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Thermodynamic Assessment of Global Warming Impacts on the Cooling Tower Performance of Rooppur Nuclear Power Plant

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Abstract

This thesis explores how changing atmospheric conditions—especially air temperature and relative humidity—affect the performance of the cooling tower at the Rooppur Nuclear Power Plant (RNPP) in Bangladesh. To study this, a thermodynamics-based mathematical model was developed to estimate the cooling tower's efficiency under different inlet air conditions. The plant's design inlet temperature and humidity are used as the baseline, and these values were varied to simulate real-world fluctuations under global warming phenomena. The analysis shows that higher ambient temperatures reduce the cooling tower's ability to reject heat. These findings reveal how sensitive the cooling system is to environmental changes and highlight the importance of considering long-term climate trends in the planning and operation of nuclear facilities. For future work, it is suggested to include varying inlet water temperatures based on actual operating conditions, assess the direct impact on condenser performance, and evaluate how global warming over the next 50 years could affect RNPP's cooling capacity.

Keywords: Mass and Heat Transfer, Evaporative Cooling, Climate Sensitivity, Air Temperature and Humidity

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Chapter 1

Introduction

1.1 Overview

Thermoelectric power plants, generate around 80% of the electricity[1], are highly dependent on water to cool the exhaust steam, carries away the heat and then dissipates it to the environment via cooling tower mechanism. Thermal power plants are built to meet up the ever increasing power demand having specified design which includes environmental, specifically climate factors such as ambient temperature, river/seawater temperature, relative humidity etc. These design factors are carefully chosen during planning stage to ensure maximum possible efficiency and reliability of operation.

Cooling towers play a crucial role in this process by rejecting excess heat to the environment, mainly through evaporation. The performance of cooling towers, however, strongly depends on outside air conditions. When the air is cooler and drier, it can absorb more heat and water vapor, helping the tower to perform efficiently. In contrast, during hot and humid weather, its ability to cool the water drops significantly. As a result, the entire thermal cycle gets affected. A higher condenser temperature means higher back pressure, which reduces the overall thermal efficiency of the plant. Therefore, the connection between climate variables and power generation efficiency is directly linked through cooling tower performance.

1.2 Motivation

Ongoing climate change and its consequences affect the performance and efficiency of thermal power plants specially the cooling performance of cooling tower. The efficiency of power plants will decrease with the ongoing rise in air and river/sea water temperatures, as their design conditions are based on long-term average climate data and do not account for abrupt changes. Nuclear power plants are particularly vulnerable to these climate-induced impacts. They typically exhibit lower efficiency and higher water requirements per unit of electricity produced compared to other thermal plant. Secondly, load of thermal power plant is limited by maximum condenser pressure, limited by design, limits the temperature of water entering condenser from cooling tower. That results the shutdown of reactor apparently, more than 30 nuclear power plants were forced to shut down in 2003 due to summer heat wave [2].

This shows how unprepared our energy infrastructure can be when design conditions are crossed due to extreme weather. When cooling water gets warmer, it cannot remove as much heat, leading to operating restrictions or even emergency shutdowns. Climate data from the past is no longer sufficient to predict future performance because temperatures are rising and extreme events like heatwaves are becoming more frequent. These challenges are not just technical, they are also economic and social. Power shortages during high demand seasons can have serious consequences on public life, economy and national security. Therefore, understanding this issue deeply and ahead of time is important to make better decisions for plant design, scheduling, water management and policy planning.

1.3 Research Gap

The Rooppur Nuclear Power Plant (RNPP) in Bangladesh, the country's first nuclear reactor, is expected to commence commissioning in 2025, marking a evolutionary boost in energy sector. As like other nuclear plants, it will rely on cooling tower to remove waste heat. So, environmental factors will affect its performance as Bangladesh is one of the innocent victims of the climate changes in the world due to its low lying geography. However, there is no work/research on how climate change induced factors such as elevated ambient and river water temperature could influence in cooling performance resulting lower efficiency of the plant from the expectation in upcoming years till its lifetime. This gap in knowledge requires a focused study on the impacts of climate change effects on the power generation of RNPP.

Rooppur will operate under the environmental conditions of the north-western region of Bangladesh, where summer temperatures can often cross 38°C and water scarcity is increasing. As the plant is designed to run for several decades, it is important to understand how future temperature trends will impact its cooling performance. No model or study has yet analyzed the daily or seasonal thermal stress that the plant might face due to rising air temperature and humidity. Given the high investment and strategic importance of RNPP, any decline in its expected performance would not only be a technical issue but a national concern. Hence, it is necessary to analyze this matter in advance and provide scientific data that can help optimize future operations or necessary policy adjustments.

1.4 Aim and Objectives

The primary objective of this research is to find out how climate change induced factors will deviate cooling tower performance based on cooling efficiency, required make up water. It will also aim to evaluate the extent at which plant efficiency will deviate from design rating. This research is mandatory because nuclear plant will provide energy security in Bangladesh while reducing carbon emission. The findings of this work will add valuable insights for policymakers, environmentalists about the challenges implied on Rooppur Nuclear Power Plant in changing climate.

This study will use thermodynamic relations to model cooling tower performance under variable ambient conditions such as daily temperature and relative humidity. Design conditions will be compared with projected climate data to calculate deviation in cooling efficiency. Based on this, changes in condenser temperature and overall thermal efficiency of the plant will be evaluated. The impact on water usage, especially the required make-up water, will also be studied to understand water stress in future. In addition to technical analysis, this research will contribute to climate adaptation strategies for nuclear infrastructure. It will highlight how changing climate can affect energy sustainability in countries like Bangladesh and why proactive planning is essential to ensure long-term energy security.

1.5 Thesis Outline

The thesis is structured into six chapters, each contributing to a comprehensive analysis of the cooling tower performance at the Rooppur Nuclear Power Plant under changing climatic conditions.

Chapter One provides the background and motivation for the study, defines the research problem, states the objectives and outlines the scope and limitations of the work. The chapter concludes with an overview of the thesis structure.

Chapter Two presents a critical review of previous research related to cooling tower performance, the influence of atmospheric conditions on thermal systems, and relevant studies on climate variability. This chapter identifies existing research gaps and positions the current study within the broader context.

Chapter Three covers the fundamental concepts related to cooling tower working principle. It introduces the governing equations and theoretical framework necessary for evaluating the tower's performance.

Chapter Four describes the development and implementation of the mathematical model used in this study. It also provides description about materials used.

Chapter Five presents the findings of the study, calculated results and comparison with other existing model.

Chapter Six summarizes the main findings of the research, discusses their practical significance, and outlines limitations of the current work. Recommendations for future research are also provided.

Chapter 2

Literature Review

The literature will emphasize the influence of climate change-induced variables on thermoelectric power plants, particularly nuclear power plants, as considerable attention has been directed toward the energy sector in this century. Additionally, this chapter will pay special attention to studies related to cooling towers and their performance under global warming effect, along with its impact on overall plant efficiency. Literature will also contain previous modeling techniques to analyze key parameters. Schaeffer et al. [3] described the vulnerability of energy sector, especially in thermoelectric power generation due to climate change variable such as air, water temperature and their impacts on cooling efficiency as a whole, plant efficiency. Perera et al. [4] stated the unpredictability to quantify the potential impacts on power supply due to extreme weather variation and showed 16% drop of power supply reliability in unpredictable future weather events. Furthermore, van Vilet et al. [5] demonstrate that 81-86 % of thermoelectric plants will show reduction in usable capacity from 2040-2069 due to climate change and water constraints i.e freshwater scarcity and elevation of water temperature. The studies also provided adaptation techniques such as replacement of fuel and cooling system types etc which will contribute in reducing water demands and decreasing the vulnerability to water constraints under climate change but did not include economic assessment in modeling.

Kopytko and Perkins [6] made an effort to analyze the effects of actual and predicted climate change on existing nuclear power plant by using five key criteria for the analysis. Their findings highlighted that rising cooling water temperatures reduce nuclear reactor energy output due to physical constraints imposed by the Carnot efficiency. Building on this, Durmayaz and Sogut [7] presented a theoretical energy analysis based on thermodynamic first law to estimate the influence of the cooling water temperature. This study assumed that the steam generator (SG) exit conditions remain constant, the PWR thermal power adjusts slowly to maintain steam properties amid seasonal cooling water temperature changes and the condenser vacuum varies with cooling water temperature at a fixed mass flow rate. The study found out 1 °C increase in temperature of the coolant extracted from environment is predicted to yield a decrease of 0.45% and 0.12% in the power output and the thermal efficiency of the pressurized-water reactor nuclear-power plant while Linnerud et al. [8] used regression estimates to illustrate the two climate impacts- reduced efficiency and reduced load. Including both impacts, the study showed that 1 °C rise in air temperature reduces output by 0.96 – 1.10% within an hour, effectively reinforces the critical link between thermal limitations and climate-induced performance reductions in thermoelectric facilities.

Several works are done based on thermodynamic analysis of secondary circuit of nuclear power plant. Ibrahim et al.[9] developed a mathematical model based on heat balance equation to analyze and evaluate the thermal performance of the secondary circuit of a nuclear power plant under the rise in cooling water temperature due to climate variable effects. The study found that a change in cooling water temperature from 15 to 30 °C would result in a decrease in plant efficiency from 37.57 to 35.3% which is equivalent of 0.16% decrement for 1 °C increase of temperature. Building on this, Khan et.al [10] developed his model based on simplified rankine cycle for the secondary loop of VVER-1200 and predicted that the plant efficiency will go down from 37.44% to 33.65% for the change of condenser pressure in 4 kPa to 15 kPa. As condenser operating pressure is directly related to tertiary circuit cooling water temperature associated with ambient air conditions, study stated that it would cost more for building nuclear power plants in tropical region than cold countries.

Some studies evaluated cooling tower performance based on different assumption and modeling under the effect of climate induced variables such as change of temperature of ambient air. Papaefthymiou et al. [11] developed a model to assess the thermal performance characteristics of a wet cooling tower under varying ambient air conditions. The analysis assumes steady-state heat and mass transfer, with the specific heat capacities of the sprayed water, serpentine water, and dry air remaining constant within the considered temperature range. It is also assumed that water and air flow in a counter flow arrangement. One notable finding was the increase in cooling tower effectiveness due to the reduced temperature difference between the cooled water and its ideal value, observed when comparing mid-summer to mid-winter conditions. In a related study, Jagadeesh et al. [12] evaluated the performance of a natural draft cooling tower across two different seasons and reported a 15.10% drop in efficiency from winter to summer. Further, Ayoub et al. [13] built up a model based on conservation laws thermodynamics - mass and energy balance- to evaluate cooling tower performance in changing climate. For sensitivity analysis, three environmental parameters were varied- Dry bulb temperature, Relative humidity and Make up water temperature. The result showed that cooling efficiency remained 100% within design limit but a non linear and drastic drop occurred as soon as parameters went over design value. The study also provided optimization of cooling tower design but suggested it would be uneconomical in present climate scenario.

Chapter 3

Theoretical Framework

A cooling tower is an essential component in thermoelectric power plant especially where water is not abundant enough. In nuclear power plant such as Rooppur, recirculating water flows from cooling tower to condenser in order to absorb heat from exhaust steam coming out of the turbine outlet and gets heated up. The hot water then enters the cooling tower to reject heat into atmosphere by interacting with air and gets cooled.

The first section of this chapter will present the theoretical background to understand how cooling process occurs in cooling tower and the factors that influence its performance. It will begin by introducing fundamental concept about evaporation as well as key variables- dry bulb and wet bulb temperature- and their impacts on evaporation. It will also explain about natural convection- a fundamental mechanism deeply associated with heat removal in cooling tower.

The following section will explain the construction of a cooling tower-specifically focusing natural draft cooling tower- followed by an explanation of its working principle. Additionally, it will highlight the possible effects of global warming on cooling tower performance and the resulting implications on condenser operating pressure. After providing a thermodynamic cycle, the section will outline the challenges currently faced by cooling towers under changing climatic conditions.

3.1 Evaporative Cooling

Evaporation is a natural process in which vaporization occurs at the surface of a liquid, typically at temperatures below the liquid's boiling point. According to Oxford English Dictionary **Evaporative Cooling** is defined as the "Reduction in temperature resulting from the evaporation of a liquid, which removes latent heat from the surface from which evaporation takes place. This process is employed in industrial and domestic cooling systems, and is also the physical basis of sweating" [14].

A cooling tower is a specialized heat and mass transfer device in which air and warm water are brought into direct contact with each other in order to reduce the recirculating water temperature. During this process, a small volume of water is evaporated as well as extraction of heat from the remaining water (sensible heat) that reduce the temperature of the water being circulated through the tower. Circulating water- which has been heated by absorbing thermal energy from exhaust steam in condenser- is pumped to the cooling tower through pipes. Water entering the cooling tower is sprayed through nozzles onto layers of heat transfer media called "fill," which slows the flow of water through the cooling tower, and creates greater surface area for the water to spread for maximum air-water contact [15]. In case of natural draft cooling tower- as the water flows through the cooling tower, it is exposed to air being drawn through the tower by the natural draft created by the temperature-induced density difference between the warm air inside the tower and the cooler ambient air outside. Evaporation stops when air becomes saturated in air-water interface and the amount of evaporation is greatly dependent on the dryness of incoming air. Higher humidity of inlet air means ineffective evaporation which results in poor cooling performance [16].

3.2 Dry & Wet bulb temperature and impacts on evaporation

Dry Bulb Temperature: Dry Bulb Temperature (DBT) – denoted as t_{db} – is basically the ambient air temperature. DBT is measured by a standard thermometer exposed to air which is shielded from moisture and radiation of the air. DBT reflects the heat content of the air, usually measured in Celsius(°C) or Fahrenheit (°F). It is an important variable in design and efficiency of cooling tower.

Wet Bulb Temperature: Wet Bulb Temperature (WBT) – denoted as t_{wb} – is defined as the lowest temperature to which something (eg. air) can be cooled under current ambient conditions by the evaporation of water only.

Ambient wet bulb temperature is measured by using psychrometer. A psychrometer applies a thin layer of water to the thermometer bulb, which is then spun in the air. After about a minute, the thermometer displays a reduced temperature. The lowest point at which further spinning does not decrease the temperature is called the wet bulb temperature. The recorded wet bulb temperature depends on both relative humidity and ambient air temperature. Wet bulb temperature fundamentally indicates the amount of water vapor the air can accommodate under current atmospheric conditions. A lower wet bulb temperature indicates drier air that can absorb more water vapor compared to air at a higher wet bulb temperature [17].

A cooling tower cools water by using latent heat of vaporization. Cooling tower design and performance is dependent on water inlet temperature, outlet temperature, flow rate and wet bulb temperature. Theoretically cooling tower can cool the inlet hot water down to wet bulb temperature of air by evaporation. But in practical scenario, the cooled water temperature is somewhat 5-10 °C higher than T_{db}. The temperature difference between inlet and outlet water is called cooling range while the difference between cooled water temperature and wet bulb temperature is called **approach**.

Impacts on Evaporation: The amount of evaporation of water is highly dependent on the difference between dry bulb and wet bulb temperature. A higher difference indicates less humid air which means air contains less water vapor. It allows air to absorb more water vapor and cools the water by a greater extent. In contrast, a smaller difference between DBT and WBT indicates higher humidity in the air, meaning air can not hold much more water vapor and evaporation is reduced and so does cooling tower efficiency.

3.3 Natural Convection

Convection is one of the major modes of heat transfer that actually occurs through two mechanisms—diffusion and advection. When energy is transferred due to the random motion of molecules, it is called diffusion, while the transport of energy due to the bulk motion of fluid is referred to as advection. Total heat transfer is the combination of both, since the molecules moving as a bulk also retain their individual random motion. Therefore, it is customary to use the term convection to represent both processes [18]. There are two types of convection processes—forced and natural convection. Here, natural convection will be discussed since it is related to the main context.

Natural convection is a mechanism where fluid motion occurs by natural means, to be specific, mass and heat is transferred by fluid motion created by density difference due to temperature gradients. There is no use of external source like fans, motors which is generally used in forced convection. The force acts behind natural convection is buoyant force. It is also known as free convection.

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3.4 Construction of a Natural Draft Cooling Tower & Working Principle

Natural draft cooling towers are unique in shape having slim middle body and wide at top and base, usually called hyperbolic towers. This type of cooling tower are very expensive to build, only found in coal or nuclear power plant where large cooling requirement exists over a long period of time. This section will provide a detailed description of the structural components, including their materials and functional significance.

3.4.1 Hyperboloid Tower

One of the prominent feature of natural draft cooling tower is their towering height and hyperboloid shape. The hyperboloid shape provide two distinguished advantages:

1. This shape allows to build the large tower with minimal amount of constructing material.
2. The hyperboloid shape creates natural convective current of air that allows continuous air flow and thus, serves cooling purpose.

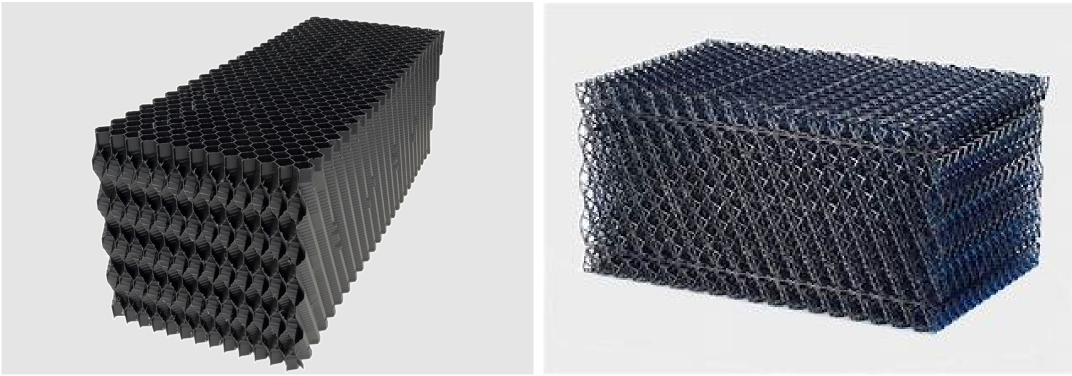
Stack Effect: When air moves upward, it accumulates heat via evaporation and sensible heat loss of water. Hot and moist air are less dense than comparatively cold and dry air. Due to this difference in densities, heated air rises up towards the top of the tower that leads to surrounding ambient air to enter the cooling tower and make a chain of continuous flow. This is called stack effect.

Materials: Rooppur NPP has four natural draft cooling tower, two for each unit. The hyperbolic tower is 175 meter tall relative to ground. The tower is a RCC (Reinforced Cement Concrete) structure in which concrete provides compressive strength and steel handles tensile stress.

Figure 3.1: Cooling tower cross-section view [19]

3.4.2 Fill

Fill is an important component in a cooling tower that expands the interaction area between incoming air that is moving upward due to density difference and circulating water falling down due to gravity. Cooling towers typically have two types of fill configuration– splash fill and film fill. Film is more effective than splash as splash employs breaking water into droplets while thin film is created over surfaces in film fill configuration which serves better cooling efficiency but expensive than splash.
Materials: Usually fills are made by PVC or polypropylene.



(a) film fill **(b) Splash fill**

Figure 3.2: Fill Variations

3.4.3 Drift Eliminators

Along with evaporation, some amount of water droplets escape from the cooling tower, which is called drift loss. The visible white plume often seen rising from natural draft cooling towers is primarily composed of this drift, representing a loss of water that must be replenished by make-up water.

To reduce drift losses, drift eliminators are used in the cooling tower. These devices are composed of parallel blades designed to remove water droplets carried by the exiting air. The eliminators force the air stream to follow a winding, multi-directional path. While air can easily navigate these changes in direction, the water droplets cannot; they strike the surfaces of the eliminator and eventually fall back onto the fill section before returning to the cooling tower basin.

3.4.4 Air Inlet and Outlet

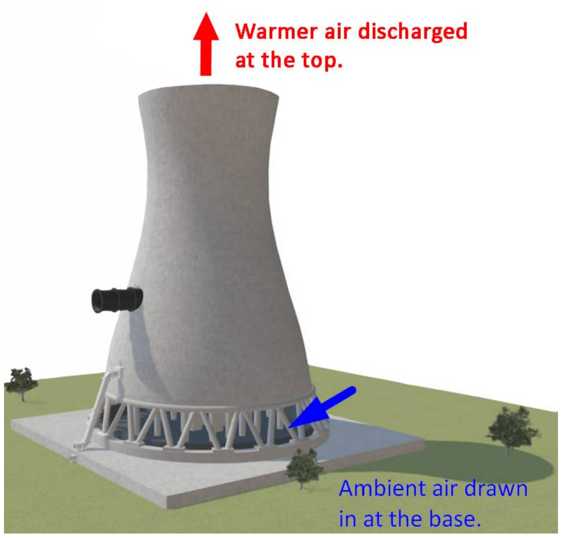


Figure 3.3: Air Flow Directions [19]

Air Inlet: For cooling purpose, air inlet allows ambient air to enter the cooling tower through the base. Usually air enters around 5-10 meter high relative to ground.

Air Outlet: Warm and highly humid air is discharged on top of the tower as shown in Figure- 3.3

3.4.5 Water Distribution System

: This system evenly distributes hot water over the fill material, maximizing heat exchange. It typically comprises spray nozzles and distribution headers made from corrosion-resistant materials like PVC or stainless steel.

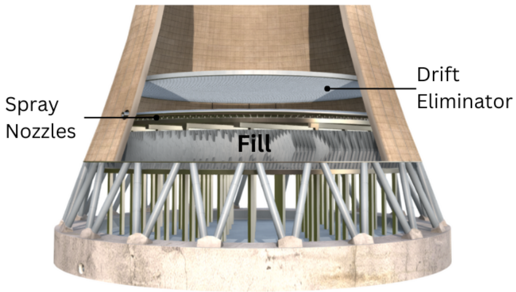


Figure 3.4: Spray Nozzle [19]

3.4.6 Working Principle

In natural draft cooling towers-also known as natural convection cooling tower-use the principle of convection to allow air circulation. Cold recirculating water absorbs heat from the turbine exhaust steam and becomes hotter. The warm water enters the cooling tower that needs to be cooled and sent back to condenser to continue the loop. This hot water is sprayed downward inside the tower while ambient air is pushed upwards. Spray nozzles are used to distribute hot water evenly over the **fill** so that maximum surface area can be achieved for the interaction between hot water and rising air and better heat transfer can obtain. As air moves upward, it gets heated and becomes less dense and rises to the top that draws in more air from outside and creates a chimney (stack) effect. Usually the density difference between hot air and cold air is very low since heat transfer coefficient in natural convection is low. So to enhance higher buoyant-driven flow - governing equation($\Delta P = \Delta \rho g H$)- these type of cooling towers are very tall typically more than 150 meter.

3.5 Global Warming possible consequences on cooling tower performance

Global warming poses a significant threat to humankind as it is responsible for extreme weather events (heatwaves, droughts) by contributing to the long-term temperature increase on the Earth's surface. As cooling tower performance deeply relies on ambient air temperature and humidity, rise in temperature will negatively affect its performance.

Global warming causes a rise in ambient air temperature. Due to the increment of inlet air temperature, air will not be able to cool hot water coming from condenser. Eventually the circulating water will have more enthalpy than it should be and affect condenser operating pressure.

Hot and Humid Weather:High humidity reduces the evaporation rate because the air already holds a large amount of moisture. As a result, the incoming warm water will not be sufficiently cooled before returning from the cooling tower to the condenser.

Hot and dry Weather Elevated ambient temperatures combined with low humidity enhance the evaporation rate, leading to greater water loss. This increased loss must be compensated by additional makeup water.

3.6 Challenges Cooling Towers Are Currently Facing

Cooling systems play a vital role in power plants etc. by removing the heat from the hot recirculating water and allowing the plant to operate efficiently. However, in recent years, several challenges have appeared that make this process more difficult. These challenges are becoming more serious due to climate change, limited water resources, and stricter environmental rules. Some of the major issues are explained below:

- **Higher Ambient Temperatures:** Due to global warming, the outside air temperature is rising in many regions. When the air is hotter, it becomes harder for cooling systems—especially cooling towers—to remove heat. This reduces the overall efficiency of the power plant and can even lead to lower electricity production on hot days.
- **Water Shortages:** Most traditional cooling systems need a lot of water to operate. But in many areas, especially during dry seasons, water is becoming scarce. This makes it difficult for power plants to get enough cooling water, which can limit their operation or force them to use more expensive technologies like dry or hybrid cooling.
- **Stricter Environmental Laws:** Governments and environmental agencies are now putting stricter rules on how much water plants can withdraw and how hot the water they release can be. These regulations aim to protect rivers and lakes but also make it harder for power plants to use traditional cooling methods.
- **Thermal Pollution:** When power plants release hot water into nearby rivers or lakes, it can harm fish and other aquatic life. This issue, known as thermal pollution, becomes more serious during warm weather, when the natural water bodies are already under stress.
- **Old Infrastructure and Changing Climate:** Many cooling systems in use today were designed based on weather conditions from decades ago. As the climate changes, these old systems may no longer perform well, leading

to more breakdowns and higher maintenance needs.

- **Energy Costs of Advanced Cooling:** Some modern cooling technologies use less water, but they require more electricity to run (for example, fans in dry cooling systems). This added energy use, known as the "parasitic load," slightly reduces the net electricity output of the plant.

In brief, cooling towers are under pressure due to changing weather, limited water supply, and tighter regulations. Power plants must now look for smarter and more efficient cooling solutions to keep running reliably in the future.

3.7 Mass and Energy Balance Equation for Natural Draft Cooling Tower

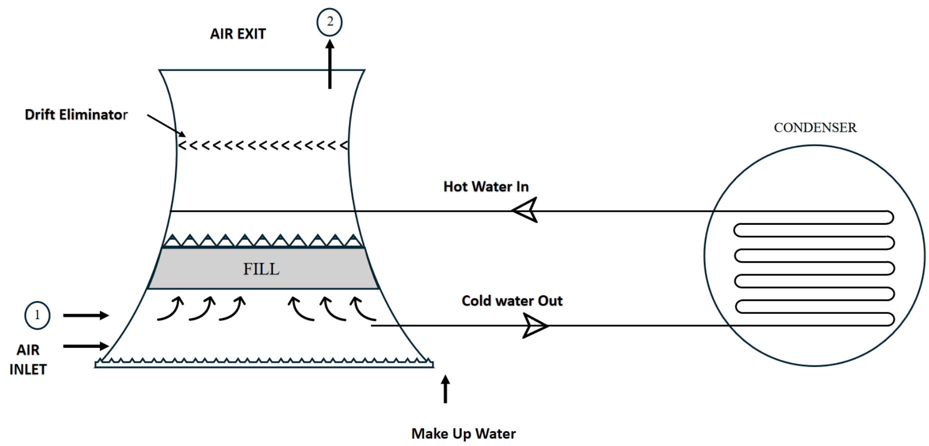


Figure 3.5: **Schematics of flow directions of Natural Draft Cooling Tower**

In Figure- 3.5, a schematics is shown. Now we will write mass balance equation for cooling tower.

Mass conservation Equation

$$\dot{m}_w^{in} + \dot{m}_a^{in}\omega^{in} + \dot{m}_w^{make-up} = \dot{m}_w^{out} + \dot{m}_a^{out}\omega^{out} \tag{3.1}$$

Here
$\dot{m}_w^{in}$ = inlet water mass flow rate (kg/s);
$\dot{m}_w^{out}$= outlet water mass flow rate (kg/s);
$\dot{m}_a^{in}$ = inlet air mass flow rate (kg/s);
$\dot{m}_a^{out}$= outlet air mass flow rate (kg/s);
$\dot{m}_w^{make-up}$= make-up water flow rate(kg/s);
ω_{in} =specific humidity of inlet air (kg_{water}/kg_{air});

ω_{out} =specific humidity of outlet air(kg_{water}/kg_{air});
Assumption: We will assume the recirculating hot water(denoted as t_w^{in}) entering cooling tower and cold water (denoted as t_w^{out}) leaving the tower will possess same flow rate. Same will follow for air as well.

$$\dot{m}_a^{in} = \dot{m}_a^{out} = \dot{m}_a$$
$$\dot{m}_w^{in} = \dot{m}_w^{out} = \dot{m}_w^c$$

Eq. 3.1 can be rewritten as;

$$\dot{m}_w^{make-up} = \dot{m}_a(\omega^{out} - \omega^{in}) \tag{3.2}$$

Eq. 3.2 can be used to calculate make- up water flow rate if air flow rate and specific humidity of inlet and outlet air are known.

Energy conservation in cooling tower

$$\dot{m}_w^{in} h_w^{in} + \dot{m}_a h_a^{in} + \dot{m}_w^{make-up} h_w^{make-up} = \dot{m}_w^{out} h_w^{out} + \dot{m}_a h_a^{out} + \dot{m}_w^{drift} h_w^{in} \tag{3.3}$$

Here,
h_w^{in} = inlet water enthalpy(kj/kg);
h_w^{out}= outlet water enthalpy (kj/kg);
h_a^{in} = inlet air enthalpy (kj/kg);
h_a^{out}= outlet air enthalpy (kj/kg);
$h_w^{make-up}$= make-up water enthalpy (kj/kg);

Energy conservation for condenser

$$\dot{m}_w^{in} h_w^{in} - \dot{m}_w^{out} h_w^{out} = Q = \dot{m}_w^c (h_w^{in} - h_w^{out})$$

Here Q is the rejected heat. So Eq.(3) can be rewritten as,

$$\dot{m}_a(h_a^{out} - h_a^{in}) - \dot{m}_w^{make-up} h_w^{make-up} = Q \tag{3.4}$$

Both Eq. 3.2 & Eq. 3.4 has an input called air flow rate that is unknown. Air flow rate $(\dot{m}_a)$, outlet air temperature(t_a^{out}) and enthalpy(h_a^{out}) will be determined for every input of inlet air temperature with its humidity. The algorithm will be described in following chapter. When the above mentioned parameters are known, rejected heat can be calculated and compare the value with designed one and evaluate efficiency.

Cold water that leaves the cooling tower will be mixed with make-up water to compensate for evaporation loss, as well as a negligible amount of loss from drift and leakage. In our work, we will not consider drift and leakage losses as they contribute a minimal amount. The outlet water temperature can be calculated by following formula -[13]

$$t_w^{out} = \frac{\dot{m}_w^{make-up} t_w^{make-up} + (\dot{m}_w^{out} - \dot{m}_w^{make-up}) t_w^{cooled}}{\dot{m}_w^{out}} \tag{3.5}$$

Here, t_w^{cooled} is the water temperature before mixing with make up water. Since evaporation loss is not considerable amount, t_w^{cooled} and t_w^{out} will be almost equal. And we will follow that in our calculation. Finally, Cooling tower efficiency will be determined by;

$$\eta = \frac{Q_{rej}}{Q_{design}} \tag{3.6}$$

In the following chapter, a detailed calculation will be provided on how we determine certain design parameters under extreme conditions. These include outlet water temperature, outlet air temperature and humidity, and most importantly, the calculation of air flow rate—all under design extreme conditions. If air flow rate, outlet air temperature and humidity are known, it is possible to calculate efficiency at various inlet air temperature.

3.8 Merkel Model

Dr. Fredrick Merkel was the first to introduce a theory for calculating cooling tower performance. In his model, heat is first transferred from the water to a thin theoretical film by convection, and then from that film to the surrounding air by evaporation. Although the theory was initially developed for counter-flow contact between water and air, it has since been applied to various types of cooling towers.

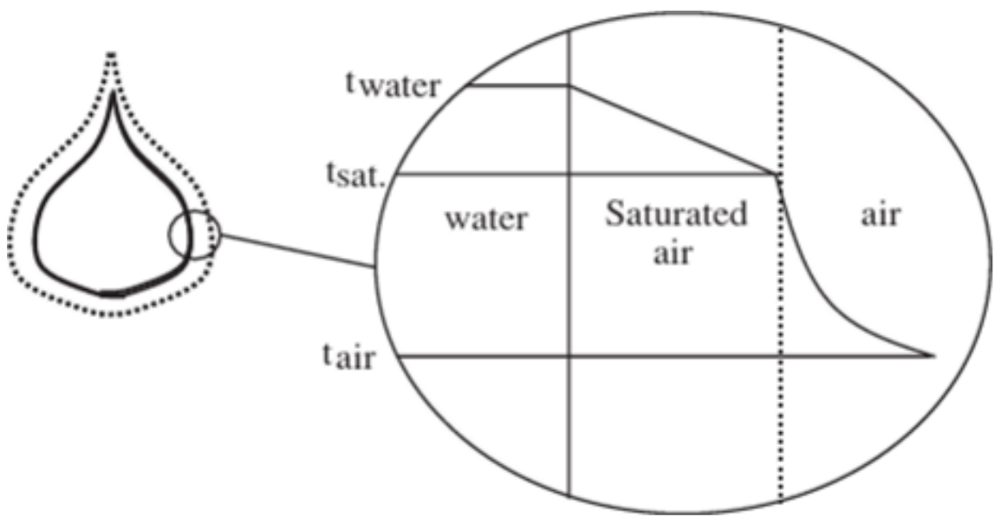


Figure 3.6: Merkel Evaporative Cooling Model [20]

Assumptions made by Merkel: [20]

1. Heat and mass transfer occur in a one-dimensional, steady-state, counter flow process between air and water.
2. Water flows as a thin film over the fill, and the air contacts this film directly, always at the water temperature.

3. The process is steady-state, with no accumulation of heat or mass.
4. Radiative and conductive heat transfers are negligible compared to convective and evaporative transfer.
5. The water vapor behaves as an ideal gas; absolute humidity is proportional to vapor partial pressure.
6. The Lewis number is assumed to be one, meaning heat and mass transfer coefficients are related.
7. The mass of evaporated water is negligible compared to the circulating water flow.
8. The specific heat of the air-vapor mixture and the latent heat of vaporization are constant.
9. The driving potential for transfer is the enthalpy difference between saturated air at water temperature and the bulk air.

So in steady state conditions, the heat loss by water is gained by air. That simplifies,

$$\dot{m_w} C_p \Delta T = \dot{m_a} \left(h_a^{out} - h_a^{in} \right)$$

This can be rewritten as

$$\frac{\dot{m_a}}{\dot{m_w}} = \frac{C_p \Delta T}{(h_a^{out} - h_a^{in})}$$

The left side is denoted by λ, often called relative air flow rate

$$\lambda = \frac{C_p \Delta T}{(h_a^{out} - h_a^{in})}$$

For the system inefficiencies, factor K is introduced.

$$\lambda = \frac{C_p \Delta T}{K(h_a^{out} - h_a^{in})} \tag{3.7}$$

In ideal case, K= 1. Eq. 3.7 will be used in our methodology.

Chapter 4

Materials and Methods

4.1 Introduction

The purpose of this study is to evaluate the cooling efficiency of the Rooppur Nuclear Power Plant (RNPP) under changing climatic conditions by analyzing the effects of varying ambient air temperature and relative humidity. Accordingly, the central problem addressed in this study is to assess how the natural draft cooling tower at RNPP will perform under variation in air temperature and humidity. A thermodynamics-based mathematical model will be employed to evaluate the performance of the cooling tower. This chapter focuses on describing the materials and tools used, along with the methods applied to analyze the stated problem. The methodology section will detail the mathematical model and explain how it is used to assess the performance of the cooling tower.

4.2 Materials

4.2.1 CoolProp

In this study, thermophysical properties of fluids were obtained using CoolProp, an open-source C++ library with wrappers for several programming environments including Python and MATLAB. CoolProp provides accurate and reliable property data for pure fluids, humid air, and mixtures based on state-of-the-art equations of state and empirical correlations. The software was used to compute properties such as:

1. Saturation temperature and pressure
2. Enthalpy and entropy of moist air
3. Density and specific heat capacity of air-water vapor mixtures
4. Density and specific heat capacity of air-water vapor mixtures

To accurately evaluate the thermophysical properties of air and water vapor mixtures under varying ambient conditions, this study employed CoolProp, an open-source thermophysical property database and calculation engine. CoolProp supports a wide range of fluids and mixtures and provides state-of-the-art equations of state, such as the **IAPWS-IF97** formulation for water and Helmholtz energy-based multi-parameter equations for many refrigerants and gases.

CoolProp was accessed through its Python interface, allowing integration with the numerical modeling workflow. Two primary functions were utilized for property evaluation:

PropsSI: The **PropsSI** (short for Properties in SI units) function is used to compute a wide range of thermodynamic properties for pure fluids or mixtures.

HAPropsSI: The **HAPropsSI** function is used to compute properties of moist air mixtures, which are essential for modeling processes involving evaporation and condensation, such as cooling tower performance. [21]

4.2.2 Use of MATLAB for Modeling and Analysis

The computational framework of this study was developed using **MATLAB R2023a** (MathWorks Inc., Natick, MA, USA), a high-level numerical computing environment widely used in engineering research for modeling, data processing, and visualization.

MATLAB was employed for multiple core tasks throughout the study, including:

- **Integration with CoolProp**: MATLAB served as the primary platform to interface with the CoolProp library through its MATLAB wrapper, enabling direct access to thermophysical and psychrometric properties using the `PropsSI` and `HAPropsSI` functions.
- **Equation Solving**: The modeling workflow involved solving nonlinear equations representing energy and mass balances in the cooling tower system. These were implemented using MATLAB's built-in solvers
- **Iteration and Looping**: Iterative calculations were required for simulating cooling tower performance under varying ambient conditions. MATLAB's loop constructs and vectorized operations were employed to efficiently handle these computations.
- **Plotting and Data Visualization**: MATLAB's plotting functions were used to generate figures.

The use of MATLAB ensured reproducibility and clarity in the modeling process, and facilitated robust numerical handling of complex thermodynamic relationships.[22]

4.3 Methodology

This section will describe the mathematical model to evaluate cooling tower performance. First, it will establish the model for design parameters, apply iterative method to find some useful parameters and verify the guess value and finally analyze cooling tower performance by using the established model.

4.3.1 Design Parameters and Assumptions

In this section, we define all parameters relevant to cooling tower performance and clearly state the assumptions underlying the analysis.

Inlet Water Temperature The hot water returning from the condenser to the cooling tower is referred to as the inlet water. In this analysis, its temperature is assumed to remain constant throughout. It is further assumed that the circulating water absorbs a consistent amount of heat in the condenser and enters the cooling tower at the same temperature, regardless of variations in the outlet water temperature.

Outlet Water Temperature The cold water that will leave the cooling tower after losing heat is called outlet water. Outlet water temperature will vary according to air thermodynamic conditions.

Water Flow rate Recirculating water that will from condenser to the tower and then fall due to gravity and go through nozzle and fill to maximize the heat exchange area with incoming air. The flow rate is assumed to remain constant in our analysis.

Inlet Air Condition Air is drawn into the tower by natural convection in natural draft cooling tower. First we will take the design extreme values for inlet air temperature and humidity to calculate some unknown parameters like air flow rate and then vary it as we are deeply concerned about rising temperature in the world due to global warming.

Outlet Air Condition The humid air will be discharged at the top of the tower to the environment is called outlet air. Outlet air condition are deeply linked to inlet air conditions and air flow rate.

Air Flow rate Air flow rate is an important factor to calculate cooling tower performance as it is seen in eq. 3.2 and eq. 3.4 where air flow rate is an unknown quantity. For a certain inlet air condition, air flow rate will remain constant both inlet and outlet.

Known design parameters are given below :

Inlet Air Condition	Inlet Water Condition	Water Flow Rate
Temperature: t_a^{in}= 30°C Humidity = 50.9%	Temperature: t_w^{in}= 60°C	$\dot{m}_w$= 100000 $\frac{m^3}{h}$

Table 4.1: Design Parameters [23]

4.3.2 Mathematical Model

Now we will generate the model to calculate air flow rate, outlet air temperature and humidity for design condition that are tabulated in table- 4.1. We will introduce four equations and utilize iterative approach to find our required parameters.

$$\lambda = \frac{C_p \Delta t}{K(h_a^{out} - h_a^{in})} \tag{4.1}$$

This equation is derived from Merkel model already shown in previous chapter. λ represents relative air flow rate, C_p is the specific heat at constant pressure for water. Δt is the temperature difference between hot water and cold water.

$$t_a^{out} = t_a^{in} + 13.7 \times 10^4 (\omega_{out} - \omega_{in}) \left(\frac{t_w^{in} + t_w^{out} - t_a^{in} - t_a^{out}}{P_1'' + P_2'' - P_1 - P_2 - 2\delta P''} \right) \tag{4.2}$$

Eq.4.2 is an empirical equation [24] that will be used to calculate outlet air temperature.

Notation meaning:

P_1''= vapor pressure at inlet water temperature;

P_2''= vapor pressure at outlet water temperature;

P_1 = vapor pressure at inlet air temperature;

P_2 = vapor pressure at outlet air temperature;

The term $\delta P''$ can be calculated from

$$\delta P'' = 0.25(P_1'' + P_2'' - 2P_m'')$$

Here P_m'' is the vapor pressure at $(t_w^{in} + t_w^{out}/2)$ °C

Now we will introduce the third equation that is related to heat exchange area of air and water.

$$F = \frac{\lambda \dot{m}_w (\omega_{out} - \omega_{in})}{\Delta\beta_p \Delta p_{cp}} \tag{4.3}$$

Notation meaning:

F = Heat exchange area between air and water (m^2);

λ = relative air flow rate (kg/s);

$\Delta\beta_p$ = mass transfer coefficient per unit vapor partial pressure (kg/m^2sPa)

Δp_{cp} = average change of partial pressure

$\Delta\beta_p$ Calculation :

$$A(Re)^n = \frac{\Delta\beta_p d}{D}$$

Here, Re is the Reynold Number, A and n are constant. Their value depends on Re.

Re	A	n
$Re < 10^4$	0.0008	1.18
$Re > 10^4$	0.028	0.8

Table 4.2: Values of A and n

From this equation we can find $\Delta\beta_p$. D is the diffusion coefficient of inlet air, d is the fill diameter. But first we need to find Reynold number.

$$Re = \frac{v_o d}{\nu_f}$$

Here v_o is the air relative velocity (m/s) . ν_f is the kinematic viscosity (m^2/s). Air flow velocity will be found from air flow rate and kinematic viscosity can be found from CoolProp in indirect way. So, first we determine Reynold number then calculate $\Delta\beta_p$.

Δp_{cp} calculation: It will be calculated directly from the following formula

$$\Delta p_{cp} = \frac{\Delta P_1 - \Delta P_2}{ln\left(\frac{\Delta P_1 - \delta P''}{\Delta P_2 - \delta P''}\right)}$$

Here, $\Delta P_1 = {P_1}'' - P_2$;
$\Delta P_2 = {P_2}'' - P_1$;

Now we will introduce the fourth equation that is related to relative air flow rate. It is a semi empirical formula. [25]

$$\lambda = \frac{F_b}{\dot{m_w}}\left(\sqrt{\frac{H(\rho_2^2 - \rho_1^2)g}{\xi}}\right) \tag{4.4}$$

This is another equation to calculate relative air flow rate. Notation meaning:
F_b = Fill cross sectional area (m^2) ;
H = Height of cooling tower relative to air inlet (m);
ρ_1= density of inlet air (kg/m^3);
ρ_2= density of outlet air (kg/m^3);
ξ = drag coefficient;

Now we will develop an iterative method based on above mentioned four equation to calculate air flow rate, outlet water temperature, outlet air temperature, outlet air humidity for inlet air design condition.

In this process, along with inlet water temperature and water flow rate, heat exchange area between air and water will be fixed.

Flowchart of our approach :

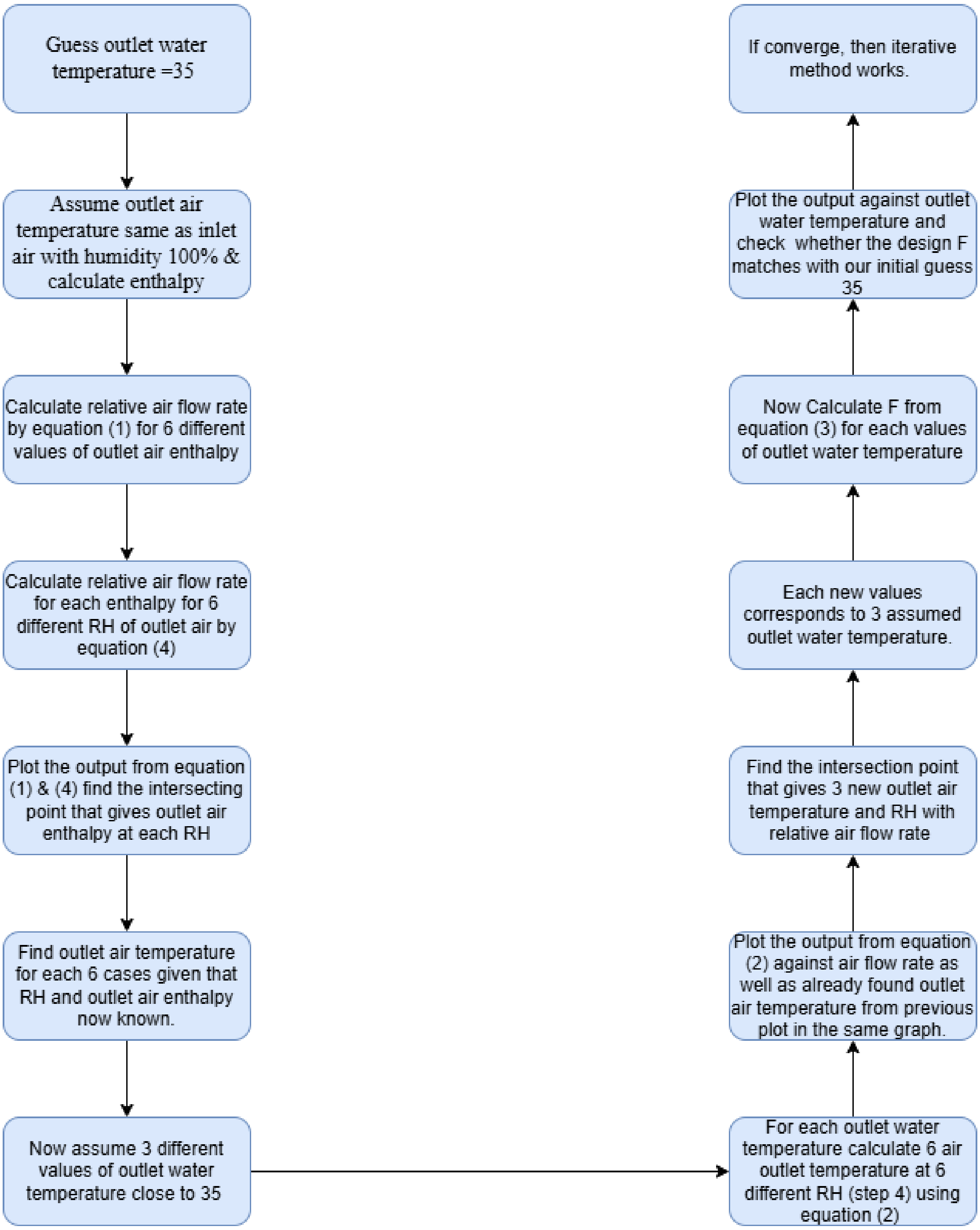


Figure 4.1: Steps of Iterative Method

Explanation

1. First we guess outlet water temperature equals to 35 and this is the minimum possible temperature for outlet water in design inlet air condition.
2. Then we will take outlet air temperature same as inlet air temperature (design value) but take humidity as 100%. We will then both calculate inlet and outlet air enthalpy.
3. After getting outlet air enthalpy in previous step, we will take 6 different values of enthalpy near to that for outlet air and calculate relative air flow rate for each value by eq. 4.1
4. Now we will take 6 different values for outlet air humidity ranging from 100% to 80%. For each values of outlet air enthalpy (stated in previous step), we will calculate relative air flow rate by eq. 4.4. So in total for each enthalpy, there will be six relative air flow rate for six different outlet air humidity.
5. Plot relative air flow rate against outlet air enthalpy for both step 3 and 4. The intersecting point gives us the outlet air enthalpy at each relative humidity.
6. Now by using CoolProp, we can get the corresponding outlet air temperature since we found outlet air humidity and enthalpy. These 6 output (outlet air temperature) will be input for eq. 4.2
7. Then we will assume 3 different values of outlet water temperature near to 35.
8. For each outlet water temperature, we will calculate outlet air temperature by eq. 4.2. Eq. 4.2 also contain outlet air temperature on the right side. The input for this will be the output of previous step. So for each outlet water temperature we will get 6 different values of outlet air temperature.
9. Plot the outlet air temperature against relative air flow rate for both step 6 and 8.
10. The intersecting point will give us three new outlet air temperature along with relative humidity and relative air flow rate.
11. Each of the new values corresponds to three assumed outlet water temperature.
12. Then using eq. 4.3, we will calculate heat exchange area between air and water for updated values of outlet air temperature and humidity.
13. Plot F against outlet water temperature and check whether the design F value matches with our initial guess 35.
14. If converge, find the values of relative air flow rate, outlet water temperature and humidity from the plot mentioned in step 9. That's how we get air flow rate, outlet air humidity and temperature.

That's the procedure for our iterative methods. And our final output will be the heat exchange area between air and water at design limit condition.

Now the plot will be shown here: From step 5; first plot will be found.

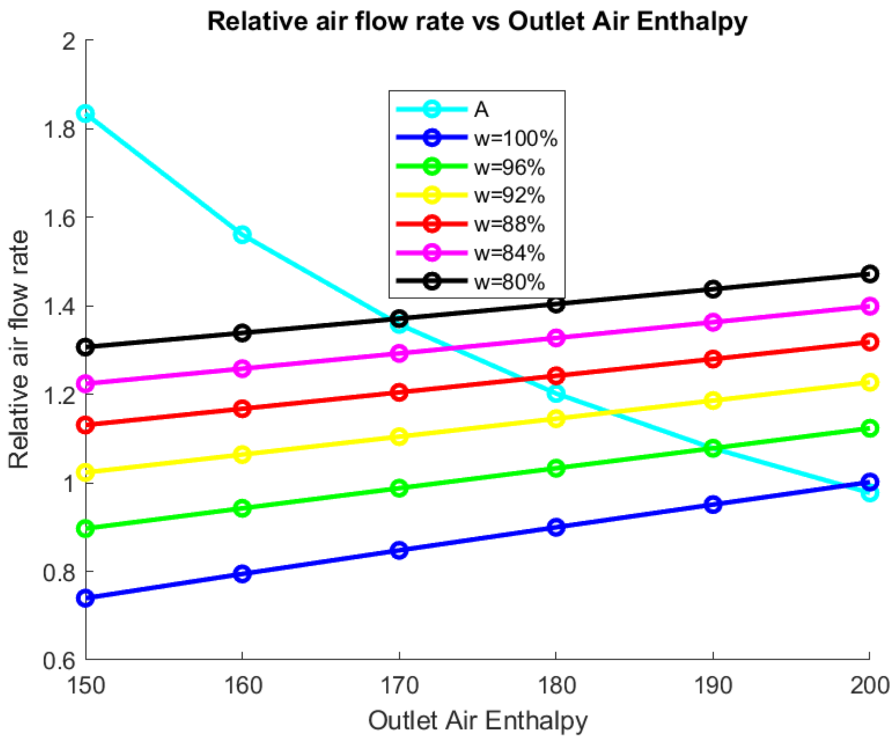


Figure 4.2: Relative Air Flow Rate vs Outlet Air Enthalpy

From Step 9, second plot will be found.

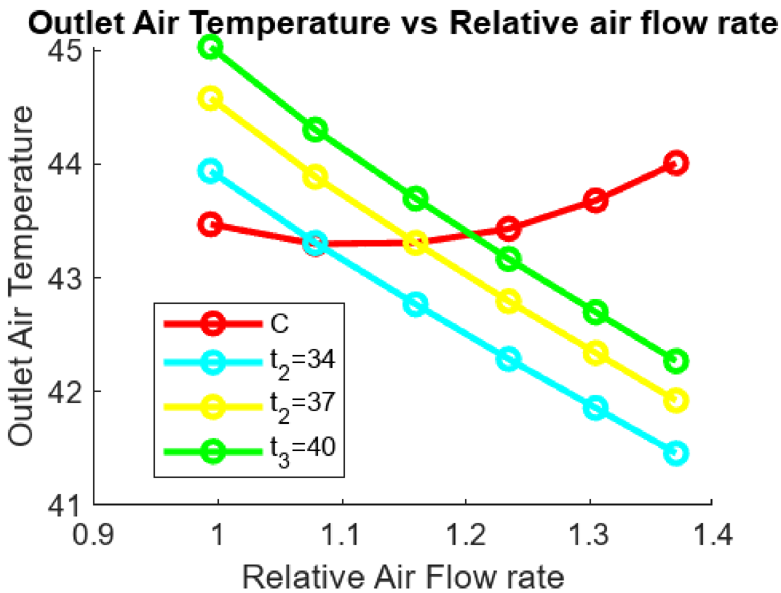


Figure 4.3: Outlet Air Temperature vs Relative Air Flow Rate

Now from step 13; F vs outlet water temperature plot is shown.

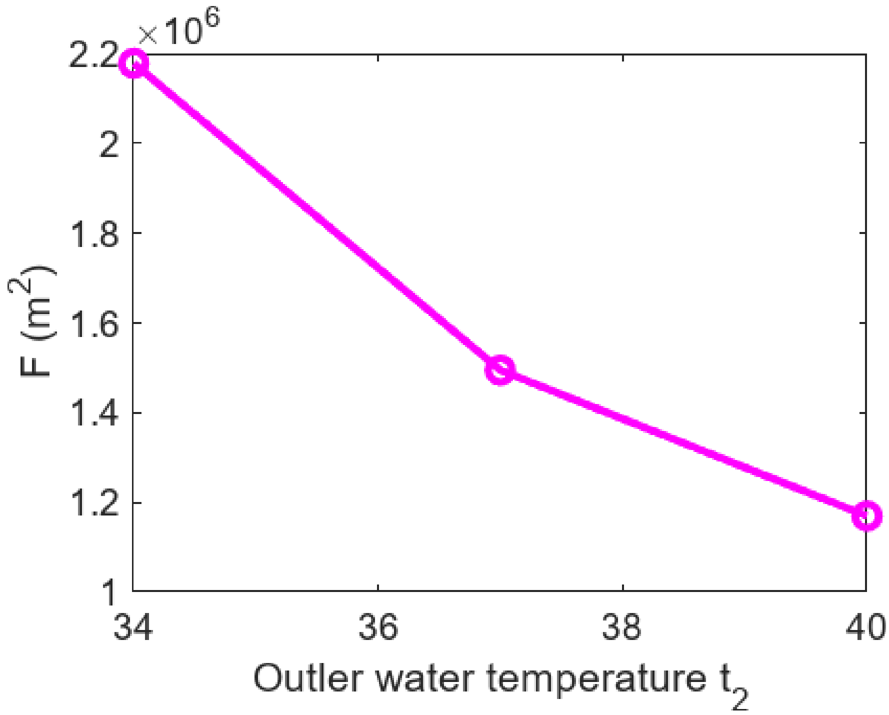


Figure 4.4: F vs Outlet Water temperature

This is our basis work till now. Now at outlet water temperature 35, we can easily find the corresponding outlet air temperature and humidity as well as air flow rate that will verify all four equations. Now by using eq. 3.2 and eq. 3.4, we can calculate how much heat will be rejected at design limit.

Chapter 5

Results and Discussion

The model developed in the previous section will be used now to evaluate the cooling tower efficiency at various ambient air condition. Under the influence of global warming, temperature increment is imminent. Inlet air temperature, relative humidity are two major environmental factors that will have direct impact on cooling tower efficiency. The analysis are performed keeping one of the factor constant at design limit and varying the other one.

5.1 Variation in Inlet air Temperature

Our design limit for RNPP cooling tower is 37.9°C. Keeping inlet air relative humidity at design limit which is 50.9%, the variation in cooling tower performance found is shown below:

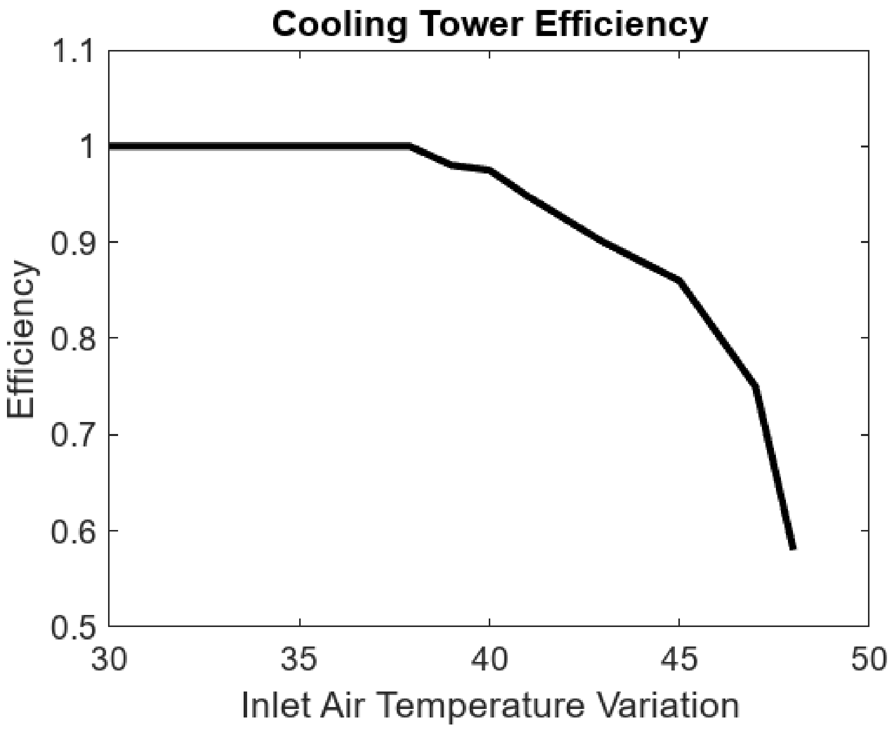


Figure 5.1: Cooling Tower Efficiency vs Inlet air Temperature

So in Figure-5.1 , effect of inlet air temperature variation is shown. Below design limit, normal performance occurs but beyond design limit, cooling tower performance drops.

5.2 Variation in Relative Humidity

Our design limit for inlet air humidity is 50.9%. In this case, inlet air temperature will be kept constant at design limit. The variation in cooling tower performance found is shown below

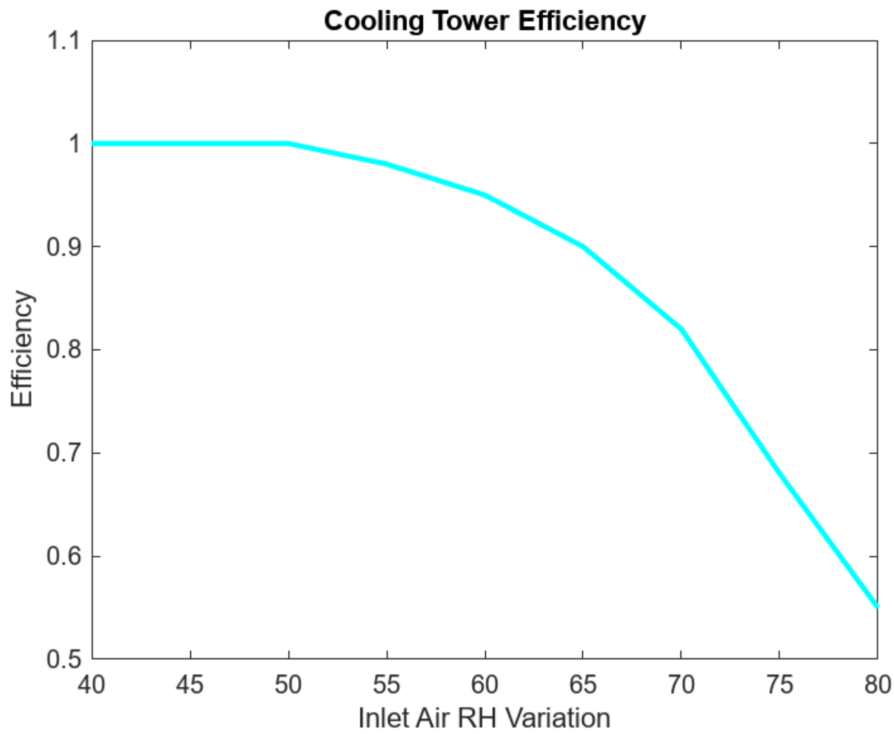


Figure 5.2: Cooling Tower Efficiency vs Relative Humidity

In Figure-5.2, the cooling tower performance remains normal till design limit while varying humidity. But as soon as, humidity goes beyond design limit, efficiency drops.

5.3 Validation

A comparison will be presented between the findings of this model and those reported by Ayoub et al. [13]. Ayoub et al. did sensitivity analysis by varying dry bulb air temperature and air humidity. His findings are given below-

Variation in Inlet Air Temperature

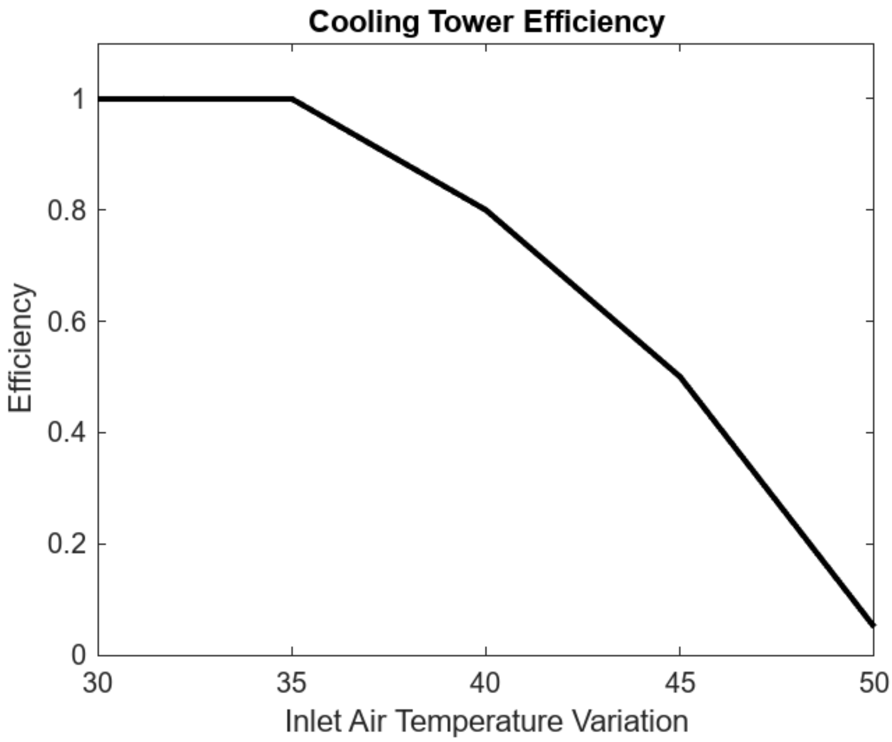


Figure 5.3: Efficiency vs Inlet Air Temperature

A non-linear drop in performance was observed in Figure 5.3. When comparing Figure 5.3 with Figure 5.1, it is evident that, in our analysis, the efficiency initially decreases almost linearly or remains close to 100% up to an inlet air temperature of approximately 40°C. Beyond this point, the efficiency begins to decline more noticeably, with a change in the rate of decrease as the inlet air temperature increases further. In contrast, the findings of Ayoub et al. indicate a sharp decline in cooling tower performance immediately after the inlet air temperature exceeds their baseline of 35°C, reaching nearly zero efficiency at 50°C. However, such drastic performance degradation was not observed in our study. Instead, for temperatures beyond 48°C, our iterative computational method failed to converge. Nonetheless, both our result and that of Ayoub et al. consistently demonstrate a non-linear efficiency drop at elevated temperatures.

Variation in Relative Humidity Consistent with previous findings, a decline in cooling tower performance is observed beyond the baseline relative humidity, which is 57% in the study by Ayoub et al. A comparison between Figure 5.4 and Figure 5.2 shows that in our analysis, the efficiency decreases gradually at first, followed by a sharp decline at higher humidity levels. However, beyond 80% relative humidity—while keeping the inlet air temperature at the design value—our iterative solution method failed to converge to a real value. In contrast, Ayoub et al. reported that cooling tower efficiency decreased to approximately 40% at 100% humidity. Despite the quantitative differences, both models align with the established understanding that cooling tower efficiency deteriorates significantly at higher humidity levels.

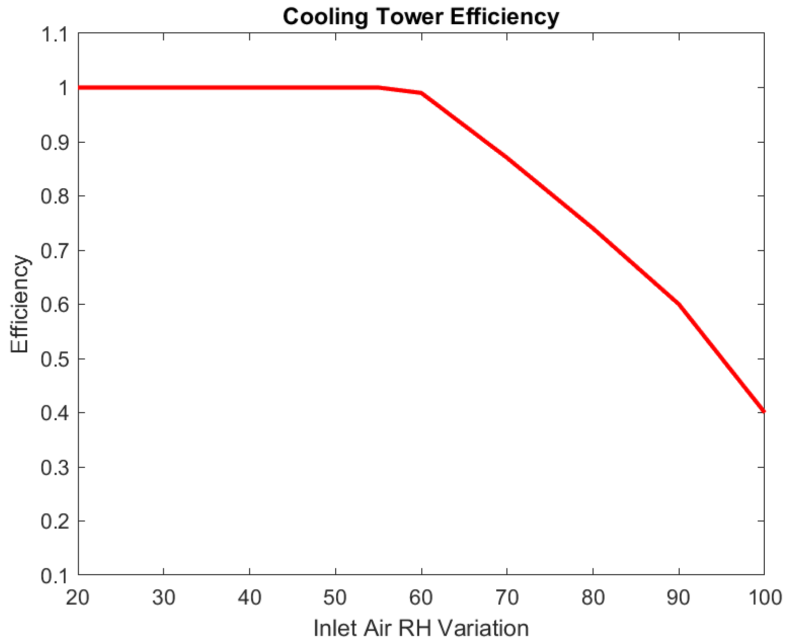


Figure 5.4: Efficiency vs Relative Humidity [13]

Although both models agree on the overall trend of efficiency decreasing with rising temperature and humidity, Ayoub et al. reported a more pronounced decline in cooling tower performance compared to our findings. This discrepancy can be attributed to differences in modeling approaches and underlying assumptions. In our analysis, factors such as drift, purge, and leakage were not considered, whereas Ayoub et al. included these effects in their model. Furthermore, we maintained a constant inlet water temperature regardless of the outlet water conditions, while Ayoub et al. adjusted the inlet air temperature based on the outlet water temperature. These methodological differences likely account for the variation in the magnitude of efficiency reduction observed between the two studies.

Chapter 6

Conclusion

The aim of this research was to evaluate the thermal performance of the cooling tower at the Rooppur Nuclear Power Plant (RNPP) under varying environmental conditions. As the plant is located in a region where atmospheric conditions can fluctuate significantly throughout the year, understanding how such variations affect cooling tower efficiency is essential. In this work, a thermodynamic-based model was developed to estimate the cooling tower efficiency under different inlet air temperatures and relative humidity levels. The base case for this analysis was taken from the design inlet air conditions, and variations were introduced to reflect different realistic scenarios the cooling tower may experience during operation.

The study found that the cooling efficiency of the tower is significantly influenced by ambient air temperature and relative humidity. Specifically, increases in air temperature tend to reduce the ability of the cooling tower to reject heat, thereby lowering its overall efficiency. This has direct implications for the thermal performance of the condenser and, by extension, the power generation capacity of the entire nuclear power plant. In high-temperature scenarios, the water leaving the cooling tower may not be sufficiently cooled before re-entering the condenser, leading to higher condenser pressure, reduced thermal efficiency of the Rankine cycle, and a drop in net electricity output.

Although the model was not applied across an entire year of data (i.e., not to all 365 days), the selected input variations still provided valuable insight into the cooling tower's sensitivity to environmental changes. This approach has laid a foundation for more extensive modeling efforts that could evaluate the system's behavior under full annual climate data, or projected future climate scenarios.

In terms of limitations, the model assumes fixed inlet water temperatures and does not dynamically adjust for outlet water conditions. This assumption simplifies the analysis but does not capture the full range of operating behaviors in an actual cooling tower system. Additionally, the study focuses only on the cooling tower component without quantifying the cascading effects on other critical components like the condenser and turbine stages. Including such dependencies in future studies would provide a more complete picture of how climate variables ultimately impact plant-level performance.

There are several promising directions for future work. One important improvement would be to vary the inlet water temperature based on outlet conditions to better simulate real-time operation. This adjustment would allow for more accurate estimations of how efficiently the cooling tower can operate under fluctuating load and weather conditions. Furthermore, the model could be extended to evaluate the direct impact of cooling tower performance on condenser backpressure and the overall efficiency of the nuclear plant.

Another vital area of future research is the inclusion of long-term climate projections. Given the growing concern over global warming and its expected effects on temperature and humidity patterns, it would be valuable to estimate how the RNPP cooling tower might perform over the next 50 years. This would involve combining climate models or future temperature scenarios with the thermodynamic cooling tower model developed in this thesis. Such a study could offer critical insights into the plant's sustainability and guide potential design improvements or mitigation strategies.

In summary, this work highlights the vulnerability of cooling tower performance to atmospheric changes and sets the stage for broader investigations into climate-resilient design and operation strategies. While the current model offers meaningful insights, expanding it with more detailed assumptions and broader datasets will be essential to fully understand and prepare for the long-term operational challenges facing nuclear power plants like RNPP in a warming world.

Appendix A

Appendix

Code for designed F calculation:

```
%%Design Parameters calculation:
t_out= 35;

C_P= 4.183;
K=1- (C_P/(2493*t_out))
del_t= 25;
t_a_in= 37.9;

rh_in=50.9/100;
h_a_in=py.CoolProp.CoolProp.HAPropsSI('H', 'T', ...
t_a_in+273.15, 'P', 101325, 'R', rh_in)/1000;
h_a_in=round(h_a_in) %inlet air enthalpy.
h_a_out= py.CoolProp.CoolProp.HAPropsSI('H', 'T', ...
    t_a_in+273.15, 'P', 101325, 'R', 1)/1000
h_a_out=round(h_a_out) %outlet air enthalpy.

%% Relative air flow rate calculation at
% different air outlet enthalpy.
h_a_out_dif=[150;160;170;180;190;200];
lambda= zeros(length(h_a_out_dif),1);
for i= 1: length(h_a_out_dif)
lambda(i)=(C_P * del_t)/(K*(h_a_out_dif(i)-h_a_in))
end

%Relative air flow rate calculation at
% different relative humidity
%%h_a_out_dif=[150 160 170 180 190 200]

m_w= 1e5 * 1000 / 3600
Fill_area= pi* (60)^2;
Height= 165;
```

```
drag=15;
rh_out=[1,0.96,0.92, 0.88,0.84,0.80];
t_a_out= zeros (length(rh_out),1);
p_v_in=py.CoolProp.CoolProp.PropsSI('P','T', ...
    t_a_in+273.15,'Q',0,'Water')* rh_in;

P=101325;
p_d_in=P- p_v_in;
R_d=287.05; R_v=461.5;
rho_a_in=p_d_in/(R_d*(t_a_in+273.15) )+
p_v_in/(R_v*(t_a_in+273.15))
rho_a_out=zeros(length(rh_out),1);
P=101325;

for j= 1: length(h_a_out_dif)
    temp_lambda= zeros(length(rh_out),1);
for i=1:length(rh_out)
t_a_out(i)= py.CoolProp.CoolProp.HAPropsSI('T', ...
'H', h_a_out_dif(j)*1e3, 'P', P, 'R', rh_out(i))- 273.15;

p_v(i)=py.CoolProp.CoolProp.PropsSI('P','T', ...
 t_a_out(i)+273.15,'Q',0,'Water')* rh_out(i);
p_d(i)=P- p_v(i);

rho_a_out(i)=p_d(i)/(R_d*(t_a_out(i)+273.15) )+
p_v(i)/(R_v*(t_a_out(i)+273.15));
temp_lambda(i)= (Fill_area/m_w)* sqrt((Height* ...
    ((rho_a_in)^2 -(rho_a_out(i))^2)* 9.8)/drag );
end

if j==1

lambda_1= temp_lambda;
elseif j==2
    lambda_2= temp_lambda;
    elseif j==3
    lambda_3= temp_lambda;
    elseif j==4
    lambda_4= temp_lambda;
    elseif j==5
    lambda_5= temp_lambda;
elseif   j==6
    lambda_6= temp_lambda;
end
end
```

```
lambda_matrix= [lambda_1,lambda_2,lambda_3,lambda_4,
    lambda_5,lambda_6];
lambda_100=lambda_matrix(:,1);
lambda_96=lambda_matrix(:,2);
lambda_92=lambda_matrix(:,3);
lambda_88=lambda_matrix(:,4);
lambda_84=lambda_matrix(:,5);
lambda_80=lambda_matrix(:,6);
hold on
plot(h_a_out_dif,lambda,'c-o','LineWidth',2)
plot(h_a_out_dif,lambda_100,'b-o','LineWidth',2)
plot(h_a_out_dif,lambda_96,'g-o','LineWidth',2)
plot(h_a_out_dif,lambda_92,'y-o','LineWidth',2)
plot(h_a_out_dif,lambda_88,'r-o','LineWidth',2)
plot(h_a_out_dif,lambda_84,'m-o','LineWidth',2)
plot(h_a_out_dif,lambda_80,'k-o','LineWidth',2)
xlabel('Outlet Air Enthalpy');
ylabel('Relative air flow rate');
title('Relative air flow rate vs Outlet Air Enthalpy');
legend('A', 'w=100%','w=96%','w=92%', ...
 'w=88%','w=84%','w=80%','Location','best')
x=h_a_out_dif;
y=lambda;
y100=lambda_100;
y96=lambda_96;
y92=lambda_92;
y88=lambda_88;
y84=lambda_84;
y80=lambda_80;
find_intersections= @(y1,y2) interp1(y1-y2,x,0);
x_100=find_intersections(y,y100)
x_96=find_intersections(y,y96)
x_92=find_intersections(y,y92)
x_88=find_intersections(y,y88)
x_84=find_intersections(y,y84)
x_80=find_intersections(y,y80)
%outlet air temperature
h_a_out_original=[x_100;x_96;x_92;x_88;x_84;x_80]
t_a_out_original= [];
rh_out_new=[];
lambda_original=[];
for i=1 : length(h_a_out_original)
    if ~ isnan (h_a_out_original(i))

temp=py.CoolProp.CoolProp.HAPropsSI('T', 'H', ...
h_a_out_original(i)*1000, 'P', 101325, 'R', rh_out(i))-273.15;
 t_a_out_original=[t_a_out_original;temp];
```

```
lambda_original=[lambda_original;interp1(x,y, ...
    h_a_out_original(i))];
 rh_out_new=[rh_out_new;rh_out(i)];
    end
end




%outlet water temp=34, find t_a_out_original_pro
% by using eq 2
t_w_in=60;
t_w_out=34;

omega_in=py.CoolProp.CoolProp.HAPropsSI('W','T', ...
    t_a_in+273.15,'P',101325,'RH',rh_in)
omega_out=zeros(length(t_a_out_original),1);
p1_double_prime=py.CoolProp.CoolProp.PropsSI('P', ...
    'T', t_w_in+273.15,'Q',0,'Water');
p2_double_prime=py.CoolProp.CoolProp.PropsSI('P', ...
    'T', t_w_out+273.15,'Q',0,'Water');
p1_unsat=py.CoolProp.CoolProp.PropsSI('P','T', ...
    t_a_in+273.15,'Q',0,'Water')*rh_in;
p_m_double_prime= py.CoolProp.CoolProp.PropsSI('P', ...
    'T',((t_w_in+t_w_out)/2)+273.15,'Q',0,'Water');
del_p_double_prime=0.25* (p1_double_prime+ ...
    p2_double_prime- 2*p_m_double_prime);

p2_unsat=zeros(length(t_a_out_original),1);
t_a_out_original_pro=zeros(length(p2_unsat),1);
for i=1: length(t_a_out_original)
 omega_out(i)=py.CoolProp.CoolProp.HAPropsSI('W', ...
'T',t_a_out_original(i)+273.15,'P',101325,'RH',rh_out(i));
p2_unsat(i)= py.CoolProp.CoolProp.PropsSI('P','T', ...
 t_a_out_original(i)+273.15,'Q',0,'Water')*rh_out(i);



t_a_out_original_pro(i)=t_a_in+13.7*10^4*
(omega_out(i)-omega_in)*((t_w_in+t_w_out- ...
 t_a_in-t_a_out_original(i))/ ...
(p1_double_prime+p2_double_prime-p1_unsat-p2_unsat(i) ...
-2*del_p_double_prime))
end
%outlet water temp=37 ;find t_a_out_original_pro
% by using eq 2
```

```
t_w_out_2=37;
p2_double_prime_2=py.CoolProp.CoolProp.PropsSI('P', ...
    'T', t_w_out_2+273.15,'Q',0,'Water');
p_m_double_prime_2= py.CoolProp.CoolProp.PropsSI('P', ...
   'T',((t_w_in+t_w_out_2)/2)+273.15,'Q',0,'Water');
del_p_double_prime_2=0.25* (p1_double_prime+ ...
    p2_double_prime_2- 2*p_m_double_prime_2);
t_a_out_original_pro_2=zeros(length(p2_unsat),1);
for i= 1: length(p2_unsat)
t_a_out_original_pro_2(i)=t_a_in+13.7*10^4*
(omega_out(i)-omega_in)*
((t_w_in+t_w_out_2-t_a_in-t_a_out_original(i)) ...
/(p1_double_prime+p2_double_prime_2-p1_unsat- ...
p2_unsat(i)-2*del_p_double_prime_2))
end

%%outlet water temp=40; find t_a_out_original_pro
% by using eq 2
t_w_out_3=40;
p2_double_prime_3=py.CoolProp.CoolProp.PropsSI('P', ...
    'T', t_w_out_3+273.15,'Q',0,'Water');
p_m_double_prime_3= py.CoolProp.CoolProp.PropsSI('P', ...
    'T',((t_w_in+t_w_out_3)/2)+273.15,'Q',0,'Water');
del_p_double_prime_3=0.25* (p1_double_prime+ ...
    p2_double_prime_3- 2*p_m_double_prime_3);
t_a_out_original_pro_3=zeros(length(p2_unsat),1);
for i= 1: length(p2_unsat)
t_a_out_original_pro_3(i)=t_a_in+13.7*10^4*
(omega_out(i)-omega_in)*((t_w_in+t_w_out_3- ...
  t_a_in-t_a_out_original(i))/(p1_double_prime+ ...
  p2_double_prime_3-p1_unsat-p2_unsat(i)- ...
  2*del_p_double_prime_3))
end
clf
hold on
plot(lambda_original,t_a_out_original,'r-o','LineWidth',2)
plot(lambda_original,t_a_out_original_pro,'c-o','LineWidth',2)
plot(lambda_original,t_a_out_original_pro_2,'y-o','LineWidth',2)
plot(lambda_original,t_a_out_original_pro_3,'g-o','LineWidth',2)
xlabel('Relative Air Flow rate')
ylabel('Outlet Air Temperature')
title('Outlet Air Temperature vs Relative air flow rate')
legend('C', 't_2=34','t_2=37','t_3=40','Location','best')

clf
hold on
plot(rh_out,t_a_out_original,'r-o','LineWidth',2)
```

```
plot(rh_out,t_a_out_original_pro,'c-o','LineWidth',2)
plot(rh_out,t_a_out_original_pro_2,'y-o','LineWidth',2)
plot(rh_out,t_a_out_original_pro_3,'g-o','LineWidth',2)
xlabel('Relative Humidity')
ylabel('Outlet Air Temperature')
title('Outlet Air Temperature vs Relative Humidity')
legend('C', 't_2=34','t_2=37','t_3=40','Location','best')
%intersection point at differnt t2
x_1=lambda_original;
y=t_a_out_original;
y34=t_a_out_original_pro;
y37=t_a_out_original_pro_2;
y40=t_a_out_original_pro_3;
find_intersections_1= @(y1,y2) interp1(y1-y2,x_1,0);
x_34=find_intersections_1(y,y34);
x_37=find_intersections_1(y,y37);
x_40=find_intersections_1(y,y40);
x_2=rh_out_new;
find_intersections_2= @(y1,y2) interp1(y1-y2,x_2,0);
rh_34=find_intersections_2(y,y34)
rh_37=find_intersections_2(y,y37)
rh_40=find_intersections_2(y,y40)
x_temp=[x_34;x_37;x_40];
x_2_temp=[rh_34;rh_37;rh_40];
lambda_34_37_40=[];
rh_34_37_40=[];
t_a_out_34_37_40=[];
for i= 1 : length (x_temp)
    if   ~ isnan (x_temp(i))
 lambda_34_37_40=[lambda_34_37_40;x_temp(i)];
rh_34_37_40=[rh_34_37_40;x_2_temp(i)]
t_a_out_34_37_40=[t_a_out_34_37_40;interp1
    (x_1,y,x_temp(i))];
    end
end




%t2= 34,36,38
fill_dia= 0.05;
B=101325;
rh_343740=[rh_34;rh_37;rh_40];
t_w_out_34_37_40=[t_w_out;t_w_out_2;t_w_out_3];

air_flow_velocity=zeros(length(t_a_out_34_37_40),1);
kinematic_visc=zeros(length (t_a_out_34_37_40),1);
```

```
for i = 1: length(t_a_out_34_37_40)
T_mean(i)= (t_a_out_34_37_40(i)+273.15+t_a_in+273.15)/2;
Diffusion_coeff(i)= (1.75*10^-5)/B *(T_mean(i)/273)^0.8 ;
den_dry_mean(i)=py.CoolProp.CoolProp.PropsSI('D', ...
    'T',T_mean(i), 'P', B,'Air');
dynamic_visc(i)=py.CoolProp.CoolProp.PropsSI('V', ...
    'T',T_mean(i), 'P', B,'Air');
kinematic_visc(i)=dynamic_visc(i)/den_dry_mean(i)
air_flow_rate(i)=lambda_34_37_40(i)*m_w;

pressure_sat_in(i)=py.CoolProp.CoolProp.PropsSI('P', ...
    'T', T_mean(i),'Q',0,'Water');
%for omega b calculation
pressure_v_in(i)=pressure_sat_in(i)*rh_in;

pressure_d_in(i)=B- pressure_v_in(i);

den_humid_mean(i)=pressure_d_in(i)/
(R_d*(T_mean(i)) )+ pressure_v_in(i)/(R_v*(T_mean(i)));

air_flow_velocity(i)=air_flow_rate(i)/
(Fill_area * den_humid_mean(i))


film_velocity(i)= ((0.24-0.23)/10)*
((t_w_in+t_w_out_34_37_40(i)- 40)) + 0.23;
end
air_relative_velo=zeros(length(air_flow_velocity),1);
reynold_no=zeros(length(air_relative_velo),1);
for i= 1: length(air_flow_velocity)
air_relative_velo(i)= air_flow_velocity(i)+ film_velocity(i)
reynold_no(i)= air_relative_velo(i)* fill_dia/ kinematic_visc(i)
end
%calculation of beta_p
beta_p=zeros (length(reynold_no),1);
for i= 1: length(reynold_no)
    beta_p(i)=( 0.0008* (reynold_no(i))^1.18 ...
        * Diffusion_coeff(i))/fill_dia
end
% del_p_cp calculation then F from equation 2

p2_double_prime_34_37_40=[p2_double_prime;
    p2_double_prime_2;p2_double_prime_3]

del_p_doubele_prime_34_37_40=[del_p_double_prime;
    del_p_double_prime_2;del_p_double_prime_3]
```

```
p2_unsat_34_36_38= zeros(length(p2_double_prime_34_37_40),1);
del_p_1=zeros(length(p2_double_prime_34_37_40),1);
del_p_2=zeros(length(p2_double_prime_34_37_40),1);
del_p_cp=zeros(length(p2_double_prime_34_37_40),1);
omega_out_34_36_38=zeros(length(t_a_out_34_37_40),1);
F=zeros(length(t_a_out_34_37_40),1);
for i= 1: length(p2_double_prime_34_37_40)

p2_unsat_34_36_38(i)=py.CoolProp.CoolProp.PropsSI('P', ...
    'T', t_a_out_34_37_40(i)+273.15,'Q',0,'Water')
* rh_34_37_40(i);

del_p_1(i)= p1_double_prime- p2_unsat_34_36_38(i);
del_p_2(i)=p2_double_prime_34_37_40(i)-p1_unsat;
del_p_cp(i)= (del_p_1(i)- del_p_2(i))/ log ((del_p_1(i) ...
  - del_p_doubele_prime_34_37_40(i))/ ...
  ( del_p_2(i)- del_p_doubele_prime_34_37_40(i)));

 omega_out_34_36_38(i)=py.CoolProp.CoolProp.HAPropsSI
 ('W','T',t_a_out_34_37_40(i)+273.15,'P',101325, ...
     'RH',rh_34_37_40(i));
 F(i)=(lambda_34_37_40(i)* m_w * (omega_out_34_36_38(i) ...
     - omega_in)) / (beta_p(i) * del_p_cp(i) )
end

clf
plot(t_w_out_34_37_40, F,'m-o','LineWidth',2)
xlabel('Outler water temperature t_2')
ylabel('F (m^2)')

F_35= interp1(t_w_out_34_37_40,F,35,'linear')
F_known= 1.950e6;
t_w_exact= interp1(F,t_w_out_34_37_40,F_known, ...
    'linear')
lambda_exact= interp1(t_w_out_34_37_40, ...
    lambda_34_37_40,t_w_exact, 'linear')
t_a_out_exact= interp1(t_w_out_34_37_40, ...
    t_a_out_34_37_40,t_w_exact,'linear')
rh_exact=interp1(t_w_out_34_37_40,rh_34_37_40, ...
    t_w_exact,'linear')
t_make_up=30;
m_a= m_w* lambda_exact
omega_exact=py.CoolProp.CoolProp.HAPropsSI('W', ...
  'T',t_a_out_exact+273.15,'P',101325,'RH',rh_exact);
h_a_out_exact=py.CoolProp.CoolProp.HAPropsSI('H', ...
 'T', t_a_out_exact+273.15, 'P', 101325, 'R', rh_exact)/1000;
h_make_up=py.CoolProp.CoolProp.PropsSI('H','T', ...
```

```
    t_make_up+273.15,'Q',0,'Water' )/1000;
m_make_up= m_a * (omega_exact-omega_in);
Q_design= (m_a*(h_a_out_exact- h_a_in)- ...
    m_make_up* h_make_up)/1000
```

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