Analysis of How Water and Air Flow Rates Affect a Cooling Tower

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Abstract

The efficiency of a cooling tower plays a critical role in its integration in a process system, affecting the cost and time. In this experiment, a cooling tower is analyzed by varying various parameters that can affect the performance. The inlet and outlet air temperatures were measured and used to calculate the NTU, which is a dimensionless parameter that relates heat and mass transfer phenomena to the cooling tower that can help quantify the performance. Based on the data collected, findings show there is an inverse relationship between NTU and $\frac{L}{G}$. These findings further confirm that letting the water be exposed to the air longer allows the water to be cooled more effectively. One example to improve the quality of the experiment in the future includes adding a dehumidifier to control the environment's humidity, which can help in controlling the conditions of the cooling tower and collecting consistent data. By doing so, the quality of the experiment can be improved.

1 Introduction

A cooling tower is a piece of equipment used to control the temperature of a system. The cooling tower takes a liquid that requires cooling, typically water, and has it flow down into the tower onto a packing material that increases the amount of air the water is exposed to thereby cooling the water down.[1] The packing material is typically designed with the temperature of the inlet water in mind to meet the specified outlet temperature of the water.[2] A fan can be used to increase the amount of air the water is exposed to in order to effectively cool the water more.[1] Various other design choices can be made to improve or meet the requirements of the system that the cooling tower is integrated to such as having a specific kind of filling material, the material that the water flows onto, a droplet separator or a nozzle designed to increase the surface area of the water droplets, the flow rate of the water or the speed of the fan.[1,3] In terms of the historical development of the cooling tower design, the topic of how a cooling tower can be integrated into a process has been discussed but only recently has the performance of the cooling tower been analyzed like that in Castro et al. and Cortinovis et al.[2,4] In each of their works, the issue of the performance of a cooling tower becomes pertinent with regards to the energy consumption and cost. Cooling towers are used in process plants that require the process fluid to be cooled to a certain requirement.[2] Another area that cooling towers are used in is generation plants where the heat produced from the heat generation process must also be removed at the same rate it is produced.[2] As a result, the design of the cooling tower in each situation is important to the process that it is integrated into. The operation of a cooling tower requires energy such as the use of a pump to flow the water throughout itself and requires a specific amount of water needed for the process.[4] Therefore, the performance of the cooling tower is an important aspect to the company operating it and for that reason the cooling tower is analyzed to determine the most efficient way to cool water to meet the desired specifications.[4]

2 Background

Cooling towers may operate differently based on a variety of external factors, but one factor that is of paramount importance due to how it will be affected is the environment. Climate change, global warming, and other environmental issues have been the subjects of discourse in recent times. As a result, different entities such as industries, countries, and other organizations have been taking major steps to take the environment into consideration in whatever actions they do. For the chemical engineering industry in particular, some examples of this have been applied for cooling towers.

For example, a cooling tower may have a different wet bulb temperature based on the geographical location of the tower.[5] Depending on the climate of the location, the wet bulb temperature will vary.[5] As a result, the cooling tower will be sized accordingly and have different operating conditions.[5] Thus, in order to determine which wet bulb temperature to use, climate parameters such as the humidity of the location were considered.[5] Another factor that can influence the design of a cooling tower and subsequently the plant operations is the amount of water available to the chemical plant. One important environmental issue that's being addressed currently is water conservation. Consequently, alternative designs to cooling towers have been researched in order to confront this issue. A promising alternative is known as a natural draft dry cooling tower (NDDCT).[6] What differentiates this tower from a regular cooling tower is that it does not use any water and relies more on weather conditions such as the wind.[6] As a result, an NDDCT can be used in areas where water is scarce. However, such a new technology is still being studied and isn't widely used throughout the industry; hopefully in the future, NDDCTs can be implemented more in order to mitigate the amount of water being used by cooling towers.[6] Finally, depending on the industry they're used for, cooling towers can be modified to reduce their environmental impact. One of these industries is the nuclear power industry. An object of concern for the nuclear power industry is the plume emitted by cooling towers, which is known to cause harm to the environment.[7] Namely, this plume is able to deposit water and salt into the atmosphere as well as fog and ice the ground, among other things.[7] In order to combat this, the design of the cooling tower was modified. This was done by changing the layout of the tower, its length, the height/diameter of its exiting ports, and other parameters.[7] Subsequently, the amount of plume entering the atmosphere is reduced due to these modifications to the design of the cooling tower.

Here in this experiment, we show how changing different parameters of the cooling tower will affect the NTU, which is defined later in this report. This was done by modifying the speed of the fan while holding the water flow rate constant and vice versa. Comparisons were made between the two experimental conditions and conclusions were drawn based off of the data gathered.

3 Theory

The objective of this lab was to observe how the number of transfer units, NTU, varied as a function of $\frac{L}{G}$. According to Eq. (1), the NTU is a dimensionless parameter that relates mass and heat transfer phenomena to cooling tower parameters and quantifies the performance of said cooling tower. Specifically, enthalpy potential difference is the driving force in Eq. (1).[8] First, the Merkel equation,

$$NTU = \frac{KaV}{L} = \int_{T_1}^{T_2} \frac{C_p}{h_s - h}\, dT \tag{1}$$

where K is the mass transfer coefficient, a is the contact area, V is the volume, L is the water flow rate, C_P is the heat capacity of water, h_s is the enthalpy of saturated air at the water temperature, h is the enthalpy of air, T_1 is the entering water temperature, and T_2 is the leaving water temperature, is utilized to obtain the NTU.[8] The entire left hand side of this equation (the non-integral expression) is known as the NTU. In order to get the enthalpy of air, the air operating line equation was used:

$$h = h_{in} + \frac{L}{G}(C_{p,water})(T - T_{out}) \tag{2}$$

where h_{in} is the enthalpy of inlet air, L is the liquid flow rate, G is the gas flow rate, C_{p} is the heat capacity of water, T is the entering water temperature, and T_{out} is the leaving water temperature. Consequently, to get h_{in}, an exponential curve was generated for the enthalpy of saturated air using data from Perry's Handbook and the following equation:

$$h_s(T) = ae^{bT} \tag{3}$$

where a and b are the coefficients for the exponential function and T is the temperature.[8]

This exponential curve was used to get an endpoint on the air operating line using the h value that corresponds with the outlet wet bulb temperature; a line was then drawn from this point until the corresponding hot water temperature since they have the same h value. From here, the slope $\frac{L}{G}$ can be used to get the operating line. The other endpoint of the line was obtained by using the cold water temperature to get the matching h value for the endpoint of the exponential curve using the exponential function. Then, a line can be drawn down to get the other endpoint of the operating line since they share the same cold water temperature. Finally, a horizontal line can be drawn from this endpoint until the y-axis to get h_{in}. Once the two lines are obtained, the integral would be taken in between these two lines to calculate the NTU.[8]

Using both Eq. (1) and Eq. (2) together, NTU was plotted against $\frac{L}{G}$ to determine the relationship between the two when a parameter was varied. Namely, L was varied while G was kept constant and vice versa and the trends were subsequently analyzed. In order to plot NTU vs. $\frac{L}{G}$ and fit the data appropriately, correlations were utilized from previous literature. Specifically, Lemouari et al. highlights the following expression as a proper model to fit the data:

$$\frac{KaV}{L} = A\left(\frac{L}{G}\right)^{B} \tag{4}$$

where A and B are the coefficients for the correlations and L and G are the same as previously defined.[9]

4 Methods

To determine the performance of the cooling tower, the inlet and outlet wet and dry bulb temperatures, the velocity and temperature of the air coming out of the cooling tower, and the temperature of the hot bath were measured. The flow rate of the water and the air was changed to determine the characteristics of the cooling tower. The range that the velocity of the air operated between was 0-7 $\mathrm{m\,s^{-1}}$ and the range that the flow rate of the water was operated between was 0.2-1.2 GPM. For each run, the parameters were chosen and a setpoint temperature was determined. With the determined setpoint temperature, the cooling tower would run until the temperatures reached steady state.

5 Results and Discussion

The results of the experimental data were collected and used to create a plot for both the air and water operating lines. Using both operating lines, Eq. (2) and Eq. (3) are used to find the NTU. NTU is determined by finding the area in between the operating lines.[8]

The overall results of the plots shows the relationship between the NTU and the water to air mass flow rate $\frac{L}{G}$. Using Eq. (1), the mass transfer groups were calculated and plotted, which in Fig. 2 shows a decaying trend. Increasing the fan speed resulted in increasing the efficiency of cooling the water in the tower. An increase in the water flow rate results in the water being cooled less efficiently. Increasing the flow rate makes cooling the water difficult since the reservoir water is being pumped into the tower at a faster rate. This results in little to no change in temperature of the reservoir water since the air coming from the fan has little to no time for the water to cool down. To summarize, the efficiency of the cooling down is all dependent on the change of the water flow rate and fan speed.

Based on Fig. 2, the decreasing trend between NTU and $\frac{L}{G}$ exhibits the limits of the cooling tower's efficiency. Allowing more cold air into the cooling tower allows for better heat transfer between water and air. Using the fans at a much faster rate will establish a higher potential

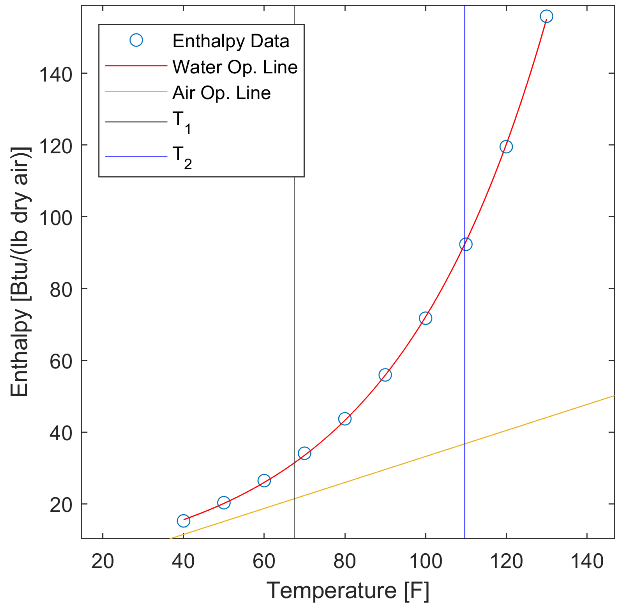

Figure 1: The figure shows the plot of enthalpy vs. temperature being graphed using two operating lines. This is one of the data sets pulled from the cooling tower experiment.

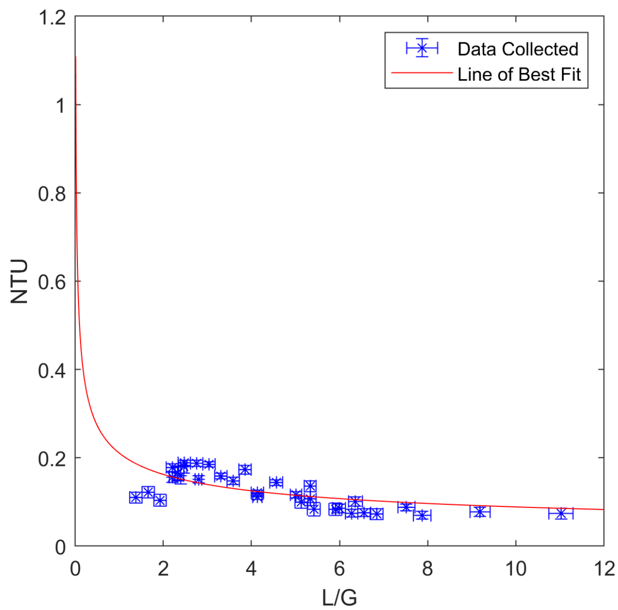

Figure 2: The figure shows the plot of NTU and $\frac{L}{G}$. The experimental data includes both recordings of various speeds of the fan with a constant water flow rate and various water flow rates a constant fan speed while keeping the speed of the fan constant.

enthalpy difference since more cold air is being blown. With air being coldest at the top of the tower, the cool air would flow down through the tower's fill and towards the bottom while collecting an amount of heat along the way. Due to the tower's fill shape, the cooling effectiveness would increase since the shape allows the water to have a higher surface area, allowing more heat to transfer. The results show that if the cold air travels too slowly from the fan, the air would be warmed up midway during the cooling process. Looking at Fig. 2, as the higher flow rate continues to increase, the lower the NTU value becomes, which results in a decrease in the cooling tower's efficiency.

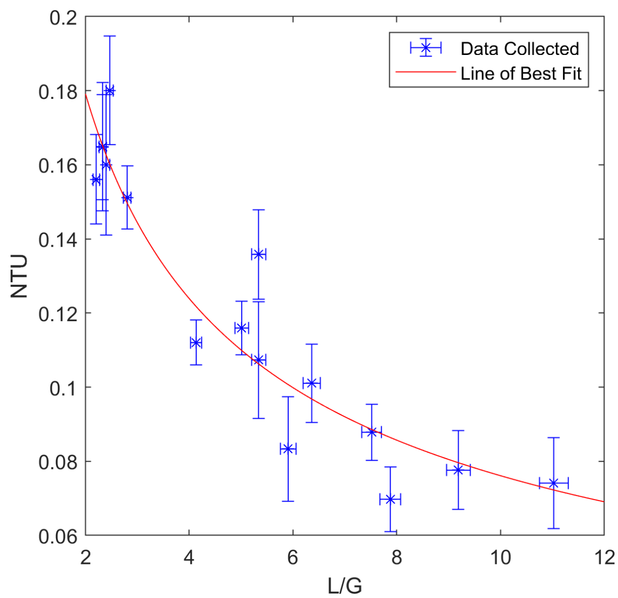

Figure 3: The figure shows the plot of NTU and $\frac{L}{G}$. The experimental data shown here is for when L is kept constant while fan speed is changing.

Looking at Fig. 3, the data displayed consists of varying the fan speed of the cooling tower while holding the water flow rate constant. The relationship between NTU and the $\frac{L}{G}$ ratio demonstrates a similar decaying trend, but the data itself does not portray it to be either exponential or linear. Instead, the data follows the correlations from Lemouari et al., which follows the form of Eq. (4).[9] The line of best fit in Fig. 3 adheres to the concept that the cooling tower's efficiency decreases as the $\frac{L}{G}$ ratio increases. The data itself does seem to be following a trend; however, the data does overlap quite a bit when the $\frac{L}{G}$ ratio is around 3 due to the inconsistent readings of the anemometer. In the future, the anemometer needs to be kept at a fixed angle using an attached mount for the cooling tower. A mount not only helps keep the anemometer stable, but the readings of the anemometer will also be consistent due to the instrument being kept in the same angled position. As for some of the other data in Fig. 3, the data tends to be spread due to the lack of cold air from the fan. With lower fan speeds, heat is not being efficiently transferred as much.

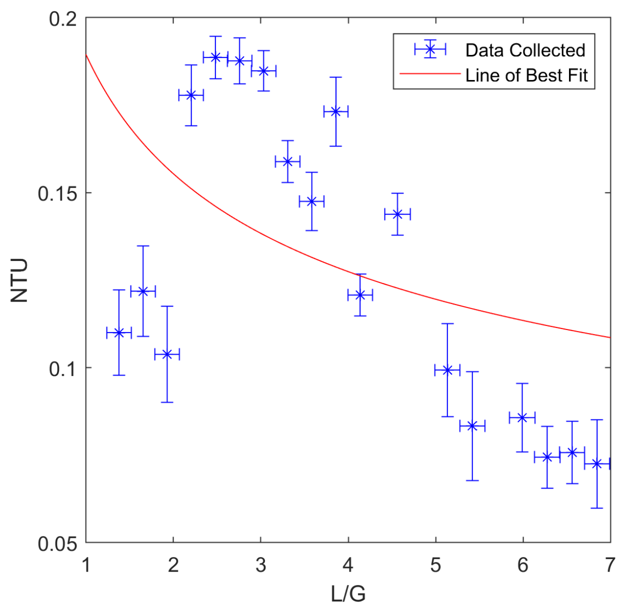

Figure 4: The figure shows the plot of NTU and $\frac{L}{G}$. The experimental data shown here is for when fan speed is kept constant while L is changing.

In addition, a separate data set was recorded to vary the water flow rates while holding the fan speed constant. In Fig. 4, the data still represents a decaying trend similar to correlations given by Lemouari et al.[9] Referring back to the fill of the cooling tower, the fill is shaped the way it is to increase the surface area of the water. Increasing the surface area of water helps the cooling tower be more efficient in cooling the water in the system. Fig. 4 shows the data being scattered around the line of best fit. As the water flow rate increases, the water will have less contact with air generated by the fan. From Fig. 4, the results demonstrate the concept that more water being added results in a lower NTU value when there is a higher $\frac{L}{G}$ ratio, which lowers the efficiency of the cooling tower. From the tower fill's shape, Eq. (1) implies that the volume of the shape does affect the data collected. In future test runs, data points can be collected using different tower fills since they can generate different cooling methods. A recommendation for this experiment is having a way to control the environment the cooling tower experiment is done in so the data collected can be more representative of cooling tower behavior and characteristics.

6 Conclusions

In this experiment the air and water flow rates were changed in the cooling tower to determine the relationship between NTU and $\frac{L}{G}$. The data shows that as $\frac{L}{G}$ increases the NTU decreases. Therefore, the findings in this experiment show that the relationship between NTU and $\frac{L}{G}$ is an inverse one. Because the NTU quantifies the performance of the cooling tower, this means it is most efficient when $\frac{L}{G}$ is small. These findings also demonstrate that having the water be exposed to air longer helps with the cooling of the water. Recommendations to improve the quality of the data include having a consistent way to place the anemometer to measure the flow rate of the air and having a way to control the environment the experiment is taking place in. For example, this can be done by adding a dehumidifier. By taking these recommendations into consideration, the quality of data can be improved.

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Appendix

1. A Comprehensive Approach to Cooling Tower Design
   - Author(s): Milosavljevic, N.; Heikkilä, P.
   - Year Published: 2001
   - Journal Name: Applied Thermal Engineering
   - 1-3 major accomplishments of this paper:
     (a) Developed a mathematical model and a computer simulator that allowed for an accurate prediction of the performance of a cooling tower.
     (b) A mixed fluted plates with corrugated pattern provided the best performance with regards to heat transfer and pressure loss.
2. Theoretical and Computational Analysis of Closed Wet Cooling Towers and Its Applications in Cooling of Buildings
   - Author(s): Hasan, A.; Sirén, K.
   - Year Published: 2002
   - Journal Name: Energy and Buildings
   - 1-3 major accomplishments of this paper:
     (a) A closed wet cooling tower was analyzed and a computational model was developed based on the closed wet cooling tower analyzed.
     (b) Using the computational model developed, the paper shows that the coefficient of performance is optimal in Helsinki, Lisbon, London and Zurich.
3. Minimization of Operational Costs in Cooling Water Systems
   - Author(s): Castro, M. M.; Song, T. W.; Pinto, J. M.
   - Year Published: 2000

- Journal Name: Chemical Engineering Research and Design
- 1-3 major accomplishments of this paper:
  (a) The paper found that the most important condition to influence the performance of a cooling tower is the humidity of the environment.

4. A systemic approach for optimal cooling tower operation
   - Author(s): Cortinovis, G. F.; Paiva, J. L.; Song, T. W.; Pinto, J. M.
   - Year Published: 2009
   - Journal Name: Energy Conversion and Management
   - 1-3 major accomplishments of this paper:
     (a) An optimization model was developed with the goal of minimizing operating cost.
     (b) Using the model that was developed, multiple optimization for were made for various cases such as requiring as relatively cooler temperatures.

5. Industrial Cooling Tower Design and Operation in the Moderate-Continental Climate Conditions
   - Author(s): Laković, M.S.; Banjac, M.J.; Laković, S.V.; Jović, M.M.
   - Year published: 2016
   - Journal name: Thermal Science
   - 1-3 major accomplishments of this paper:
     (a) Discussed how cooling towers can operate differently based on the climate conditions of their geographical locations.
     (b) Discovered that cooling towers will also be sized accordingly based off these different operating principles.

6. On the water footprint in power production: Sustainable design of wet cooling towers

   - Author(s): Guerras, L.S.; Martín, M.
   - Year published: 2020
   - Journal name: Applied Energy
   - 1-3 major accomplishments of this paper:
     (a) Highlighted the types of sustainable designs of cooling towers that are currently being researched and pursued in recent times.
     (b) Determined that water consumption is the key factor to take into consideration when designing sustainable cooling towers.

7. Evaluation of impacts of cooling tower design properties on the near-field environment

   - Author(s): Lee, J.
   - Year published: 2018
   - Journal name: Nuclear Engineering and Design
   - 1-3 major accomplishments of this paper:
     (a) Discussed the strategies that nuclear plants are undertaking in relation to reducing the environmental impact of their cooling towers.
     (b) Concluded that varying the size/length of the cooling tower, the air flow rate, and other specifications will reduce the amount of pollution from cooling towers going into the atmosphere.