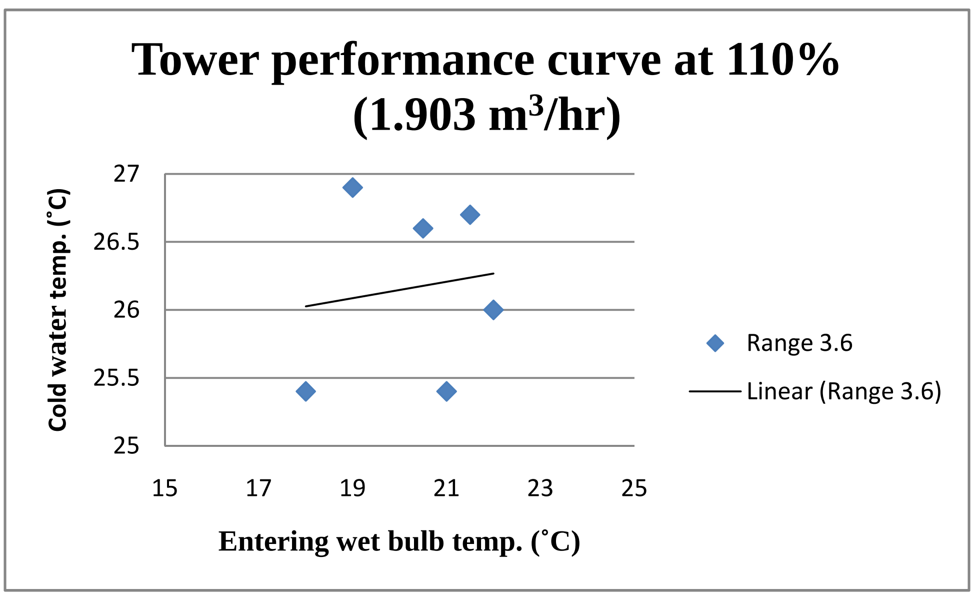


Fig 4.3: Cold water temp. (˚C) vs Inlet wet bulb temp. (˚C) at 1.903 m^3/hr

4.1.2 NTU Observation with varying range and DBT, WBT difference

NTU is the tower demand. With the increase in difference between wet bulb and dry bulb NTU has been increased. Range means difference between inlet and outlet temperature. More range means more cooling. In graph NTU increased with range.

NTU	DBT-WBT
0.3649	3
0.475	3.5
0.4637	4
0.4382	5
0.4979	5.5

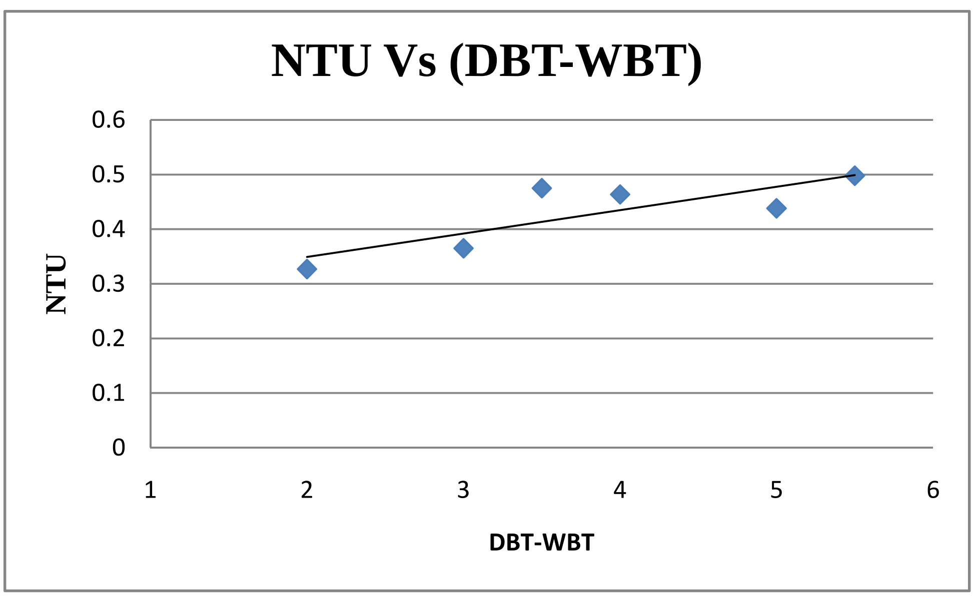


Fig 4.4: NTU vs (DBT-WBT)˚C

NTU	T_w	range
0.3269	22	2.7
0.3649	20	3
0.4382	18	3.5
0.475	19	3.9
0.4637	21	4.1
0.4979	21	4.5

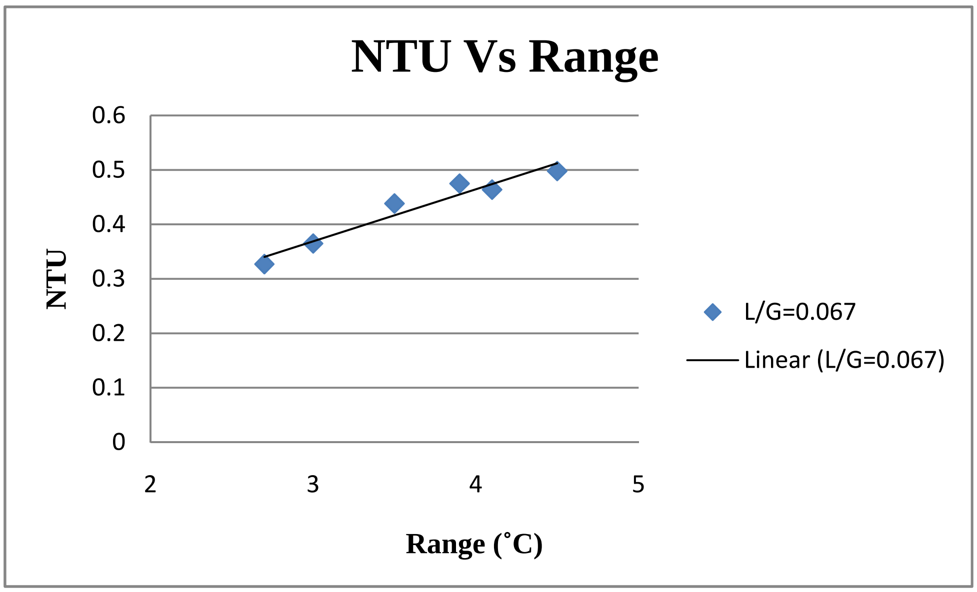


Fig 4.5: NTU vs Range

NTU	DBT-WBT
0.3264	2
0.365	3
0.475	3.5
0.4612	4
0.4385	5
0.4979	5.5

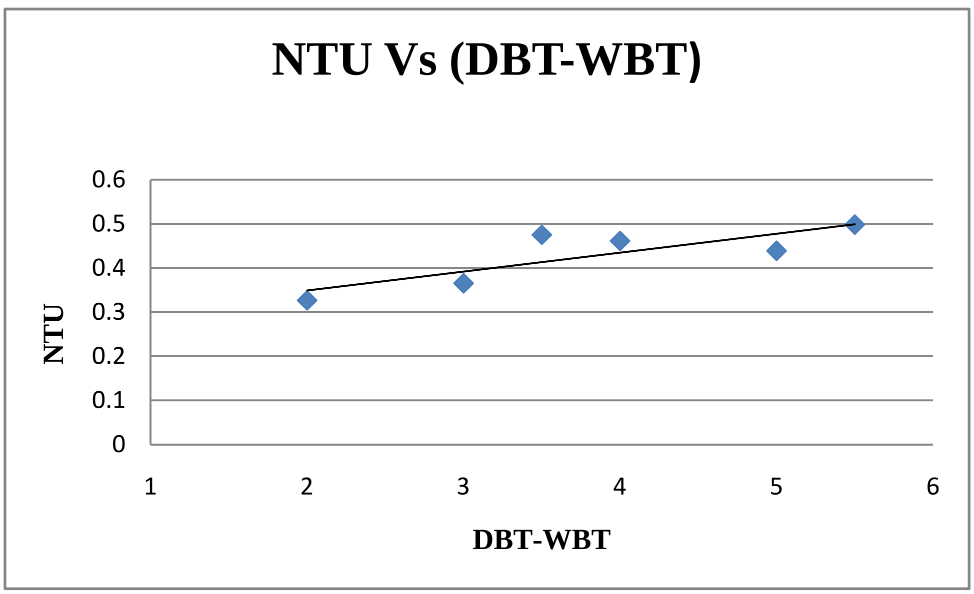


Fig 4.6: NTU vs (DBT-WBT)˚C

NTU	T_w	Range
0.3264	22	2.7
0.365	20	3
0.4385	18	3.5
0.475	19	3.9
0.4612	21	4.1
0.4979	21	4.5

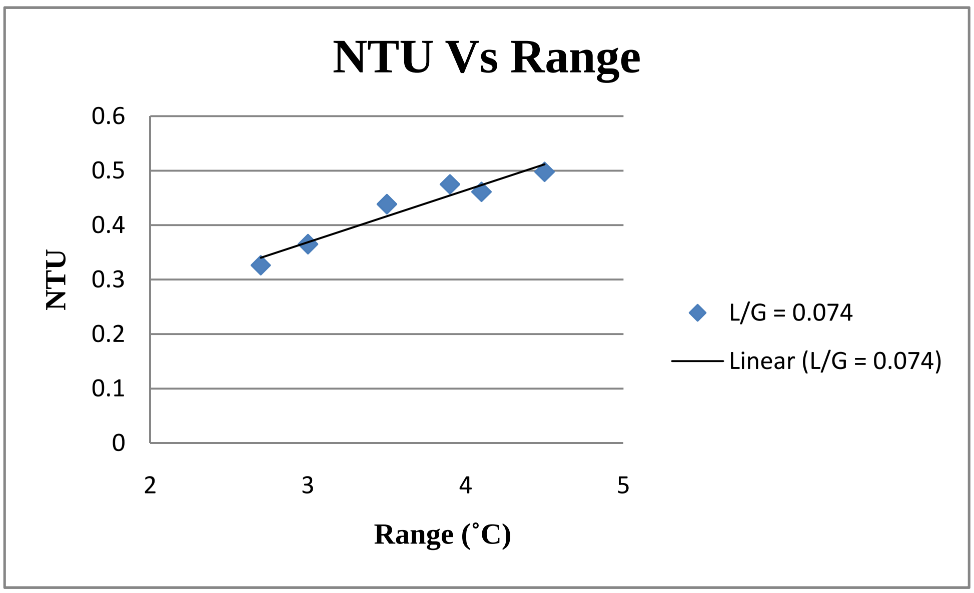


Fig 4.7: NTU vs Range

NTU	DBT-WBT
0.3269	2
0.3652	3
0.4636	3.5
0.4638	4
0.4386	5
0.5035	5.5

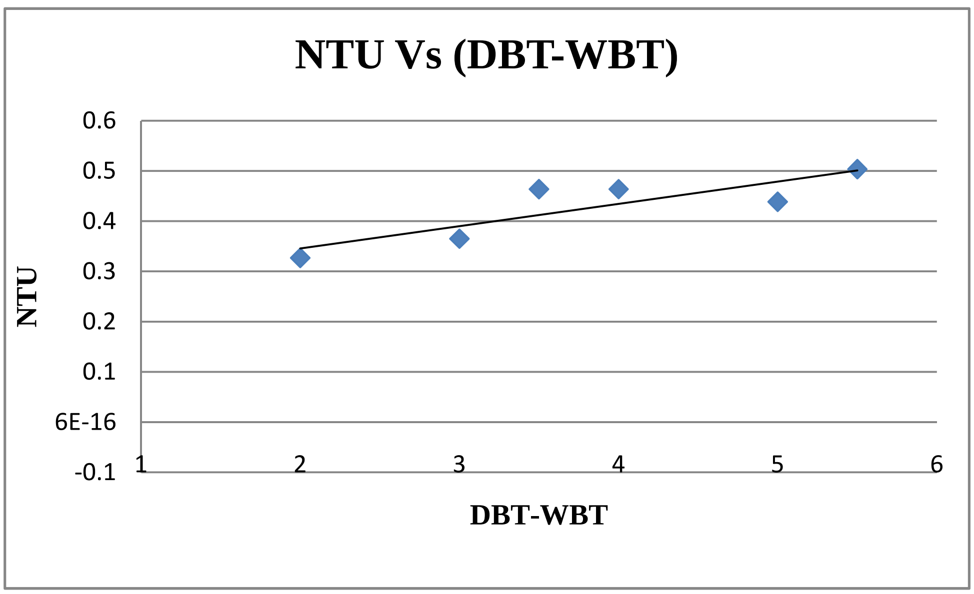


Fig 4.7: NTU vs (DBT-WBT)˚C

NTU	T_w	Range
0.3269	22	2.7
0.3652	20	3
0.4386	18	3.5
0.4636	19	3.9
0.4638	21	4.1
0.5035	21	4.5

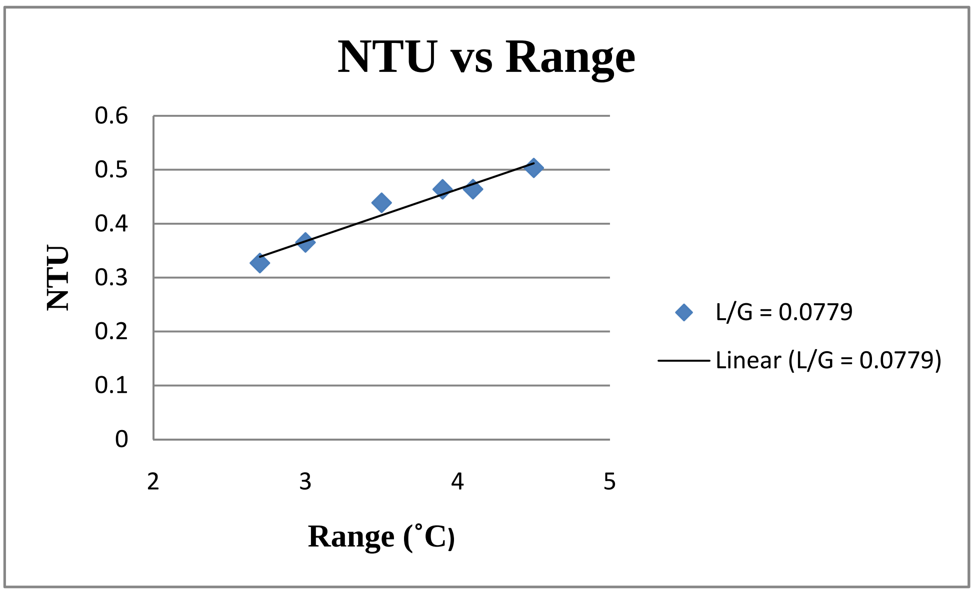


Fig 4.9: NTU vs Range

4.2 Discussion

By analyzing the graphs of cooled water temperature vs inlet wet bulb temperature of air we can find that with the increase in wet bulb temperature, the cooled water temperature also increases. That's because with increase in wet bulb temperature the relative humidity increases so cooling of water decreases. NTU is the tower demand. With the increase in difference between wet bulb and dry bulb NTU increases. Range means difference between inlet and outlet temperature. More range means more cooling. In graph NTU increases with range.

Chapter 5

Conclusion

5.1 Conclusion

The thesis was about experimental investigation and performance analysis of counter flow induced draft cooling tower. The main purpose of this study was to work on developing mathematical model for cooling tower and examine methodically the performance of a model of closed loop 10 RT counter flow induced draft bottle type cooling tower. A model of closed loop circuit of cooling tower has been developed for the project. Parametric study of counter flow induced draft cooling tower is presented by a thermo-hydraulic-performance optimization analysis. Different (L/G) values were studied for the best thermo-hydraulic performance of counter flow induced draft cooling tower.

The effect of difference between dry bulb and wet bulb temperature of inlet air on optimum performance of cooling tower was studied. The difference between wet bulb and dry bulb temperature of air has great influence on the NTU and effectiveness of cooling tower. For greater (L/G) values the effectiveness of cooling tower was increased. The increase in water temperature must be combined with increase of water mass flow rate for the same air flow rate. Cooled water temperature vs wet bulb temperature graphs were plotted to analysis the cooling performance of cooling tower.

The designed setup can also be used as lab apparatus for investigating the performance of cooling tower.

5.2 Limitations:

During project we faced some limitations -

- The setup is not portable.
- External heat source is required.
- Cooling tower cannot decrease the required temperature if percentage RH is too high.
- Cooling tower efficiency depends on approach.
- Infill of cooling tower has to be changed in regular basis. This is not cost effective.
- It is very tough to maintain constant air flow rate
- The motor of cooling tower supports 380 v, 3-phase connection which is not easy to find everywhere.
- Air velocity changes frequently
- The setup is costly

5.3 Recommendation:

For future Study some recommendations are offered -

- Heat source used in the setup is 1.5 kw water heater. More powerful heat source should be used for heating the inlet water to the cooling tower.
- Air flow rate measured during collecting data was very low. The air flow rate should be higher.
- 0.5 hp pump was used in the experiment, for higher flow rate 1 hp pump can be used.
- Values should be taken at steady state condition.
- Using water heater as external heat source is very risky. Necessary safety action should be taken during water heating.
- Consultation with lab assistance before run the setup is necessary.
- Students should know how to use the equipment.
- Avoid any mistakes and errors to get best results from the experiments.

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14. Deterministic Study on the optimum performance of counter flow Cooling Tower. 2012

Appendix: A

Data Collection

A.1

Flow rate of water (L) m^3/h	Flow rate of air (G) m^3/h
1.903	18.09
1.730	18.09
1.557	18.09
1.230	18.09
1.340	18.09
1.410	18.09
1.120	18.09
1.080	18.09
0.980	18.09
0.920	18.09

A.2

T_1 $°C$	T_2 $°C$	T_3 $°C$	T_4 $°C$	T_5 $°C$	T_6 $°C$
23	18	24.1	22.1	28	24.5
25	21	25.9	24.2	27.9	23.8
22.5	19	23.7	21.8	30	26.1
24	22	24.8	23.1	28	25.3
26	21.5	27.1	25.9	29	26.1
23.5	20.5	24.5	22.8	29	25.9

A.3

Water Side (Range =3.5 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	18.35	77.35	H_{a1}+(0.1×L/G×range)	50.73	26.62	0.0375
T_{w1}+(0.4×range)	19.40	82.77	H_{a1}+(0.4×L/G×range)	50.80	31.97	0.0312
T_{w1}+(0.6×range)	20.10	84.20	H_{a1}+(0.6×L/G×range)	50.85	33.35	0.0299
T_{w1}+(0.9×range)	21.15	88.50	H_{a1}+(0.9×L/G×range)	50.92	37.58	0.0266
Sum of 1/(h_w-h_a)						0.1252
NTU value = Sum × Range						0.4382

A.4

Water Side (Range = 4.1°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	21.41	90.31	H_{a1}+(0.1×L/G×range)	60.74	29.57	0.0338
T_{w1}+(0.4×range)	22.64	95.30	H_{a1}+(0.4×L/G×range)	60.83	34.48	0.0290
T_{w1}+(0.6×range)	23.46	98.38	H_{a1}+(0.6×L/G×range)	60.89	37.50	0.0260
T_{w1}+(0.9×range)	24.69	103.13	H_{a1}+(0.9×L/G×range)	60.98	42.17	0.0237
Sum of 1/(h_w-h_a)						0.1131
NTU value = Sum × Range						0.4637

A.5

Water Side (Range =3.9 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	19.39	81.02	H_{a1}+(0.1×L/G×range)	53.98	27.04	0.0369
T_{w1}+(0.4×range)	20.56	86.07	H_{a1}+(0.4×L/G×range)	54.05	32.02	0.0312
T_{w1}+(0.6×range)	21.34	89.50	H_{a1}+(0.6×L/G×range)	54.11	35.39	0.0282
T_{w1}+(0.9×range)	22.51	93.41	H_{a1}+(0.9×L/G×range)	54.19	39.22	0.0254
Sum of 1/(h_w-h_a)						0.1217
NTU value = Sum × Range						0.4750

A.6

Water Side (Range =2.7°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	22.27	93.14	H_{a1}+(0.1×L/G×range)	64.41	28.73	0.0348
T_{w1}+(0.4×range)	23.08	96.83	H_{a1}+(0.4×L/G×range)	64.47	32.36	0.0309
T_{w1}+(0.6×range)	23.62	98.58	H_{a1}+(0.6×L/G×range)	64.5	34.08	0.0293
T_{w1}+(0.9×range)	24.43	102.89	H_{a1}+(0.9×L/G×range)	64.56	38.33	0.0260
Sum of 1/(h_w-h_a)						0.1910
NTU value = Sum × Range						0.3269

A.7

Water Side (Range =4.5 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	21.95	92.40	H_{a1}+(0.1×L/G×range)	62.50	29.9	0.0334
T_{w1}+(0.4×range)	23.3	97.10	H_{a1}+(0.4×L/G×range)	62.60	34.5	0.0289
T_{w1}+(0.6×range)	24.2	101.15	H_{a1}+(0.6×L/G×range)	62.66	38.49	0.0259
T_{w1}+(0.9×range)	25.55	107.29	H_{a1}+(0.9×L/G×range)	62.75	44.54	0.0224
Sum of 1/(h_w-h_a)						0.1106
NTU value = Sum × Range						0.4979

A.8

Water Side (Range = 3°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	20.8	87.7	H_{a1}+(0.1×L/G×range)	59.02	28.68	0.0348
T_{w1}+(0.4×range)	21.7	91.1	H_{a1}+(0.4×L/G×range)	59.08	32.02	0.0312
T_{w1}+(0.6×range)	22.3	93.15	H_{a1}+(0.6×L/G×range)	59.12	34.03	0.0293
T_{w1}+(0.9×range)	23.2	97.18	H_{a1}+(0.9×L/G×range)	59.18	38.00	0.0263
Sum of 1/(h_w-h_a)						0.1216
NTU value = Sum × Range						0.3649

A.9

Water Side (Range =3.5 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	18.35	77.35	H_{a1}+(0.1×L/G×range)	50.74	26.61	0.0375
T_{w1}+(0.4×range)	19.40	82.77	H_{a1}+(0.4×L/G×range)	50.82	31.95	0.0312
T_{w1}+(0.6×range)	20.10	84.20	H_{a1}+(0.6×L/G×range)	50.87	33.33	0.0300
T_{w1}+(0.9×range)	21.15	88.50	H_{a1}+(0.9×L/G×range)	50.95	37.58	0.0266
Sum of 1/(h_w-h_a)						0.1253
NTU value = Sum × Range						0.4385

A.10

Water Side (Range = 4.1°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	21.41	90.31	H_{a1}+(0.1×L/G×range)	60.74	29.57	0.0338
T_{w1}+(0.4×range)	22.64	95.30	H_{a1}+(0.4×L/G×range)	60.84	34.48	0.0290
T_{w1}+(0.6×range)	23.46	98.38	H_{a1}+(0.6×L/G×range)	60.90	37.50	0.0266
T_{w1}+(0.9×range)	24.69	103.13	H_{a1}+(0.9×L/G×range)	61.00	41.17	0.0237
Sum of 1/(h_w-h_a)						0.1125
NTU value = Sum × Range						0.4612

A.11

Water Side (Range =3.9 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	19.39	81.02	H_{a1}+(0.1×L/G×range)	53.98	27.64	0.0369
T_{w1}+(0.4×range)	20.56	86.07	H_{a1}+(0.4×L/G×range)	54.06	32.01	0.0312
T_{w1}+(0.6×range)	21.34	89.50	H_{a1}+(0.6×L/G×range)	54.12	35.38	0.0282
T_{w1}+(0.9×range)	22.51	93.41	H_{a1}+(0.9×L/G×range)	54.21	39.20	0.0255
Sum of 1/(h_w-h_a)						0.1218
NTU value = Sum × Range						0.4750

A.12

Water Side (Range =4.5 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	21.95	92.40	H_{a1}+(0.1×L/G×range)	62.51	29.89	0.0334
T_{w1}+(0.4×range)	23.3	97.10	H_{a1}+(0.4×L/G×range)	62.61	34.49	0.0289
T_{w1}+(0.6×range)	24.2	101.15	H_{a1}+(0.6×L/G×range)	62.68	38.47	0.0259
T_{w1}+(0.9×range)	25.55	107.29	H_{a1}+(0.9×L/G×range)	62.79	44.54	0.0224
Sum of 1/(h_w-h_a)						0.1106
NTU value = Sum × Range						0.4979

A.13

Water Side (Range = 2.7°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	22.27	93.18	H_{a1}+(0.1×L/G×range)	64.41	28.77	0.0347
T_{w1}+(0.4×range)	23.08	96.98	H_{a1}+(0.4×L/G×range)	64.47	32.51	0.0307
T_{w1}+(0.6×range)	23.62	98.70	H_{a1}+(0.6×L/G×range)	64.51	34.19	0.0292
T_{w1}+(0.9×range)	24.43	102.58	H_{a1}+(0.9×L/G×range)	64.57	38.01	0.0263
Sum of 1/(h_w-h_a)						0.1209
NTU value = Sum × Range						0.3264

A.14

Water Side (Range =3 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	20.8	87.7	H_{a1}+(0.1×L/G×range)	59.02	28.68	0.0348
T_{w1}+(0.4×range)	21.7	91.1	H_{a1}+(0.4×L/G×range)	59.09	32.01	0.0312
T_{w1}+(0.6×range)	22.3	93.15	H_{a1}+(0.6×L/G×range)	59.13	34.02	0.0293
T_{w1}+(0.9×range)	23.2	97.18	H_{a1}+(0.9×L/G×range)	59.20	37.98	0.0263
Sum of 1/(h_w-h_a)						0.1216
NTU value = Sum × Range						0.3650

A.15

Water Side (Range =3.5 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	18.35	77.35	H_{a1}+(0.1×L/G×range)	50.74	26.64	0.0375
T_{w1}+(0.4×range)	19.40	82.77	H_{a1}+(0.4×L/G×range)	50.82	31.95	0.0312
T_{w1}+(0.6×range)	20.10	84.20	H_{a1}+(0.6×L/G×range)	50.88	33.33	0.0300
T_{w1}+(0.9×range)	21.15	88.50	H_{a1}+(0.9×L/G×range)	50.96	37.54	0.0266
Sum of 1/(h_w-h_a)						0.1253
NTU value = Sum × Range						0.4386

A.16

Water Side (Range = 4.1°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj) E
T_{w1}+(0.1×range)	21.41	90.31	H_{a1}+(0.1×L/G×range)	60.74	29.57	0.0338
T_{w1}+(0.4×range)	22.64	95.30	H_{a1}+(0.4×L/G×range)	60.84	34.46	0.0290
T_{w1}+(0.6×range)	23.46	98.38	H_{a1}+(0.6×L/G×range)	60.90	37.48	0.0266
T_{w1}+(0.9×range)	24.69	103.13	H_{a1}+(0.9×L/G×range)	60.00	41.13	0.0237
Sum of 1/(h_w-h_a)						0.1131
NTU value = Sum × Range						0.4638

A.17

Water Side (Range =3.9 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	19.39	81.02	H_{a1}+(0.1×L/G×range)	53.98	27.04	0.0369
T_{w1}+(0.4×range)	20.56	86.07	H_{a1}+(0.4×L/G×range)	54.07	32.00	0.0312
T_{w1}+(0.6×range)	21.34	89.50	H_{a1}+(0.6×L/G×range)	54.13	35.37	0.0282
T_{w1}+(0.9×range)	22.51	93.41	H_{a1}+(0.9×L/G×range)	54.22	39.19	0.0225
Sum of 1/(h_w-h_a)						0.1188
NTU value = Sum × Range						0.4636

A.18

Water Side (Range =2.7 °C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	22.27	93.14	H_{a1}+(0.1×L/G×range)	64.41	28.73	0.0348
T_{w1}+(0.4×range)	23.08	96.83	H_{a1}+(0.4×L/G×range)	64.48	32.35	0.0309
T_{w1}+(0.6×range)	23.62	98.58	H_{a1}+(0.6×L/G×range)	64.52	34.06	0.0293
T_{w1}+(0.9×range)	24.43	102.89	H_{a1}+(0.9×L/G×range)	64.58	38.01	0.0261
Sum of 1/(h_w-h_a)						0.1211
NTU value = Sum × Range						0.3269

A.19

Water Side (Range = 4.5°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	21.45	90.03	H_{a1}+(0.1×L/G×range)	60.75	29.28	0.0341
T_{w1}+(0.4×range)	22.80	96.00	H_{a1}+(0.4×L/G×range)	60.85	31.13	0.0284
T_{w1}+(0.6×range)	23.70	98.91	H_{a1}+(0.6×L/G×range)	60.92	37.99	0.0263
T_{w1}+(0.9×range)	25.05	104.99	H_{a1}+(0.9×L/G×range)	61.03	43.96	0.0227
Sum of 1/(h_w-h_a)						0.1119
NTU value = Sum × Range						0.5035

A.20

Water Side (Range =3°C)			Air Side		Enthalpy Difference	
Description	T_w (°C)	h_w (Kj/Kg)	Description	h_a (Kj/Kg)	h_w-h_a (Kj/Kg)	1/(h_w-h_a) (Kg/Kj)
T_{w1}+(0.1×range)	20.8	87.7	H_{a1}+(0.1×L/G×range)	59.02	28.68	0.0348
T_{w1}+(0.4×range)	21.7	91.1	H_{a1}+(0.4×L/G×range)	59.09	32.01	0.0312
T_{w1}+(0.6×range)	22.3	93.15	H_{a1}+(0.6×L/G×range)	59.14	34.01	0.0294
T_{w1}+(0.9×range)	23.2	97.18	H_{a1}+(0.9×L/G×range)	59.21	37.97	0.0263
Sum of 1/(h_w-h_a)						0.0217
NTU value = Sum × Range						0.3652

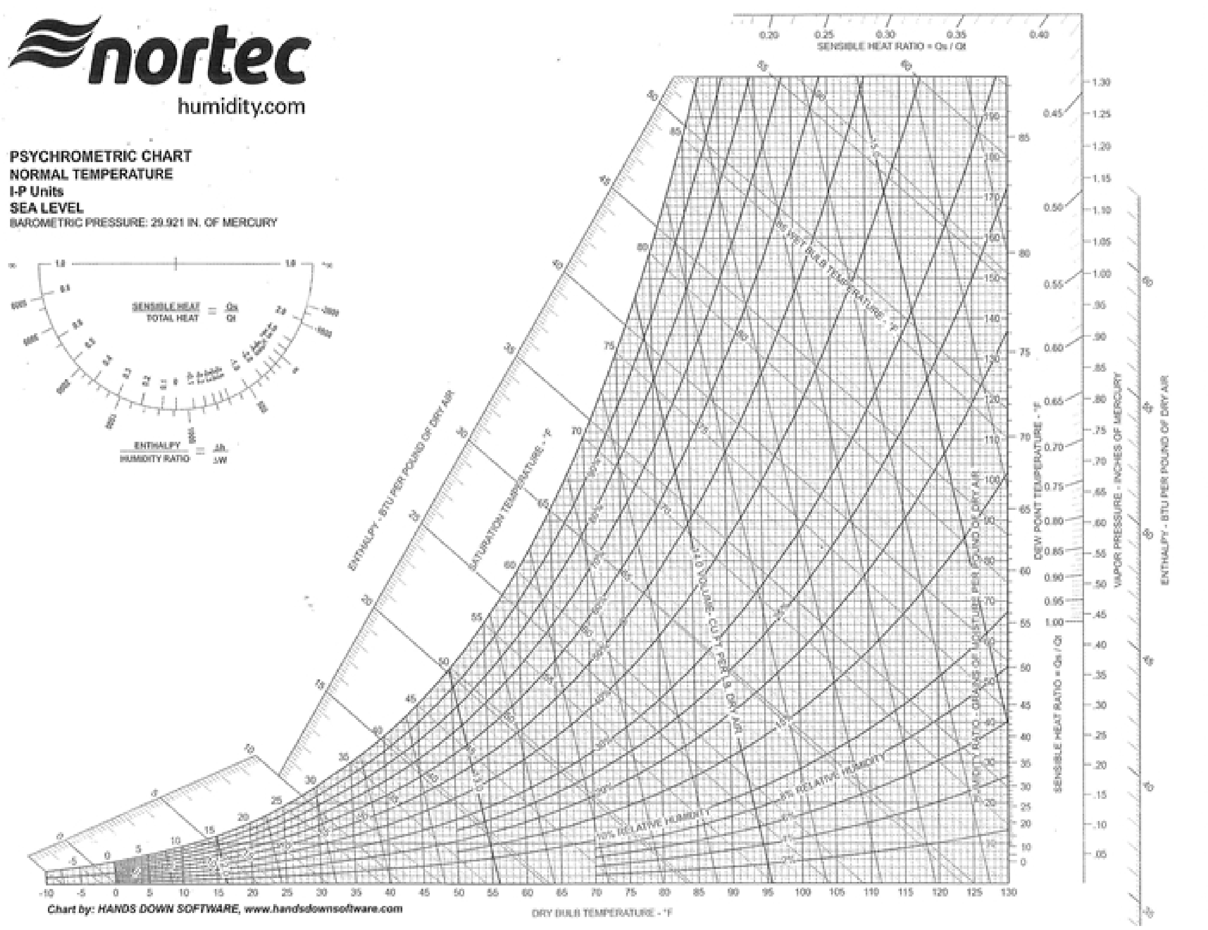

Fig: Psychometric Chart