“EXPERIMENTAL PERFORMANCE ANALYSIS OF INDOOR AND OUTDOOR EVAPORATIVE HEAT EXCHANGER SYSTEMS”

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Approval

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DECLARATION

It is hereby declared that except for the contents where specific reference have been made to the work of others, the study contained in this thesis is the result of investigation carried out by the author. No part of this thesis has been submitted to any other university or other educational establishment for a degree, or other qualification.

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Dedicated

to

"This thesis has been dedicated our parents and teachers".

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ABSTRACT

Cooling towers are evaporative heat transfer devices in which atmospheric air cools warm water with direct contact between the air and the water by evaporating cooling of water. The main objective of this study is to analysis the cooling tower performance, experimental analysis of the performance indoor outdoor evaporative heat exchanger system. This was done by establishing and modifying experimental set up constructing computer program and varying the quality of circulating fluids by adding together at different ratio. Natural and induced draft cooling tower and computer program gives us the various data required for calculation. From the result obtained a comparative study on terms of tower characteristics (Kav/L), water to air flow ratio (L/G), efficiency, range, percentage of make-up water and evaporation heat loss are presented in graphical form. The graph showed that the performance of cooling tower is affected by the type of cooling tower and the quality of circulating fluids. The graphical analysis shows the cooling tower characteristics and efficiency decrease with an increase in (L/G) the induced draft cooling tower shows better performance than natural draft cooling tower. The result also shows that with the adding of toner with water cooling tower performance increase and as tower percentage increases the tower performance also increase.

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Chapter 1

INTRODUCTION

1.1 Introduction

Cooling tower is equipment to reduce outlet temperature of water stream by extracting heat from water by addition of sensible heat to air up to saturated condition and evaporation of Water itself which dissipate to environment and CT used in chemical, petrochemical industries, Air conditioning and refrigeration system. In the last decade numerous researchers have work on the performance of cooling tower with different parameter like wet, entropy, energy and Temperature of water involve which affected the component such as drift eliminator, fill area and purpose is to increase heat transfer rate of water with direct contact of air. The main cause to reduce heat transfer is scaling and fouling of each component of cooling tower, researchers Investigate method to remove scaling and fouling. In manufacturing industries for process Cooling. In heating-ventilation and air conditioning (hvac) cooling tower operation based on Sensible cooling and evaporative cooling. In sensible cooling hot water is cooled to a lower Temperature without phase change of water. But in evaporative cooling few of water content is Evaporated during the process by absorbing heat from rest of the water. It is found that most of the heat transfer takes place in cooling tower are due to this evaporation. Through evaporative Process 70 percent of heat is dissipated to atmosphere. On the basis of heat load conditions Various types of cooling tower is designed and manufactured. Each type of cooling tower has Different size and dimensions for different application. Cooling towers can be classified on the Basis of air flow, shape, construction, fill and heat transfer. In this thesis project we try to study Performance of two types of cooling tower. One of them is counter flow natural draft cooling Tower and another one is induced draft cooling tower. Natural draft cooling tower is the one Which uses the atmospheric air flow and in case of induced draft air induced inside the cooling Tower with the use of an induced fan. Firstly, natural draft and induced draft cooling tower are Studied and their performance are compared. Effectiveness of cooling tower at different Operating condition (flow rate, water inlet temperature) are calculated to identify the optimum Condition. For water inlet outlet temperature reading thermocouple were used to obtain digital On an electronic display. For different air data Arduino circuit were used. Dry bulb temperature and humidity sensor is used to get a computerized data. From the data obtain in the computer other data were calculated with the use of psychometric chart. Using the first law of Thermodynamic effectiveness of cooling tower is obtained. Then we repeat the whole process Once again and measure all the parameters including humidity, enthalpy, dry bulb temperature, Wet bulb

temperature and others using working fluid which is a mixture of ink and water. After That we compare this data with the data obtain by using natural water earlier. Then effectiveness at different condition is compared through graphical and analytical way. Finally, limitation of the thesis project is highlighted and few recommendations is being made.

1.2 Objectives of Thesis

- To construction the Experimental Setup and Data Collection Procedure.
- To analyze the performance of the experimental heat exchanger developed in this study.
- To compare the thermal efficiency and cooling performance of the fabricated heat exchanger with a conventional air conditioning system.

1.3 Historical Background

Modern water-cooling towers were invented during the industrial age to disintegrate waste heat from industrial processes when natural cooling water sources were unavailable. By the early 20th century, advances in cooling towers were fueled by the rapidly growing electric power Industry. The cooling loads created by the generation of electric power led to the development of large, custom-built structures typically constructed of wood. Cooling tower development Continued to be based on the needs of these power-and-process users until the emergence of the commercial air conditioning market, which led the development of the modular, independently certified cooling towers of today. The development of the commercial air Conditioning industry defined new criteria for cooling tower development. Contrary to process Cooling towers, equipment intended for air conditioning applications had to be compact enough to fit in the restricted spaces available on commercial buildings. Cooling towers also had to Meet the construction schedules of the rapidly growing demand for air-conditioned buildings That characterized post-World War II America. With most air conditioning installations located in heavily populated urban areas, sound became a very important application consideration, and many municipal building or fire codes discouraged the use of combustible materials, Including wood, in cooling tower

construction. The above criteria could not be easily met by Many cooling tower designs of the day that traced their origins to industrial applications. By the late 1950s, factory-assembled cooling towers, incorporating quiet centrifugal fans and constructed of galvanized steel, were developed for commercial air conditioning projects. Innovations during the 1960s combined the cold-water basin and fan sections of these factory-Assembled, forced-draft cooling towers into one piece. This design innovation reduced space Requirements and operating weights, facilitated cleaning of the cold-water basin, provided Protection for mechanical components, and simplified access to the fan-drive system. By the 1970s, the application of these cooling towers on commercial air conditioning systems Accounted for approximately half of the HVAC cooling tower installations. The energy crisis of the mid-1970s placed increased awareness on energy efficiency in all Aspects of American life, including commercial air conditioning systems. The operating Characteristics of the centrifugal fan cooling tower began giving way to the energy reduction Offered by the propeller fan units of industrial-style cross flow cooling towers. In the ensuing Years, design strategies focused on incorporating the HVAC cooling tower characteristics into the propeller fan, industrial cross flow cooling tower. As development progressed into the 1980s and 90s, designs continued to concentrate on Increasing thermal efficiency, simplifying maintenance, and reducing installation costs. The Development of new, high-efficiency film fills, produced from lightweight, flame-retardant PVC, reduced the size and weight of cross flow cooling towers. Propeller fans, originally Selected solely on air-handling considerations, incorporated sound characteristics as important Selection criteria. New, belt-driven fan-drive systems were developed to provide reliable unit Operation and reduce maintenance costs associated with the gear-driven systems of industrial Style units. Internal piping systems that reduced field piping requirements and allowed service Personnel to perform routine maintenance of the water distribution system without mounting the fan deck was developed for cross flow cooling towers. Today, factory-assembled, cross Flow cooling towers are considered to be the preferred configuration for air conditioning Applications for their dependable, year-round operating reliability, accessible maintenance Features, and low installation costs. A significant milestone of the 1980s was the resurgence of a certification standard for the independent verification of cooling tower thermal performance. It had long been recognized

That the thermal processes involved with cooling tower performance were not well understood, Making the accurate prediction of thermal capabilities very difficult. Con-sequent, thermal Ratings published by cooling tower manufacturers were only as reliable as the manufacturers' Best available technology. In 1981, the Cooling Tower Institute (currently the Cooling Technology Institute or CTI) updated and revised its certification standard STD-201. STD- 201Established a procedure for manufacturers to voluntarily obtain independent verification that alpine of cooling towers performs in accordance with the manufacturers' published thermal Performance ratings. CTI certification ensures that owners and operators receive full value for Their investment because the cooling tower performs at full-rated capacity. Furthermore, it Eliminates the potential for years of excessive operating costs due to deficient equipment, and can actually reduce first cost by eliminating the need to oversize equipment or to perform a Field acceptance test to verify performance. In 1996, STD-201 was expanded to include closed-circuit, as well as traditional open-circuit, Cooling towers. Today, many manufacturers actively participate in the CTI Certification Program by voluntarily submitting their open- and closed-circuit cooling tower lines to the Scrutiny of the certification process. By the 1950s, galvanized steel had become the principal Material of construction for factory-assembled cooling towers. The protective zinc layer of Galvanized steel provided effective corrosion protection from the naturally corrosive Environment found in service. Combined with an effective water treatment program, Galvanized steel cooling towers are designed to provide exceptionally long service life for Evaporative cooling equipment. In the 1970s, EPA regulations restricted the use of chromates, a widely used, highly reliable Corrosion inhibitor in many cooling systems, including HVAC systems. The resultant changes in water treatment programs were less effective at controlling corrosion rates, thereby Increasing maintenance costs and potentially impacting the life of galvanized steel evaporative Cooling equipment. In response, cooling tower manufacturers began using higher grades of Galvanized steel for additional corrosion protection and incorporating non-metallic materials, Where suitable. Stainless steel components became available as added-cost options for projects Desiring extended equipment life. The need for corrosion protection beyond that provided by galvanized steel alone, without the High cost of stainless steel, was answered in 1981 by the development of special hybrid polymer Coating systems

for galvanized steel. This cost-effective, additional corrosion protection for Galvanized steel is still in widespread use today. Today's leading cooling towers combine the Latest in advanced materials technology to achieve the optimum balance between corrosion Resistance, product durability, long life, and cost. Based on their specific function, cooling Tower components are designed using the materials with the best combination of corrosion Resistance and physical properties.

1.4 Motivation

In this age of industrialization there is continuous growth manufacturing industries, chemical industries, nuclear and thermal power plant. Each of these sector deal with heats and heat transfer. A lots of waste heat is generated. Rejection of this heat is a major concern in all these industries. So, this a main motivation factor. Besides this there are few other motivation factors like reducing thermal pollution due to waste heat, to study heat transfer in different mode practically and keen interest to work in power generation sector.

1.5 Thesis Organization

- In chapter one introduction, objectives, history of cooling tower and motivation to work in this project has been highlighted.
- In chapter two basic concept on heat transfer, first law and second law of thermodynamics, modes of heat transfer, cooling tower and classification of cooling tower has been discussed.
- In chapter three mathematical modeling, parameters and constructional element is discussed.
- In chapter four experimental set up and procedure are explained.
- In chapter five result and discussion on findings of the experiment is being

high lightened through graphical analysis.

- In chapter six of this paper is comprised of conclusion, limitation and recommendation.

Chapter 2

LITERATURE REVIEW

2.0 Basic Concept

The cooling tower are mostly chemical industries, process industries, power plant and heating ventilation and air conditioning where high heat transfer performance and high effectiveness are mostly required. There factors that affect the performance of counter flow cooling tower like water flow rate, air flow rate, fill porosity, water to air ratio, fouling, heat ,leakage in the atmosphere. We have worked on cooling tower by using Merkel equation and Poppe's equation to calculate effectiveness of cooling tower by considering the effect of water and air flow rate, ambient wet bulb temperature, tower characteristics. Following are the main objectives:

- To observe the effects of process variables on the outlet temperature of the water. Such as

1. Inlet water flow
2. Inlet air velocity
3. Water flow rate

For this following step needs to be perform

a. Modeling of cooling tower
b. Experimental reading and data collection
c. Effectiveness calculation
d. Optimization of effectiveness

2.1 First Law of Thermodynamics

Fact about converting mechanical work into heat energy is introduced before many years ago. Normally the unit of heat energy is kcal or kj. This is the amount of heat required by 1 kg of water to raise its temp by 1°c or 1k. since amount of heat varies with temperatures of water that's why defining particular value of temperature for this unit is worthwhile.

The amount of heat received or rejected by a working body during the process of heating or cooling is given by $Q=mc\ (T_2-T_1)$ where

Q = heat gained or lost by the body, kcal M =mass of the body, kg

T_2-T_1 = temperature rise of body °c or °k C= an experiment factor kcal/kg°k

Specific heat the substance is defined as the amount of heat that enters or leaves a unit mass of the substance when it experiences 1 Degree change in temperature. As Specific heat is a function of temperature so,

$\Delta Q=mcdT$

The product m×c is separately termed as heat capacity or water equivalent of the body. Adiabatic index is the ratio of Cp/Cv

Cp for air is 0.240kcal/kg°k Cv for air is 0.1715 kcal/kg°k

We also know Q=W/J where

Q= quantity of heat in kcal that is converted into work

W= work in mkg that is obtained at the expense of heat

J= coefficient of proportionality called mechanical equivalent of heat.

We may summarize the different aspects of thermodynamic work and heat: Work and heat are not properties of the system. They exist only during interaction between the system and the boundary. They appear when change of state occurs and disappear when the process has been completed. When a system is undergoing a change of state, work and heat cross the system boundary and properties of the system change. Work and heat are path functions and inexact differential. Heat is transferred because of difference in temperature between the system and its surroundings. Work transfer is however by reasons other than temperature. Mechanical work is only one form of thermodynamic work and is calculated with the help of equation $W= pdv$

A fluid flow through a pipe of uniform area of cross section and velocity over the cross section is uniform.

Force = pressure intensity × cross sectional area, F=pA Work done/sec, W=force × velocity

=pAC

= pV

Where c is uniform velocity and v is the volume of gas flowing per second. The analysis of the steady flow system is based on following assumption: Rate of mass inflow is same as rate of mass outflow and the ass of the fluid remains constant within the system. No change in chemical composition of the system and hence no change in chemical energy is involved. Both at entry and exit the fluid is uniform in composition state and velocity. Rate at which heat and work traverse the boundaries are constant. State of fluid at any point is same at all times [1]

2.1 Second Law of Thermodynamics

Statement of second law is impossible to construct an engine working on cyclic process whose sole purpose is to convert all the heat supplied to it into equivalent amount of work". According to this law working on cyclic process means there is no change in internal energy for the complete cycle, cannot receive heat from a heat source and delivery work W=Q. It was stated that all forms of energy are not equally amenable to transformation which means some forms of energy are more valuable than others. In particular it is known to us that work energy can easily be converted into heat energy like stirring operation. On the other hand, it is not possible to convert heat into work easily. It will be realized that large reservoir of heat at room temperature cannot do any work because it cannot transfer heat.

The conditions for a reversible process may be laid down as follows:

- There should be no friction, solid or fluid.
- Heat must be transferred only through an infinitely small temperature difference.

The process in series of the process must proceed in series of equilibrium States for example the process must precede at infinitely slow pace For this reason, we may say that reversibility is neither attainable nor desirable in practice. However, it may be used to set a standard efficiency. Endeavour should be made to attend this efficiency whilst still maintaining satisfactory rate of working. The second law of thermodynamic is directly linked with the thermal efficiency of engine. The efficiency is defined as the ratio of work output from a system to heat input into the system. But for the restriction put by the second law of thermodynamics it would have been possible to convert all heat into work and achieve an ideal efficiency of hundred percent. However, according to second law of thermodynamics it in it is necessary to have heat sink to which some heat energy is to be rejected does if Q1 and Q2 are heat energy is supplied to and

rejected by an engine working on a cyclic process then thermal efficiency is given by [1]

Nth =W/Q1= (Q1-Q2)/Q1

The time I turn down the time that time the time that time that time efficiency however does not serve the purpose adequately in case of heat pump and refrigerator the main purpose of heat pump is to supply heat say Q1 heat source at higher temperature and during this cycle work is supplied to a pump. This is called coefficient of performance or C.O.P.

C.O.P (pump) =Q1/W=Q1/Q1-Q2

In the same way since the purpose of refrigerator is to draw out heat Q2 from the food stuff with the help of work W the coefficient of performance for refrigerator may be written as:

C.O.P (refrigerator) =Q2/W=Q2/Q1-Q2

It will be realized from the foregoing deliberations that amount of heat transferred by all engines working on Carnot cycle and between the same limits of temperature will be same and hence their efficiencies will be equal. However, Carnot cycle consists of reversible process. If an engine works on a cycle consisting of one or more irreversible processes, then its efficiency will be different from the Carnot engine. Carnot showed that efficiency of such an engine will always be less than that of Carnot engine. This fact is known as Carnot's theorem and may be stated as follows No engine on a cyclic process is more efficient than Carnot engine when working between the same limits of temperature.

2.2 Modes of Heat Transfer

Heat transfer which is the spread of energy from one region to another which is the result of temperature gradient takes place by the following three modes:

- Conduction
- Convection
- Radiation

Heat transmission, in majority of real situations, occurs as a result of combinations of these modes of heat transfer.

Example: The water in a boiler shell receives its heat from the fire badly conducted, convicted and radiated heat from the fire to the shell, conducted heat through the shell and conducted and convicted heat from the inner shell wall, to the water. Heat always flows in the direction of lower temperature. The above three modes are similar in that

a temperature differential must exist and the heat exchange is in the direction of decreasing temperature; each method, however, has different controlling laws.

2.2.1 Heat Transfer by Conduction:

Conduction is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance. By lattice vibration: The faster moving molecules or atoms in the hottest part of a body transfer heat by impacts some of their energy to adjacent molecules. By transport of free electrons: Energy flux is provided by free electron in the direction of decreasing temperature—for metals, especially good electrical conductors, the electronic mechanism is responsible for the major portion of the heat flux except at low temperature. In case of gases, the mechanism of heat conduction is simple. The kinetic energy of a molecule is a function of temperature. These molecules are in a continuous random motion exchanging energy and momentum. When a molecule from the high temperature region strikes with a molecule from the low temperature area, it drops energy by collisions. In liquids, the mechanism of heat is nearer to that of gases. However, the molecules are more closely spaced and intermolecular forces come into play.

2.2.2 Heat Transfer by Convection

Convection transfers heat within a fluid by mixing of one portion of another. Convection is applicable only in case of fluid medium. It directly connected with the transport of medium itself. Convection constitutes the microform of the heat transfer since macroscopic particles of a fluid moving in space cause the heat exchange. This mode of heat transfer is met with in situations where energy is transferred as heat to a flowing fluid at any surface over which flow occurs. This mode is basically conduction in a very thin fluid layer at the surface and then mixing caused by the flow. The heat flow depends on the properties of fluid and is independent of the properties of the material of the surface. [2]

1.Free or natural convection:

Free or natural convection occurs where the fluid circulates by virtue of the natural differences in densities of hot and cold fluids; the denser portions of the fluid move

downward because of the greater force of gravity, as compared with the force on the less dense. [2]

2.Forced convection:

When the work is done to blow or pump the fluid, it is said to be forced convection

2.2.3 Heat Transfer by Radiation

Radiation is the transfer of heat through space or matter by means other than conduction or convection. Radiation heat is thought of as electromagnetic waves or quanta (as convenient) an emanation of the same nature as light and radio waves. All bodies radiate heat; so a transfer of heat by radiation occurs because hot body emits more heat than it receives and a cold body receives more heat than it emits. Radiant energy (being electromagnetic radiation) requires no medium for propagation and will pass through a vacuum.

2.3 Cooling Tower

A cooling tower is a device that is used to cool a water stream while simultaneously rejecting heat to the atmosphere. In systems involving heat transfer, a condenser is a device that is used to condense the fluid flowing through it from a gaseous state to a liquid state by cooling the fluid. This cooling to the fluid flowing through a condenser, is generally provided by a cooling tower. Cooling towers may also be used to cool fluids used in a manufacturing process. As a result, we see that cooling towers are commonly used in

1. HVAC (Heating Ventilation and Air-Conditioning) to reject the heat from chillers
2. Manufacturing to provide process cooling
3. Electric power generation plants to provide cooling for the condenser

Cooling tower operation is based on evaporative cooling as well as exchange of sensible heat. During evaporation of cooling in cooing tower, a small amount of the water that is being cooled is evaporated in affecting stream of air to cool the rest of the water. Also when hot water comes in contact with cool air, there is sensible heat transfer whereby the water is cooled. The major amount heat transfer to the air is through evaporative cooling while only about 25% of the heat transfer is through sensible heat. [3]

2.3.1 Types of Cooling Tower

Cooling towers can be classified in many different ways as follows

- Classification based on heat transfer method
  - Wet cooling tower
  - Dry Cooling tower
  - Fluid Cooler
- Classification on the Basis of Shape
  - Package type
  - Field Erected type
- Classification on the Basis of Construction
  - Field Erected
  - Factory assembled
- Classification on The Basis of Air Flow
  - Cross flow
  - Counter flow
- Classification on the basis of Air Draft
  - Atmospheric tower
  - Natural Draft Tower
  - Mechanical Draft Tower
    1. Forced Draft
    2. Induced Draft
- Classification based on type of Fill
  - Spray Fill
  - Splash Fill
  - Film Fill
  -

2.3.1.1 On the basis of Heat Transfer Mode

Wet cooling towers are the most common type of cooling towers and the ones referred to when talking about cooling towers. As explained earlier, they operate on the principle of evaporative cooling. The water to be cooled and the ambient air come in direct contact with each other. This thesis will look mainly at the performance prediction of wet cooling towers since they are the most widely used In a dry cooling tower there is a surface (e.g. tube of a heat exchanger) that separates the water from

the ambient air. There is no evaporative cooling in this case. Such a tower may be used when the fluid to be cooled needs to be protected from the environment. In a fluid cooler water is sprayed over tubes through which the fluid to be cooled is flowing while a fan may also be utilized to provide a draft. This incorporates the mechanics of evaporative cooling in a wet cooling tower while also allowing the working fluid to be free of contaminants or environmental contact.

2.3.1.2 On the Basis of Shape

Package type cooling towers are preassembled and can be easily transported and erected at the location of use. These are generally suitable for applications where the heat load to be rejected is not very large (most HVAC and process load applications). Field erected type of towers are usually much larger to handle the larger heat rejection loads and are custom built as per customer requirements. Most of the construction /assembly of the tower takes place at the site where the tower will be located. This thesis will be to build a model that predicts the performance of package type towers. Although the performance of field erected type towers may be similar to package type towers, the predicted performance may not be very accurate as a result of the unique and requirement specific construction of field erected type towers.

2.3.1.3 On the Basis of Construction

Field erected towers are those on which the primary construction actively takes place at the site of ultimate use. All large tower and many small towers are prefabricated, piece-marked and shipped to the site for final assembly. Labor or supervision for final assembly are generally provided by the manufacturer. Factory assembled towers undergo virtually complete assembly at the point of manufacture, where upon they are shipped to the site as few sections as the mode of transportation will permit. Factory assembled towers are also known as “packaged” or” unitary” towers.

2.3.1.4 On the Basis of Air Flow

In a cross flow tower the direction of air flow is perpendicular to that of the water flow i.e. the water flows vertically downward through the fill, while the air flows horizontally thorough the fill. In a counter flow tower, the direction of air flow is directly opposite to that of the water flow i.e. as the water flows vertically downwards through the fill, the air flows vertically upwards through it. Figure shows the configuration of cross flow and counter flow cooling tower Configurations.

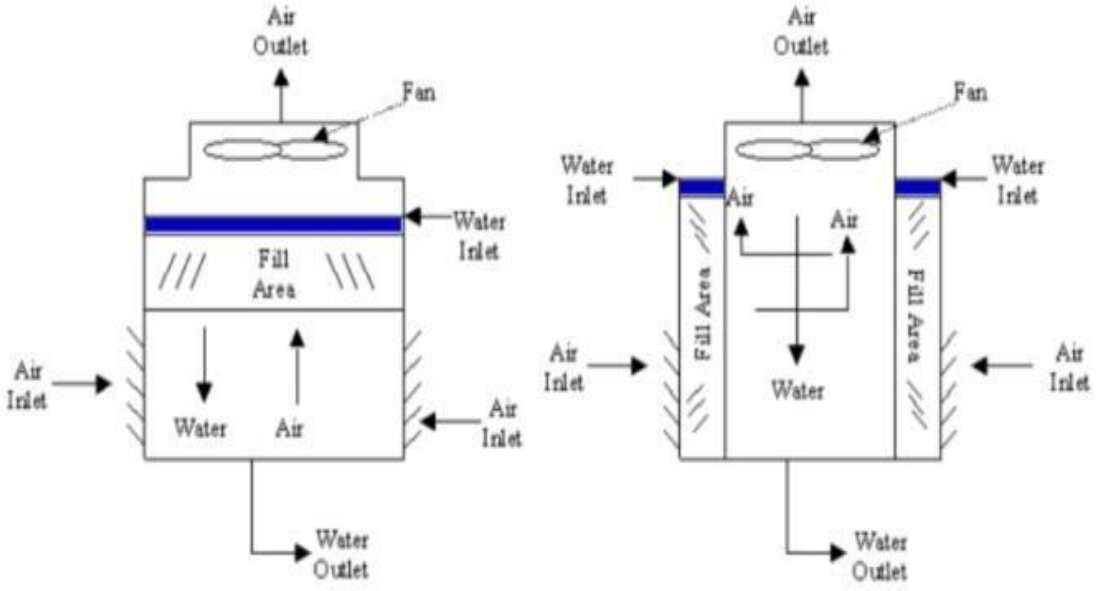


Figure 2.1: Configuration of cross flow and counter flow cooling tower.

2.3.1.5 On the basis of Air Draft

In an atmospheric tower the air enters the tower through louvers driven by its own velocity. This kind of a tower is inexpensive. Since the performance is greatly affected by wind conditions it is largely inefficient and is seldom used when accurate and consistent cold-water temperatures are required. A natural draft tower (also known as hyperbolic cooling tower) is similar to an atmospheric tower in that there is no mechanical device to create air flow through the tower. However, it is dependable and consistent unlike an atmospheric tower. The air flow through the tower is a result of the density differential between hot and less dense air inside the tower as compared to the relatively cooler and denser ambient air outside the tower. The hot air rises up through the tower while cool ambient air is drawn in through inlets at the bottom of the tower. Natural draft towers are extensively used in electric power generation plants and areas where there is higher relative humidity. These towers are much more expensive as compared to other tower types and conspicuous by their hyperbolic shape which is so designed because

- The natural upward draft is enhanced by such a shape
- This shape provides better structural strength and stability

Sometimes natural draft towers are equipped with fans to augment the air flow and are referred to as fan assisted natural draft towers or hybrid draft towers. Mechanical draft towers have one or more fans that are used to move the air through the tower to provide predictable and consistent performance making them the tower of choice in most HVAC and process applications. A mechanical draft tower can be subdivided in two types, namely, forced draft towers and induced draft towers. The tower is termed a forced draft tower if the fans are arranged so as to blow air into The tower. Thus there is a positive pressure in the tower fill as compared to the outside. In this case the fans are generally located at the point where the air enters the tower. The tower is termed an induced draft tower if the fans are arranged so as to push air out of the tower. Thus there is a negative pressure in the tower fill as compared to outside. The fan is located at the point where the air leaves the tower. Figure shows the configuration of the cooling tower for forced draft and induced draft fans.

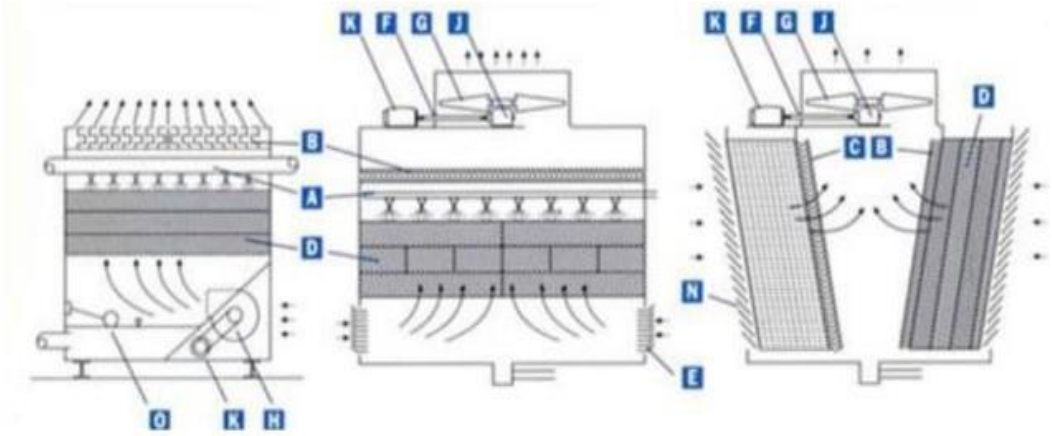


Figure 2.2: Configuration of forced draft and induced draft fans

2.3.1.6 On the basis of type of fill

In a spray fill tower the water is broken down into small droplets so that the area of contact between the water surface and air is increased. So in a way spray fill is not really a fill because there is no packing in the tower. Small droplets of water are created by spraying through nozzles, which are contained within the tower casing, through which there is airflow. The drawbacks of this kind of a fill are low efficiency, large tower size and large airflow requirement. In a splash fill tower, there are slats of wood, PVC or ceramic material over which the water cascades down the tower. As the water splashes over the slats, it forms small droplets which allow for better tower performance. A splash fill is shown in Figure.

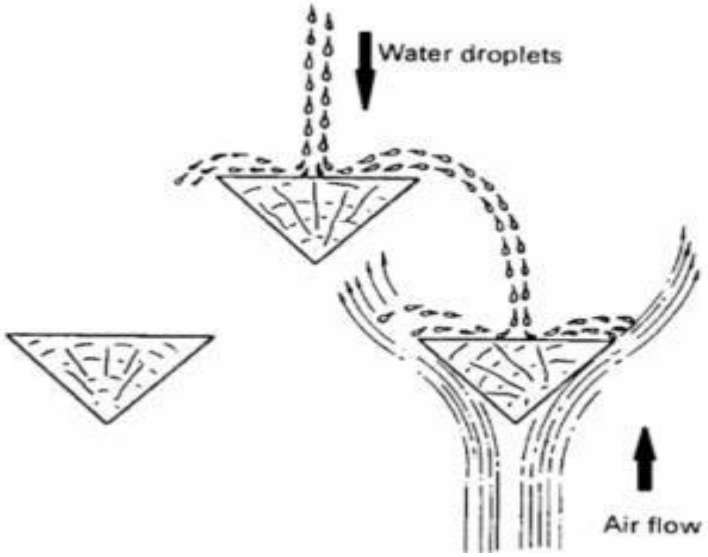


Figure 2.3: A splash fill configuration

In a film fill, large surface area is provided for the water to flow over, which causes it to form a thin film. Because of this large contact area between the water surface and air, efficient evaporative cooling is seen. In this kind of a tower, the pressure drop as the air flows through the tower is lower as compared to the previous types and thus lesser fan power is needed to move the air through the tower. An example of a film fill for a cooling tower is shown in Figure Film fill is less expensive and more efficient than splash fill and has resulted in its widespread use in cooling towers.



Figure 2.4: A film fill configuration

CHAPTER 3

Design & Construction

3.1. Mathematical Modeling

a. Thermal Zones (Rooms or Spaces)

- Energy balance equation:

  In HVAC systems, the energy balance equation ensures that all the energy entering and leaving a control volume (like a room, duct, or equipment) is accounted for. The general energy balance equation for a steady-state HVAC system is:

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}_{in} \cdot h_{in} = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out} \cdot h_{out}$$

Where,

- $\dot{Q}$ = rate of heat transfer
- $\dot{W}$ = rate of work input / output (KW). e.g. fans. Compressor
- $\dot{m}$ = mass flow rate of air (kg/s)
- h = specific enthalpy (KJ/kg)

For a closed HVAC system like an air-handling unit, you may simplify the equation depending on assumptions (e.g., steady flow, negligible work output, etc.). For a room

$$\dot{Q}_{sensible} + \dot{Q}_{latent} = \dot{m} \cdot c_p \cdot (T_{supply} - T_{room})$$

Where,

- c_p = specific heat capacity of air (about 1.005 KJ/kg. k)
- T_{supply} and T_{room})= supply and room air temperatures

b. Air Handling Unit (AHU)

• Sensible heat transfer:

For an Air Handling Unit (AHU), the energy balance focuses mainly on the heat exchange between the incoming air and the cooling or heating coils. The most

commonly used energy balance equation for AHUs is:

$$\boldsymbol{Q_{sensible} = \dot{m} \,.\, c_p \,.\, (T_{in} - T_{out})}$$

Where,

- $\boldsymbol{Q_{sensible}}$ = sensible heat load (kW)
- ṁ = mass flow rate of air (kg/s)

  = *p*. v
    - *p* = air density (~ 1.2 kg/m³)
    - v = volumetric flow rate (m³/s)
- $\boldsymbol{c_p}$ = specific heat capacity of air (about 1.005 KJ/kg. k)
- $\boldsymbol{T_{in} - T_{out}}$ = air temperature at inlet and outlet of the coil (°C)

- **Mass flow rate**

$$\dot{m} = \; p \,.\, \dot{V}$$

Where,

- ṁ = mass flow rate of air (kg/s)
- *p* = air density (~ 1.2 kg/m³)
- V̇ = volumetric flow rate (m³/s)

C. Cooling/Heating Coils

- Effectiveness-NTU model:

$$\dot{Q} = \epsilon \,.\, \boldsymbol{C_{min}} \,.\, (\boldsymbol{T_{hot\,.in} - T_{cold.in}})$$

- Q = actual heat transfer rate (KW)
- ϵ = effective of the heat exchanger (dimensionless)
- $\boldsymbol{C_{min}}$ = minimum heat capacity rate (KW/°C or KJ/s-K)

  C = ṁ . $\boldsymbol{c_p}$
- $\boldsymbol{T_{hot\,.in}}$ = inlet temperature of the hot fluid (°C)
- $\boldsymbol{T_{cold.in}}$ = Inlet temperature of the cold fluid (°C)

Coil effectiveness from NTU:

Counterflow Heat Exchanger:

$$\epsilon = \frac{1-e^{-NTU(1-C_r)}}{1-C_r\,.\,e^{-NTU(1-C_r)}}$$

Parallel Flow:

$$\epsilon = \frac{1-e^{-NTU(1-C_r)}}{1+C_r}$$

D. Fan and Blower

Fan power:

$$P = \frac{\Delta p \cdot v}{\eta_{\boldsymbol{total}}}$$

Where,

- P = fan power input (KW)
- Δp = total pressure rice (Pa)
- V = airflow rate (m^3/s)
- η_{total} = Total efficiency

E. Control System (PID or Advanced)

- **Temperature setpoint control:**

$$\boldsymbol{u(t)} = K_P \cdot et + K_i \int_0^t e(T)\,dT + K_d.\frac{de(t)}{dt}$$

where

- u(t) = controller output (e.g. valve position fan speed)
- e(t) = r(t) = y(t) error setpoint r(t) minus measured value y(t)
- K_P = proportional gain (controls reaction to current error)
- K_i = integral gain (eliminates steady-state error)
- K_d = derivative gain (predicts error trend to improve stability)

3.2 Parameters

1. These relate to the heating and cooling performance:

Parameter	Unit	Description
Supply Air Temperature	°C or °F	Air leaving the AHU or terminal units
Return Air Temperature	°C or °F	Air returning from the zone

Parameter	Unit	Description
Zone Temperature	°C or °F	Temperature inside the conditioned space
Relative Humidity	%	Moisture content of air
Enthalpy	kJ/kg	Energy content of air (used in psychometrics)
Sensible Heat Load	kW	Heat load affecting air temperature
Latent Heat Load	kW	Heat load due to humidity control
Total Heat Load	kW	Sensible + Latent loads

2.Airflow Parameters

Parameter	Unit	Description
Airflow Rate (CFM)	m^3/h or CFM	Volume of air supplied/returned
Air Velocity	m/s or FPM	Air speed in ducts
Static Pressure	Pa or inWC	Resistance in duct system
Air Changes per Hour (ACH)	1/hr	Fresh air exchanges per hour
Ventilation Rate	L/s per person	Required fresh air for occupants

3.Equipment Parameters

a. Cooling Equipment

(Chiller, DX Unit) Parameter	Unit	Description
Cooling Capacity	kW or TR	Maximum cooling output
COP / EER / SEER	—	Energy efficiency ratios

b. Heating Equipment (Boiler, Heat Pump)

Parameter	Unit	Description
Heating Capacity	kW	Maximum heating output
Efficiency	%	Fuel-to-heat conversion efficiency

c. Heating Equipment (Boiler, Heat Pump) :

Parameter	Unit	Description
Heating Capacity	kW	Maximum heating output
Efficiency	%	Fuel-to-heat conversion efficiency

d. Fan and Blower:

Parameter	Unit	Description
Fan Power	kW	Energy used to move air
Fan Efficiency	%	Conversion of electrical to mechanical energy
Pressure Rise	Pa	Required for duct system overcome

4.Control Parameters:

Parameter	Unit	Description
Setpoint Temp	°C	Desired indoor temperature
Setpoint RH	%	Desired humidity level
PID Gains (Kp, Ki, Kd)	—	Control system tuning
VFD Frequency	Hz	Variable speed fan or pump control

5.Environmental & Building Parameters:

Parameter	Unit	Description
Outdoor Temperature	°C	Ambient air temp (weather)
Solar Heat Gain	W/m²	Heat added through windows
Occupancy	Persons	Affects internal gains
Lighting & Equipment Load	W	Internal heat sources

3.4 Component

1. Air Handling Components

Component	Function
Air Handling Unit (AHU)	Conditions and circulates air; contains coils, fan, filters
Fan Coil Unit (FCU)	Smaller unit that provides localized heating/cooling
Variable Air Volume Box (VAV)	Regulates air volume to different zones
Ductwork	Distributes supply and return air throughout the building
Diffusers & Grilles	Final air distribution at zone level
Dampers	Control or shut off airflow in ducts

2.Cooling Components:

Component	Function
Chiller	Removes heat from chilled water used in cooling coils
Cooling Tower	Rejects heat from the condenser water of the chiller
Evaporator Coil	Transfers heat from air to refrigerant
Condenser Coil	Rejects heat from refrigerant to air or water
Refrigerant	Medium for heat transfer in DX systems

3.Control & Regulation:

Component	Function
Thermostats	Set and control room temperature
Sensors	Measure temperature, humidity, CO_2, airflow, etc.
Building Management System (BMS)	Centralized control and automation
Actuators	Adjust dampers, valves, etc., based on control signals
Variable Frequency Drives (VFDs)	Control motor speed for fans and pumps

4.Ventilation Components

Component	Function
Fresh Air Intake	Supplies outdoor air for ventilation
Exhaust Fans	Remove stale air from indoors

Component	Function
Energy Recovery Ventilator (ERV)	Transfers heat and moisture between incoming and outgoing air streams
Filters (MERV-rated)	Clean incoming air of particulates and contaminants

5.Water and Refrigerant Circuit Components

Component	Function
Pumps	Circulate chilled/hot water through coils
Expansion Tank	Maintains pressure in closed-loop systems
Valves (control, isolation, balancing)	Manage water flow direction, volume, and isolation
Compressor	Compresses refrigerant for heat transfer cycle
Expansion Valve	Drops refrigerant pressure to allow evaporation

3.4.1 Cooling Tower

A cooling tower is a heat rejection device that rejects waste heat to the atmosphere through the cooling of a water stream to a lower temperature. Cooling towers may either use the evaporation of water to remove process heat and cool the working fluid to near the wet-bulb air temperature or, in the case of closed-circuit dry cooling towers, rely solely on air to cool the working fluid to near the dry-bulb air temperature.

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
- 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
- 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

3.4.2 Pump

A pump is a device that moves fluids (liquids or gases) by mechanical action. Pumps can be classified into three major groups according to the method they use to move the fluid: direct lift, displacement, and gravity pumps. Pumps operate by

some mechanism and consume energy to perform mechanical work by moving the fluid. Pumps operate via many energy sources, including manual operation, electricity, engines, or wind power, come in many sizes, from microscopic for use in medical applications to large industrial pumps. Mechanical pumps serve in a wide range of applications such as pumping water from wells, aquarium filtering, pond filtering and aeration, in the car industry for water-cooling and fuel injection, in the energy industry for pumping oil and natural gas or for operating cooling towers.

Specification:

- Power: 0 .5 hp
- Total head: 30 meters
- Static head: 6 meters
- Voltage: 220 v

3.4.3 Reservoir

A reservoir that can hold hot water to be cooled above the heat transfer surface. The water is forced down through nozzles into the fill by gravity where it is then cooled by the air. A drum of 24-inch length and 22-inch diameter is used as heating tank.

3.4.4 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. We have used a “Variable Area Flow Meter (Rotameter)”. These flow meters are process-proven flow meters, for maximum repeatability and reliability. [4]

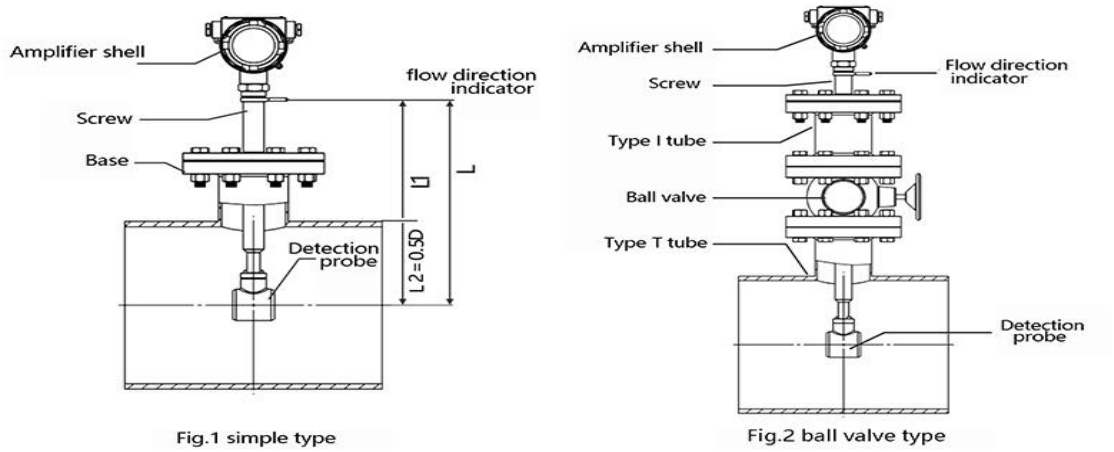


Figure 3.4: Plastic variable area flow meter

Plastic variable area flow meter:

- Most cost-effective solution for non-corrosive and low pressure applications
- Excellent measurement repeatability which provides process stability and consistency
- Fluid Type: Gas, Liquids
- Accuracy: 2-10% FS
- Max Pressure: 100 psig
- Max Temperature 72oC (160o F) Output
- Type: Visual Indication

3.4.5 Thermocouple

A thermocouple is a simple, robust and cost-effective temperature sensor used in a wide range of temperature measurement processes. It consists of two dissimilar metal wires, joined at one end. When properly configured, thermocouples can provide measurements over a wide range of temperatures. 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. [6]



Figure 3.5: Thermocouple Sensor [5]

3.4.6 Humidity Sensor

Humidity Sensors are very important devices that help in measuring the environmental humidity. Technically, the device used to measure the humidity of the atmosphere is called Hygrometer. Humidity Sensors or Hygrometers can be classified based on the type of humidity it is used for measuring i.e. Absolute Humidity (AH) sensors or Relative Humidity (RH) sensors. Humidity Sensors can also be classified based on the parameter used for measuring Humidity I.e. Capacitive Humidity Sensors, Electrical Conductivity (or Resistive) Humidity Sensors and Thermal Conductivity Humidity Sensors. There are other types of Humidity Sensors or Hygrometers like Optical Hygrometer, Oscillating Hygrometer and Gravimetric Hygrometer.

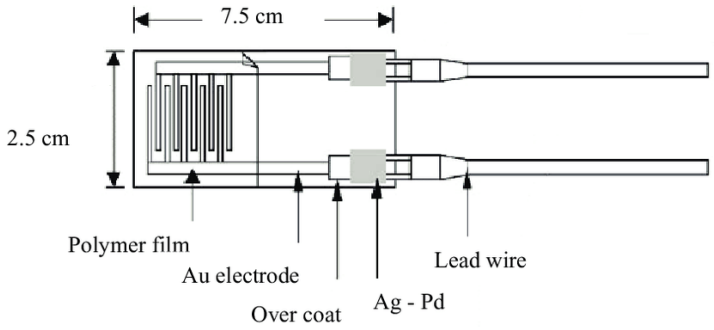


Figure 3.6; Humidity sensor

3.4.7Anemometer

An anemometer is an instrument used to measure the speed or velocity of air (gases) either in a contained flow, such as airflow in a duct, or in unconfined flows, such as atmospheric wind. To determine the air velocity, anemometers detect change in some physical property of the fluid or the effect of the fluid on a mechanical device inserted into the flow.

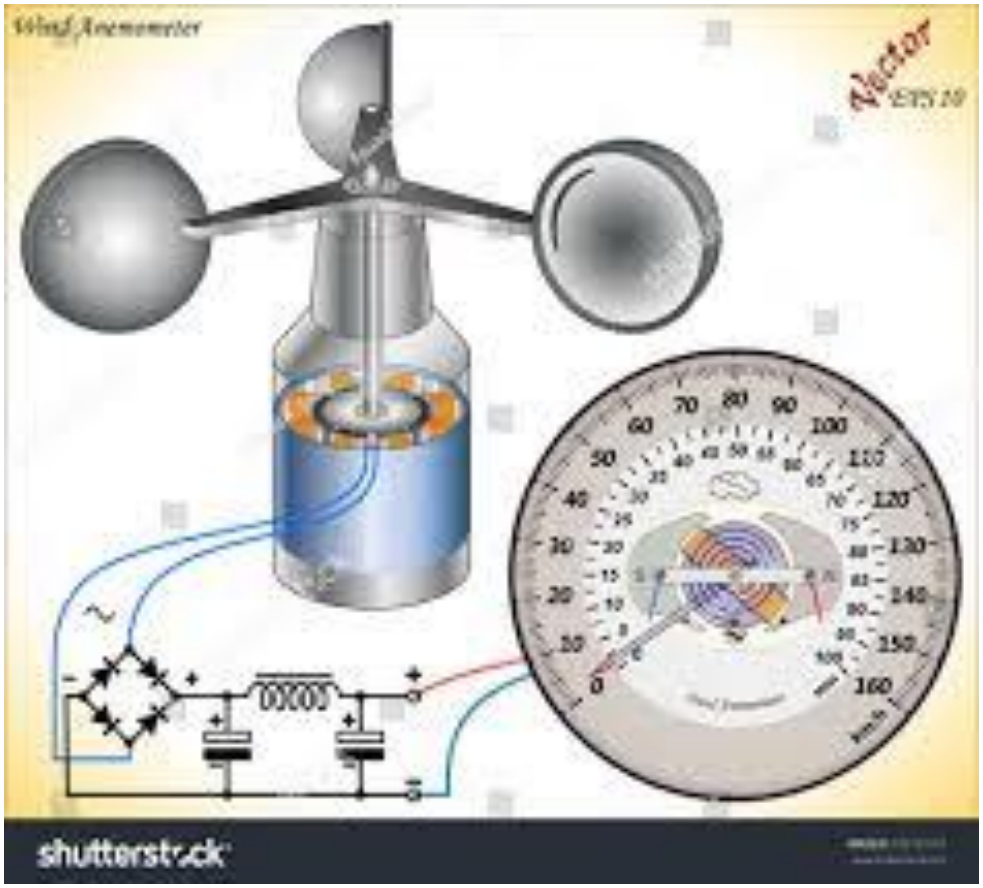


Figure 3.7: Anemometer

3.4.8 Thermocouple Controller

As the name implies, a thermocouple 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. [7]



Figure 3.8: Thermocouple Controller.

3.4.9 Arduino

Arduino is an open-source platform used for building electronics projects. Arduino consists of both a physical programmable circuit board (often referred to as a microcontroller and a piece of software, or IDE (Integrated Development Environment) that runs on your computer, used to write and upload computer code to the physical board. The Arduino platform has become quite popular with people just starting out with electronics, and for good reason. Unlike most previous programmable circuit boards, the Arduino does not need a separate piece of

hardware (called a programmer) in order to load new code onto the board – you can simply use a USB cable. Additionally, the Arduino IDE uses a simplified version of C++, making it easier to learn to program. Finally, Arduino provides a standard form factor that breaks out the functions of the micro-controller into a more accessible package. [8]

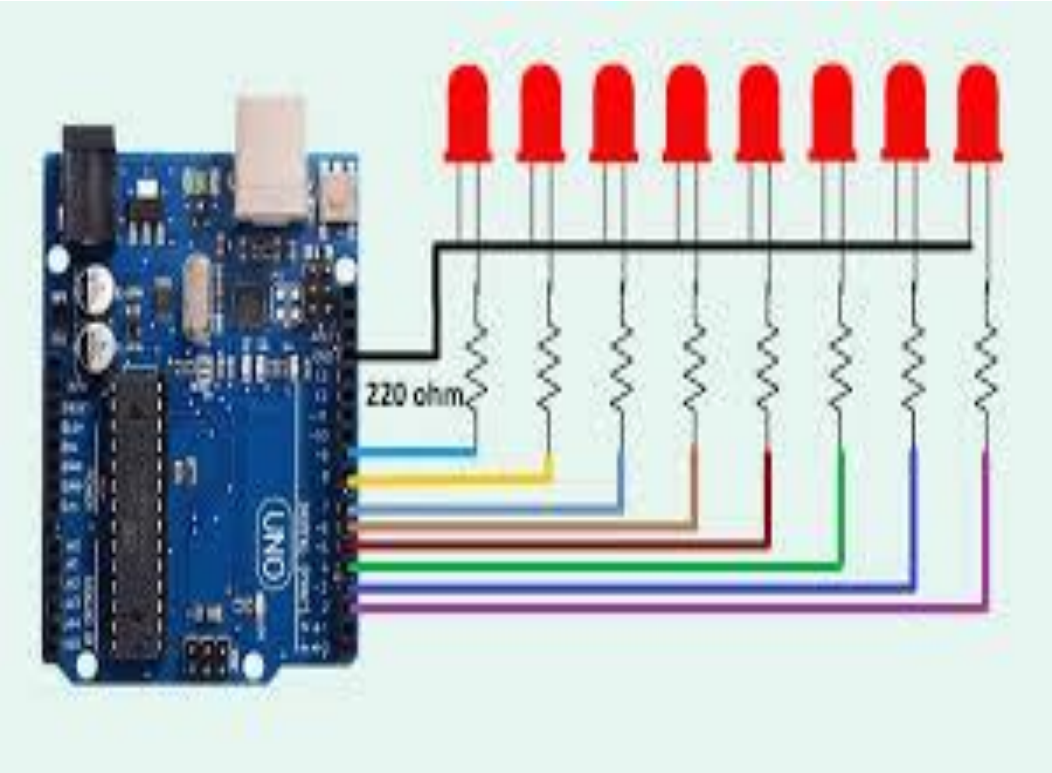


Figure 3.9: Arduino Circuit.

Chapter - 4

Experimental Set Up and Procedure

4.1 Developed Experimental Setup

4.2 Schematic Diagram

4.3 Water Circuit

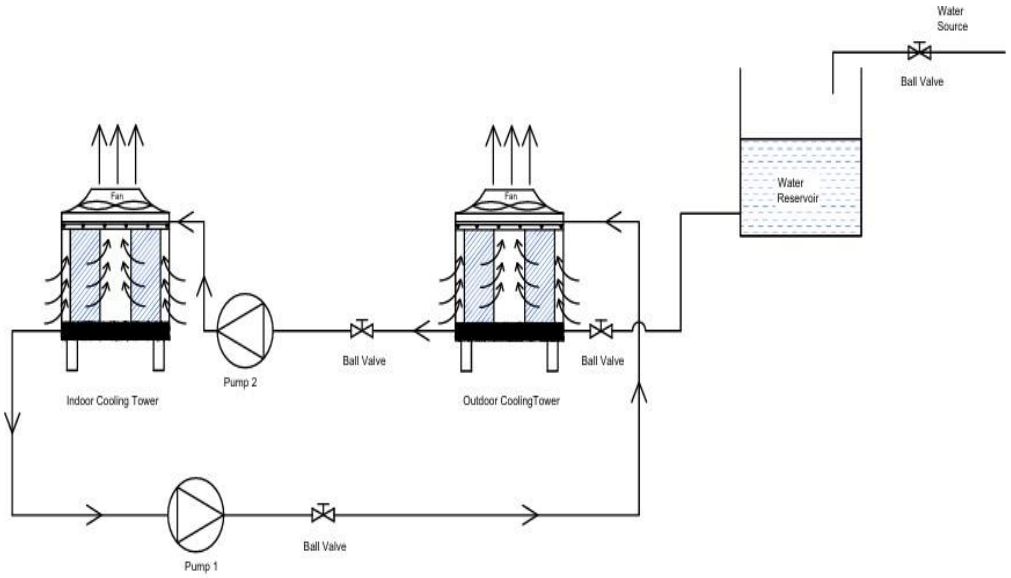


Fig:- Cooling Circuit.

Description:

In this circuit a heat source is used to heat the water present in the reservoir. Here as a heat source gas and burner is used. When the water being heated then the flow started. A gate valve is used to control the speed of the water. Just after gate valve a thermocouple is placed to measure the dry bulb temperature of the water. A pump is used to circulate the flow of water and another gate valve is used to control the speed of the water. A flow meter is used to measure the flow rate of the water and a thermocouple is used to measure the dry bulb temperature of the water once again before it passes through cooling tower. During passes through cooling tower the temperature of the hot water is reduced. Then wet bulb

temperature of the water is measured through thermocouple just after the water passed through cooling tower. Again a pump is used to ensure the circulation of water through pipe and a gate valve is used to control the speed of the water. Then wet bulb temperature of the water is measured once again and water returns to reservoir and cycle continues.

Flow Chart:

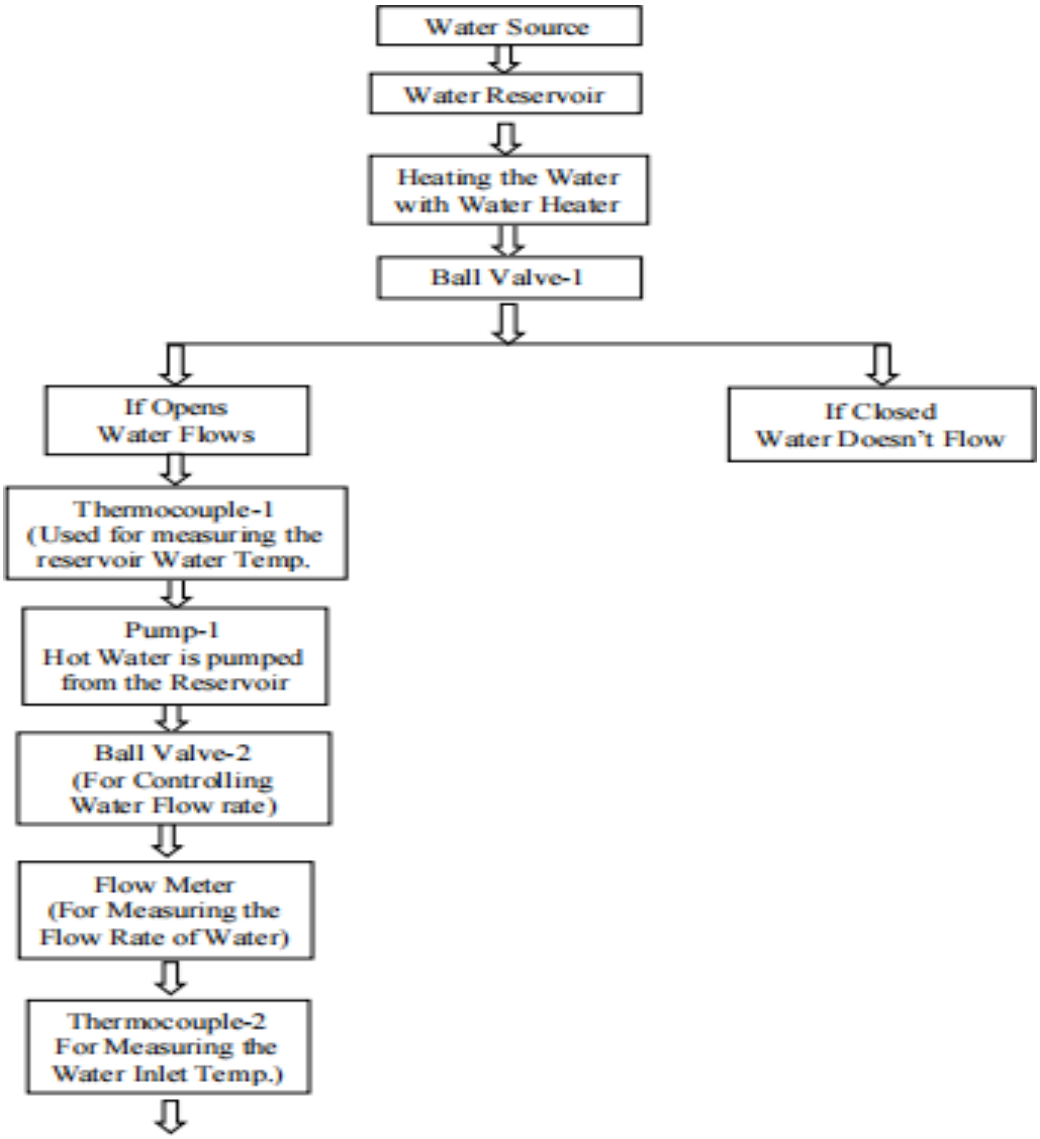


Fig: - Flowchart diagram.

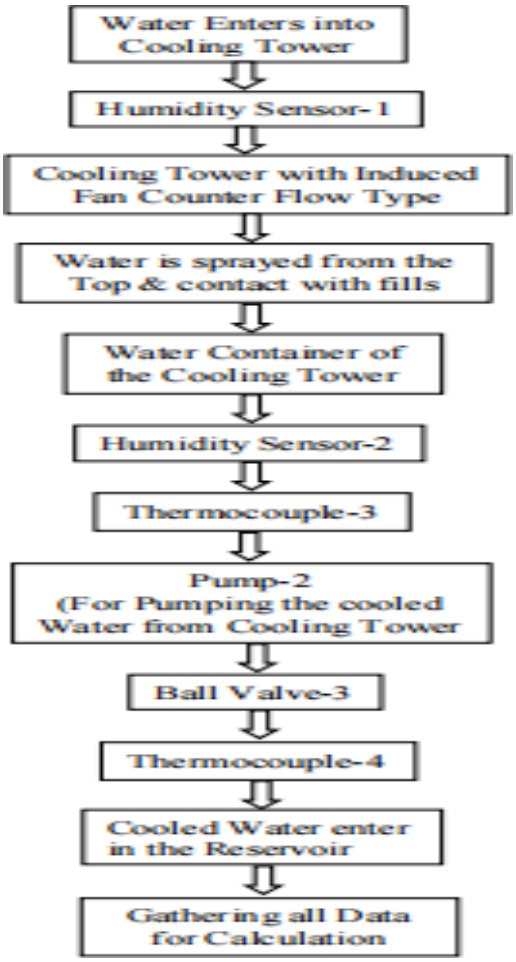


Fig: - Flowchart diagram.

4.4 Air Circuit

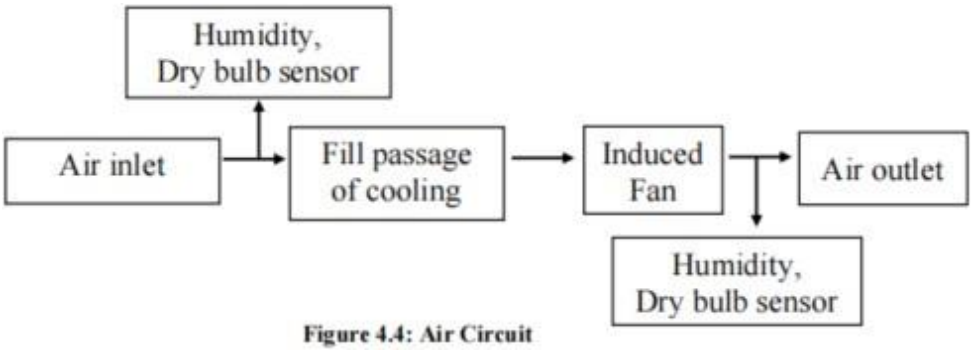


Figure 4.4: Air Circuit

Description:

Air enters through the lower passage of the cooling tower, while entering through the passage there is a dry bulb sensor which gives us the value of humidity of air entering the passage. Continuous air goes through the fill of the cooling tower and it cools down while the induced fan dissipates the heat from the air. Cooled air then goes out through the upper portion of the cooling tower and into the atmosphere. With the help of another dry bulb sensor, we get the value of humidity of the air going out in the atmosphere.

4.5 Water Properties Measurement

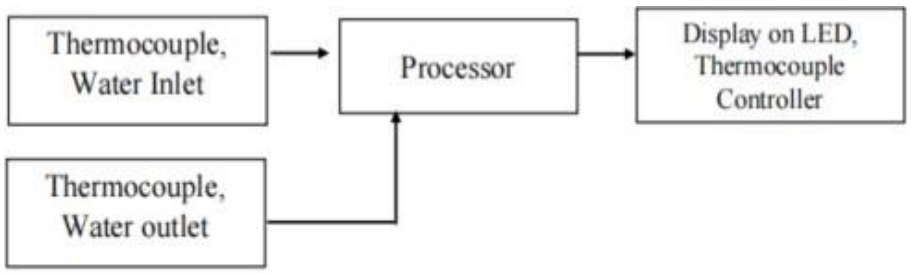


Figure 4.5: Water Properties Measurement Chart

Description:

Water enters through the inlet of cooling tower from a reservoir via a pump of 0.5 hp capacity. There is a water proof temperature sensor which gives us the reading of temperature. An Arduino (which is an open-source computer hardware and software company, project and user community that designs and manufactures single-board microcontrollers and microcontroller kits for building digital devices and interactive objects that can sense and control objects in the physical world) is used here. The water proof sensor which is connected with the Arduino gives us the water properties of the inlet water and displays on the computer screen. Another water proof temperature sensor is attached with the outlet and that is connected with the Arduino and gives us the water properties of the outlet water in the computer display.

4.6 Air properties measurement

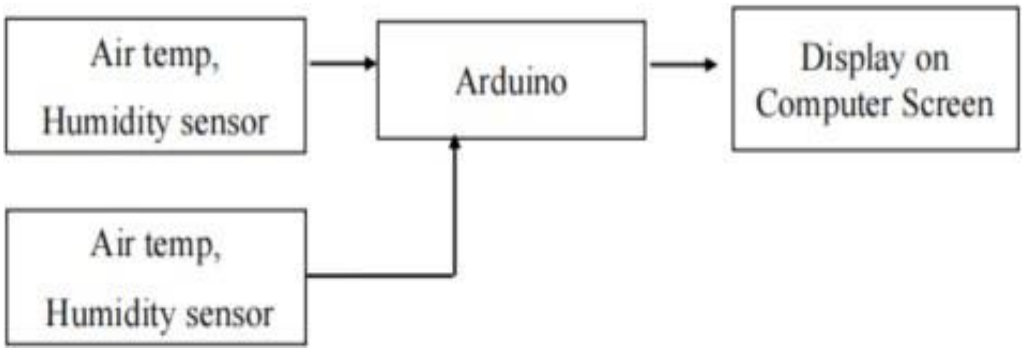


Figure 4.6: Air Properties Measurement Chart

Description:

Air enters through the lower part of the cooling tower and through an air temperature humidity sensor (which is connected with an Arduino) we get the air properties at the inlet in the computer display. Another air temperature humidity sensor is at the upper portion of the cooling tower connected with the Arduino gives us the air properties at the outlet in the computer display.

4.7 Data Collection & Calculation

1. Cooling Range: $R_a = T_{wi} - T_{wo}$

Inlet Water temperature T_{wi} = 42.6 ˚C

Outlet Water temperature T_{wo} = 25.2 ˚C

R_a = 42.6-25.2 = 17.4 ˚C

2. **Cooling Approach**

$R_{th} = T_{wi} - T_2$

Outlet Water temperature T_{wi} = 25.2 ˚C

Wet bulb temperature T_2 = 22 ˚C

R_{th} =25.2-22= 3.2˚C

3. Cooling Efficiency= $\frac{Range}{Range + Approach}$ X 100%

Inlet water temperature = 42.6˚C

Outlet Water temperature= 25.2˚C Wet bulb temperature= 22˚C

17.4/17.4+3.2x100= 84.46%

4. Change in Heat Content Water, $Q = \dot{m}_{w_1} \times c_p \times \Delta T$

Q_1 =1x2.2x(42.5-25.2)

=37.4 J/kg

Chapter – 5

Result & Discussion

5.1 Cooling Tower Characteristics Analysis

Observation	Cooling Range + Approach, R_{th} (˚C)	Cooling Range, R_a (˚C)	Cooling efficiency η %	Change in Heat Content Water, Q_1 (J/kg)
1	20.6	17.4	84.46 %	37.4
2	18	15	71.42 %	33.0
3	14	12	85.71%	26.4
4	14	10	71.41 %	22

5.2 Comparison of Other Cooling System

1. System Type

Feature	Natural Draft Cooling (with small pumps/fans)	AC (Split or Window type)
Cooling Method	Evaporative or airflow-based (low-power fans)	Compressor-driven refrigeration cycle
Electricity Use	Very Low (e.g., ~20 Wh)	High (typically 900–1500 W or more)
Environmental Impact	Low (no refrigerants)	Higher (uses refrigerants like R-32, R-410a)

2.Power & Energy Cost Comparison

Natural Draft Cooling:

- Total power: 19.84 W
- Daily energy use: 19.84 W × 24 hrs
- = 476.16 Wh = 0.476 kWh/day
- Monthly energy: ~14.28 kWh/month
- Yearly energy: ~171.41 kWh/year
- Cost: 831.33 Tk/year (at 4.85 Tk/kWh)

Typical 1-Ton AC:

- Rated power: ~1.1 kW (depending on model and EER/COP)
- Daily use (if 8 hrs./day): 1.1 kW × 8 = 8.8 kWh/day
- Monthly use: ~264 kWh/month
- Yearly use: ~3,168 kWh/year
- Cost: 3,168 × 4.85 = 15,364.8 Tk/year

Cost saving & Environment Friendly

Factor	Best Option
Energy Saving	Natural Cooling
Cost Saving (Yearly)	Natural Cooling
Comfort & Performance	Air conditioner
All-weather Usability	Air conditioner
Eco-Friendliness	Natural Cooling

Chapter – 6

Conclusion

6.1 Conclusion

A comparative study is tried to be carried out in this paper between different cooling fluids with different quality and quantity. First water was taken as cooling fluid and then toner was mixed with water to see whether the efficiency of the cooling tower increases or not. The tower characteristics, efficiency, make up water and heat loss due to evaporation of natural and induced draft cooling with different quality of circulating fluids were evaluated. From the obtained values it was found that when L/G increases it was observed that both efficiency and cooling tower characteristics increase. It is seen that if the flow rate is increased the efficiency of the tower decreases. It was found that due to addition of toner with water the efficiency, range, evaporation heat loss increases. From this comparative study it is seen that using toner and water mixture the efficiency of the tower increases. When water was used in natural draft cooling the efficiency was in average 22% and cooling range was 3º C but when toner mixture was used the efficiency has increased to 26-27% in average and the cooling has jumped to 5º C. The other properties are also shown in graphical representation for both ink and water as cooling fluids.

6.2 Limitations

- Heat source we designed is not controllable and is time consuming.
- We did not calculate the heat content variation due to friction in pipe.
- Flow meter we used have limitation of maximum value 30 L/m.
- No drift eliminator was used.
- Heat loss due to conduction convection drift and windage was not calculated.
- Sensor, we used was able to sense air dry bulb temperature and humidity.
- Then we had to go to psychometric chart to find wet bulb temperature which have probability of having human error.
- Health hazard and environmental hazard of toner was not considered.

- There was a single circuit as a result the cooled water was getting mixed with hot water from the reservoir, as a result the temperature was dropping in the reservoir that was being heated.

6.3 Future Scope

- In this experimental study the heat loss through the pipe & pipe were not being considered. So, in further studies these heat losses can be calculated for getting a better result.
- In this thesis work air mass flow rate was assumed as constant throughout. For further study air mass flow rate at each cell of cooling tower can be calculated.
- In our experimental studies, we could not make arrangement for varying the value of air mass flow. So, in further approach, induced fan (ID fan) with varying speed capacity can be used. Thus, cooling tower performance for carrying air mass flow can be analyzed.
- The cooling water used in our experiment was natural supplied water which contains large fraction of iron. This iron was deposited on flow meter and flow meter accuracy was hampered. So, water treatment plant can be established.
- In our experimental studies we have used a mixture of water and toner. And toner has detrimental effect on environment. So further studies on how to reduce the environmental and health hazard can be done.
- Cost effectiveness of using toner can be studied further.
- A water temperature control system can be developed in further study.
- Heat source we used was combined of 2kw. So time taken to achieve the desire temperature was quite long. So, by increasing heat source capability time taken can be reduced.
- To increase the efficiency of the tower the present single circuit can be divided into two different circuit. One is hot water and another is cold water circuit.

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Appendix A: Physical Properties of Cooling Fluids Used in Cooling Tower Performance Analysis

Property	Units	Water (H_2O)	Ethylene Glycol (50%)	Propylene Glycol (50%)	Al_2O_3–Water Nanofluid (0.1–1%)
Density (ρ)	kg/m³	997	~1,050	~1,030	~1,000–1,100
Specific Heat (Cp)	kJ/kg·K	4.18	~2.4	~2.5	3.8–4.1
Thermal Conductivity (k)	W/m·K	0.6	0.25–0.3	0.2–0.25	0.65–0.8
Dynamic Viscosity (μ)	mPa·s	0.89	~2.5	~3.0	~1.0–2.0
Boiling Point	°C	100	~107	~106	~100
Freezing Point	°C	0	~-37	~-31	~0
Evaporation Suitability	–	High	Low	Low	Moderate
Corrosivity	–	Medium	High (without inhibitor)	High (without inhibitor)	Depends on nanoparticle type
Environmental Safety	–	High	Toxic	Biodegradable	Varies (research-dependent)
Cost Index	Relative Scale	1.0 (baseline)	~1.8	~2.2	~3.0+

Appendix B: Cooling Tower Performance Metrics with Various Cooling Fluids

Performance Metric	Units	Water	Ethylene Glycol (50%)	Propylene Glycol (50%)	Al_2O_3–Water Nanofluid
Cooling Range	°C	8–15	6–12	6–12	10–16
Approach Temperature	°C	2–5	4–8	4–8	1.5–4
Effectiveness	%	75–90	60–80	60–80	85–92
L/G Ratio (Liquid/Gas)	kg/kg	1.2–1.5	1.5–1.8	1.5–1.8	1.1–1.4
Cycle of Concentration (COC)	–	3–7	2–4	2–4	3–6
Blowdown Rate	% of flow	Low	Moderate	Moderate	Low–Moderate
Pump Power Requirement	Relative Scale	1.0 (baseline)	~1.3–1.5	~1.4–1.6	~1.1–1.3
Thermal Efficiency Loss	%	–	10–25% lower than water	10–25% lower than water	2–10% improvement over water
Make-up Water Requirement	% of total flow	Standard	Slightly higher	Slightly higher	Standard

Appendix C: Economic and Lifecycle Cost Comparison of Cooling Fluids in Cooling Towers

Cost Factor	Units / Scale	Water	Ethylene Glycol (50%)	Propylene Glycol (50%)	Al_2O_3–Water Nanofluid
Initial Fluid Cost	USD/L	~$0.001–0.005	~$1.5–2.5	~$2.0–3.0	~$10.0+
Annual Operating Cost	% of system cost/year	Low	Medium–High	High	High
Pump Energy Cost Increase	% compared to water	–	+15–30%	+15–35%	+5–15%
Chemical Treatment Cost	Relative scale	Medium	High	High	High–Variable
Maintenance Frequency	Per year	1–2×	2–3×	2–3×	Variable
System Cleaning Interval	Years	2–3	1–2	1–2	1–2
Corrosion Inhibitor Requirement	–	Moderate	Required	Required	Required or Additive Dependent
Total Lifecycle Cost (10 yrs)	Relative scale (Water=1)	1.0 (baseline)	~2.0–2.5	~2.5–3.0	~3.5+
Environmental Disposal Cost	Relative	Low	Moderate–High	Low–Moderate	Unknown/Under Study