Exponential Decay Relationship in Cooling Towers

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Abstract

Evaporative cooling is commonly used for efficient heat dissipation in industrial processes. This experiment analyzed the performance of a counterflow cooling tower, investigating the relationship between the number of transfer units (NTU), which quantifies cooling effectiveness, and the liquid to gas mass flow ratio (L/G). We used Merkel's equation to model the system and collected experimental data by varying liquid and gas flow rates while monitoring water temperature and air humidity. Results demonstrated that NTU and L/G displayed an exponential decay relationship, which confirmed theoretical expectations. Greater cooling efficiency was captured at lower L/G ratios, while deviations at higher L/G values indicated the influence of external fluctuations. These findings highlight the significance of flow control optimization and improved temperature control in industrial applications of cooling towers. Future work should investigate the impacts of crossflow cooling configurations and stronger humidity control to reduce external variability and potentially improve efficiency.

1 Introduction

Evaporative cooling has been the most commonly used technique in industries to remove excess heat generation into the environment. It is one of the most cost-effective and historic methods developed.[1] This technique is widely implemented in power plants, petrochemical refineries, HVAC systems and chemical processing industries to reject waste heat efficiently.

There are two major considerations when conducting evaporative cooling: maintenance and environmental impacts. Controlling water makeup quality, preventing fouling and scaling and minimizing contamination into the environment are strong priorities. Effective cooling water chemistry handling is also crucial to prevent biofouling and scaling, all of which can reduce inefficiency and increase operational costs. Additionally, evaporative cooling reduces the consumption of potable water and ensures that the discharge of chemicals from leaking heat exchangers (HX) is controlled, making the process an environmentally friendly approach in industrial settings. As such, continuous research has been invested into minimizing the annual costs of running the process worldwide.[2]

One of the main ways this process has been incorporated in industrial settings is through the use of cooling towers. In many process industries, cooling towers are usually built with ordinary combustible materials.[3] They operate by letting water cool by exposing its surface to air. This process of involves two components: latent heat-transfer to vaporization and sensible heat-transfer from the difference between the ambient and water temperatures. Approximately 80% of heat removal occurs in the former. Merkel's theory provides the most accepted analysis for the cooling tower process.[2]

By conducting experimental measures and comparing results to experimental measurements and theoretical expectations, the different operational parameters such as water flow rate and air temperature, can influence cooling efficiency. Understanding the fundamental principles of cooling towers will provide insight into application in process industries and help in optimizing industrial cooling systems.[2]

2 Background

The most common cooling system is the traditional air conditioning unit due to to low maintenance costs and its ability to be used indoors and/or in humid environments. Evaporative cooling is an intriguing and rapidly expanding alternative in many areas due to significantly lower energy costs; however, standard cooling towers are only properly functional in drier climates and their performance decreases substantially in humid climates. This is solely because cooling towers use ambient air and thus cannot cool below the wet-bulb temperature of the ambient air.[4]

Common models for modern evaporative cooling include natural draft, forced draft, and induced draft mechanisms. Forced and induced draft systems are forms of mechanical draft evaporative cooling. The former uses a powered blower at the inlet to push air into the system with the downside of a large energy cost, while induced draft uses a fan at the exit of the cooling tower, sucking hot, wet air through the tower. Natural draft cooling towers rely on buoyancy to create air flow, so it cannot be used in many circumstances, but is often preferred as it requires no power for any fans.[5]

Evaporative coolers can be assigned to one of three categories: direct evaporative cooling (DEC), indirect evaporative cooling (IEC), and dew-point evaporative cooling (DPEC). Of these, DEC is most historically common due to simplicity and lower costs at the drawback of increasing surrounding air humidity. IEC is a newer technique that eliminates humidity changes at the cost of efficiency and energy costs by creating two channels for dry and wet air and transferring heat from the dry channel to the wet channel, where a difference in vapor pressure enables evaporation through a water film.[6] DPEC, also known as the M-cycle, is a recent innovation that instead eliminates the limitation of only cooling up to the wet-bulb temperature and allowing cooling up to the dew point temperature by pre-cooling the "working" air before entering the wet channel.[6,7]

Cooling towers are additionally modeled as either counter-flow or cross-flow heat exchangers. Counter-flow towers have water enter at the top opposite the air entering from the bottom, causing air to escape out the top of the tower after heat transfer. Cross-flow towers have air flow perpendicular to the water flow entering at the top. Significant research has been done determining their advantages and disadvantages relative to each other. For example, in M-cycle evaporative coolers, cross-flow setups demonstrated greater efficiency, while counter-flow exchangers have greater cooling capacity and dew-point and wet-bulb effectiveness.[7]

Here, we show the performance metrics and heat transfer dynamics of direct evaporative counter-flow cooling towers and evaluate their efficiency by determining their number of transfer units, $NTUs$ based on the Merkel equation. Specifically, a small induced draft system that produces minimal temperature change was analyzed and compared to a larger forced draft cooling tower, which was the main focus of the experiment. By measuring both wet-bulb and dry-bulb temperatures, the effect of humidity on cooling tower performance was determined. Additionally, we varied both liquid and gas inlet flow rates separately with one or the other at adifferent, but constant flow rate to diagnose trends and discover their effects on efficiency by developing a model that relates specifically the liquid to gas mass flow rate L/G to NTU.

3 Theory

For heat exchangers, performance and heat transfer rate can be standardized by evaluating their number of transfer units ($NTUs$), which is a dimensionless variable. Merkel's equation can be used to model the counter-flow cooling tower apparatus in this experiment,

$$NTU = \frac{KaV}{L} = \int \frac{C_p}{h_s - h} dT \tag{1}$$

where K is the mass transfer coefficient, a is contact area, V is active cooling volume, L is the liquid coolant flow rate, C_p is the heat capacity of liquid water, h_s is the enthalpy of saturated air, $h_i n$ is the air operating line. For this experiment, $\frac{KaV}{L}$ is not calculated and is ignored as equivalent to NTU. h varies based on another equation,

$$h = h_{\text{in}} + (\frac{L}{G})C_p(T - T_{\text{out}}) \tag{2}$$

where h_{in} is the previously calibrated enthalpy of the inlet air, L/G is the ratio of liquid to gas mass flow rates, T is water inlet temperature, and T_{out} is water outlet temperature.

A calibration curve in the form of ae^{bT} can be plotted for h_s as a function of T based on tabulated values from Perry's Chemical Engineers' Handbook, as shown in Fig. 4.[8] With coefficients determined for a and b, values for both h_s in Eq. (1) and h_{in} in Eq. (2) can be determined, with the former determined using outlet liquid temperature and the latter related by inlet liquid temperature.

Humidity plays an important role in the calculation of L/G. This is because the cooling tower can only bring water temperature down to the external wet-bulb temperature. Therefore, efficiency of these towers can vary heavily depending on the difference between wet-bulb and dry-bulb temperatures in the system. Additionally, external humidity requires L/G to be represented as a mass flow ratio to account for differing air densities. Efficiency (η) of the cooling tower is calculated as,

$$\eta = \frac{T - T_{\text{out}}}{T - T_{\text{wb, inlet}}} \times 100\% \tag{3}$$

where T is once again the inlet water temperature, T_{out} is outlet water temperature, and $T_{\text{wb, inlet}}$ is the wet-bulb temperature at the air inlet. Essentially, the efficiency represents the total heat transfer by the system compared to the maximum possible heat transfer, at which the outlet water temperature would equal the wet-bulb temperature of ambient air entering the system. As such, less humid conditions which result in lower ambient wet-bulb temperature should create a larger temperature gradient between the wet-bulb temperature and inlet water temperature, and therefore also return a larger temperature drop for the exiting liquid, signifying a more effective cooling system.

4 Methods

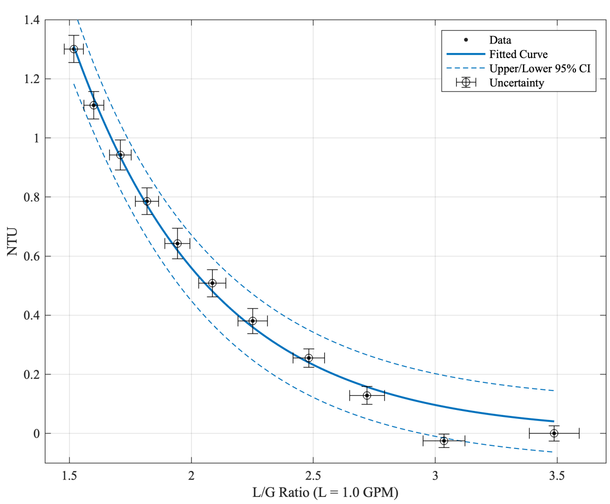
A heated tank was set up as a source of hot water. A pump was used to create flow of water from the tank to the top inlet of the counter flow cooling tower. After the water gas run down the cooling tower, the output was sent back to the tank, closing the circuit. The flow of water is varied by a flowmeter to produce flow rates of 0.3 gallons per meter (GPM) to 1 GPM on a basis of 4m/s of air flow. The upwards air current of velocities 2m/s to 6m/s was produced by a blower on a basis of 1 gallon per minute of water. The wind was channeled through the cooling tower and into a ventilation duct to exit the system. An anemometer and hygrometer were placed at the exit of the vent to measure the air's speed and humidity, respectively. The experiment was conducted at standard atmosphere and pressure. Six different thermocouples were attached at different reference points within the cooling tower. The thermocouples were sensors for inlet and outlet temperatures for water, dry-bulb air and wet-bulb air. These signals were then transmitted to a controller where the temperatures were outputted and recorded. The controller also output the temperature of the source water (heated tank). A similar set up was also done with a smaller cooling tower with a built-in fan.

5 Results

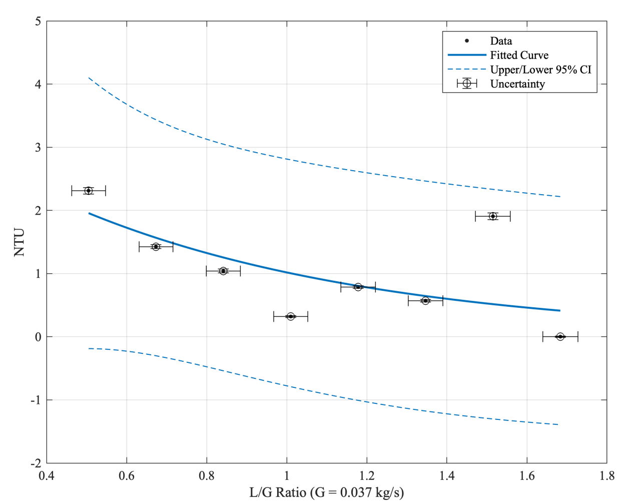
Air humidity remained between 94% and 97% over a two-week period, precluding analysis of its impact on cooling tower performance. Instead, to evaluate the cooling tower performance described in Section the water outlet temperature was primarily tested as a function of the liquid-to-air mass flow rate ratio (L/G).

Fig. 1a, Fig. 1b, and Fig. 2a are different combinations of L/G using the same cooling tower. Either L or G was varied at once to make analysis simpler. All of the following figures are fitted as a one-term exponential decay with a 95% confidence intervals included. Air flow rate, liquid flow rate and temperature values at smaller L remained near constant once the system stabilized (5-10 seconds). Hence, only one reading was considered per data point.

The smaller cooling tower in Fig. 3 recorded temperature values for each second. Hence, their average is considered and corresponding standard deviation is propagated into NTU's uncertainty calculation.

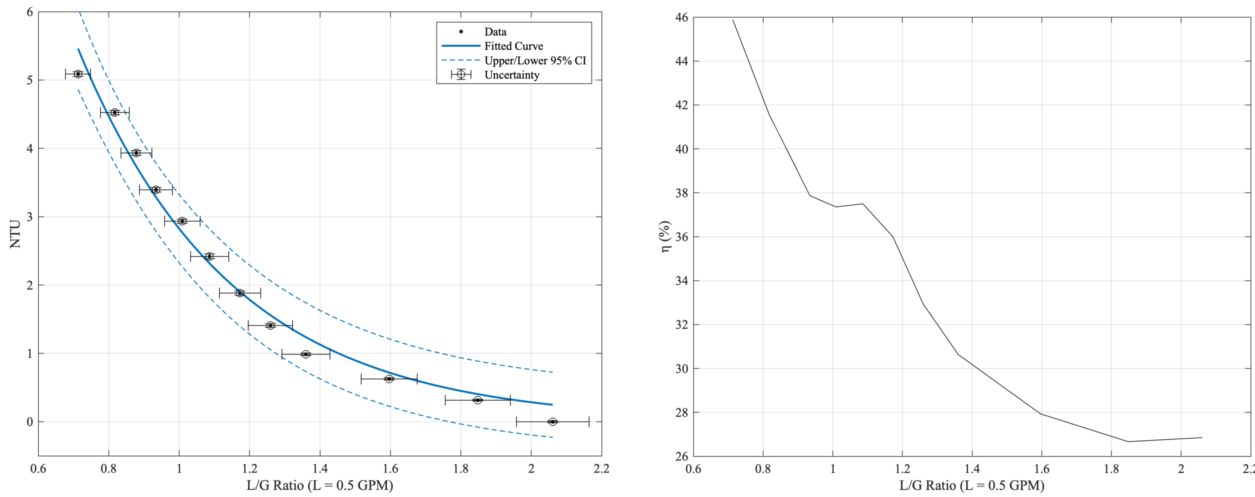


(a) **Figure 1a**.



(b) **Figure 1b**.

Figure 1: Effect of Varying Gas (a) or Liquid (b) Flow Rate on Number of Transfer Units.



(a) **Figure 2a**. (b) **Figure 2b**.

Figure 2: Number of Transfer Units at Lower Liquid Flow Rate (a) and Corresponding Efficiency (b).

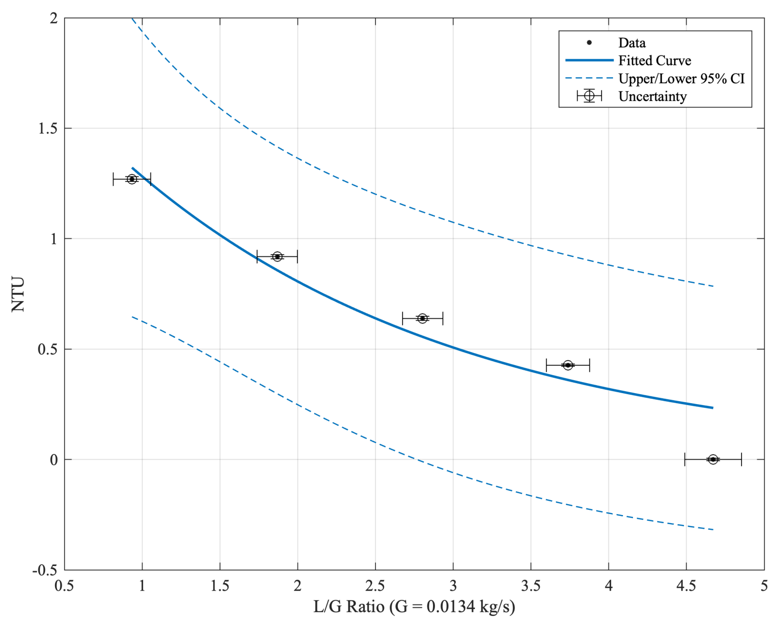


Figure 3: Number of Transfer Units at Fixed Air Velocity Using a Smaller Cooling Tower Compared to Previous.

6 Discussion

Results in Section 5 follow the decay trend expected and outlined in Section 3. Maximum heat transfer and maximum efficiency η both occur at lower L/G ratio. This is expected due to higher surface area at lower liquid flow rate (L). This is the function of the sprinkler at the top the tower and the plates that follow. In addition, the residence time for a defined water volume is smaller at higher L. Even though, the air is gaining almost as much heat at higher L, the liquid loses less energy per unit mass since there is more of it.

The combinations of L/G made in earlier figures in Section 5 include different flow rate (Fig. 2a and Fig. 1a) each fixed while varying G, varying L at a fixed G (Fig. 1b), and varying L in smaller cooling tower (Fig. 3). A linear fit could be made for Fig. 1b and Fig. 3. However, an exponential decay fit was used instead to remain consistent with other fitted data. This is the result of varying L for either of the cooling towers while G remained constant. It was observed that at higher L, the reservoir temperature would drop significantly ($\sim 10°C$), altering the temperature of liquid entering the tower due to its circulation through the reservoir. Hence at higher L, the entering liquid temperature tends closer to inlet wet-bulb temperature of air and therefore reducing heat transfer at lower L than would be expected otherwise. The effect would be minimized by recording temperatures very quickly into changing L. However, that would not allow the system to stabilize. Another way would be to heat up the water reservoir between each data collection. This was not done due to time constraints.

Efficiency as plotted in Fig. 2b was calculated by Eq. (3), which is maximized when the temperature difference between entering liquid and inlet wet-bulb of air is highest. For the data in Fig. 2a, inlet wet-bulb temperature average is $13.46°C$, and the lowest water outlet temperature achieved is $22.9°C$. From looking at the trend in Fig. 2a, number of transfer units tend to zero at lower outlet water temperatures. Hence, for the given conditions ($L = 0.5GPM$ and $L/G > 2$), at least $10°C$ difference between L and G for any effective heat transfer.

The smaller cooling tower in Fig. 3 has smaller number of transfer units per L/G ratio than all L and G variation made earlier with the larger cooling tower. The heat transfer decreases with higher L as expected. With NTU values close larger tower running at 1 GPM (Fig. 1a), supplied liquid still did not lose much energy, at most a $3.3°C$ decrease in water temperature was observed at $0.2GPM$. The higher than expected heat transfer is due to enthalpy of air nearing saturation enthalpy in the smaller tower ($(h_s - h) \mid_{L/G=0.93} = 8.76\, kJ/kG$), in turn raising the number of transfer units as in Eq. (1).

	Inlet Temperature (°C)	Temperature Drop (°C)	L/G Ratio
Fixed L (1.0 GPM)	43.8	8.8	1.52
Fixed L (0.5 GPM)	30.7	7.8	0.71
Fixed G (0.037 kg/s)	38.6	13.4	0.51
Fixed G (0.0134 kg/s)	35.5	3.3	0.93

Table 1: Maximum Temperature Drop, Corresponding Inlet Temperature and L/G Ratio

It is expected that a higher temperature gradient between inlet water and inlet wet bulb of air would maximize temperature drop. However, from Table 1, fixed G at 0.037 GPM has maximum temperature with lower inlet temperature than fixed L at 1.0 GPM (inlet air wet-bulb temperature is near constant at 14 °C for all trials). It is instead found that the system is more sensitive to L/G ratio than inlet temperature regarding extent of temperature drop. Even though a lower L/G might no always yield a higher number of transfer units, it is still a trend for any fixed L. This is due fluctuation in temperature in water reservoir when L is varied.

7 Conclusions

The results of this experiment showed that the the number of transfer units (NTU) and cooling efficiency does decrease as the liquid-to-gas flow ratio (L/G) increases. This confirmed the theoretical expectations based on Merkel's equation. The data demonstrated an exponential decay relationship between NTU and L/G, with lower liquid flow rates resulting in higher residence time and improved heat transfer efficiency. Moreover, the sensitivity of cooling tower performance to inlet water temperature and humidity levels are highlighted by the temperature drops at different flow conditions. While general trends were consistent with theory, there are deviations at higher L/G ratios. This suggested that uncertainties were introduced by source temperature fluctuations.

Future experimentation on cooling towers can focus on improving measurement precision by implementing longer stabilization times to minimize external factors. Also, investigating alternative cooling tower configurations, such as cross-flow designs could be insightful in optimizing heat transfer efficiency. These refinements would enhance the reliability of experimental data and contribute to more economic approaches in cooling tower applications in industrial settings.

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Appendix

1. Psychometry, Evaporative Coooling, and Solids Drying

    - Author(s): B.A. Finlayson and L.T. Biegler
    - Year published: 2008
    - Journal name: Psychometry
    - 1-3 major accomplishments of this paper:

        (a) Describes main considerations when conducting evaporative cooling

2. A comprehensive review on evaporative cooling systems

    - Author(s): N. Kapilan, A. M. Isloor, S. Karinka
    - Year published: 2023
    - Journal name: Results in Engineering
    - 1-3 major accomplishments of this paper:

        (a) Highlights the strengths and challenges of evaporative cooling systems

3. Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities

    - Author(s): D. P. Nolan
    - Year published: 2019
    - 1-3 major accomplishments of this paper:

        (a) Provides tactics on how to revise and upgrade company policies to support safer designs and equipment

4. A review of dew-point evaporative cooling: Recent advances and future development

    - Author(s): G. Zhu and T. Wen and Q. Wang and X. Xu

- Year published: 2022
- Journal name: Applied Energy
- 1-3 major accomplishments of this paper:
  (a) Determines the main characteristics of DPEC and offers possible research topics to be pursued in the future.

5. Comparative study of the performance of the M-cycle counter-flow and cross-flow heat exchangers for indirect evaporative cooling – Paving the path toward sustainable cooling of buildings
   - Author(s): C. Zhan and Z. Duan and X. Zhao and S. Smith and H. Jin and S. Riffat
   - Year published: 2011
   - Journal name: Energy
   - 1-3 major accomplishments of this paper:
     (a) Compares counter-flow and cross-flow M-cycle heat exchangers (DPEC) and determines their advantages and disadvantages.
     (b) Created a computer model to determine cooling performance of DPEC heat exchangers.

6. Indirect Evaporative Cooling – an energy efficient way for air conditioning
   - Author(s): M. L. Chen and X. L. Liu and E. Hu
   - Year published: 2013
   - Journal name: Advanced Materials Research
   - 1-3 major accomplishments of this paper:
     (a) Compares the performance of Australia's first major IEC evaporative cooling system to standard air conditioning.

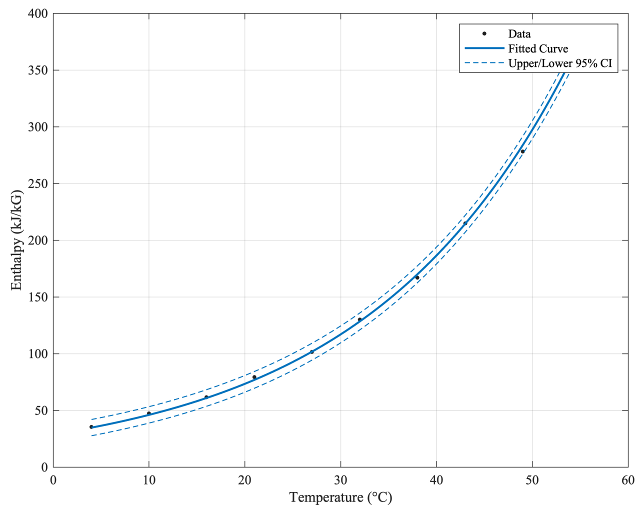

Figure 4: Calibration curve for $h_s(T)$ used to determine values for h_s and h_{in} used in Eq. (1) and Eq. (2), respectively.