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Estimation of Outlet Water Temperature of a Cooling Tower Based on Weather Data in Kuala Lumpur, Malaysia

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ABSTRACT

The study centres on predicting the outlet water temperature of a cooling tower in Kuala Lumpur (KL) by evaluating weather data, with the goal of reducing energy usage through improved forecasting. The objective of the study is to develop an accurate prediction equation for obtaining the wet-bulb temperature (T_w) using the dry-bulb temperature (T_d) and relative humidity (R_h). This study also aims to prove the coefficient of performance (COP) of refrigeration cycles that are cooled by water from cooling towers. Using a weather station equipped in the UTM-KL campus, the T_d and R_h were measured for every minute. The T_w was calculated by applying the bisection method and Sprung's formula to obtain the prediction equation for T_w. The maximum prediction error of the proposed equation for T_w was 0.15 °C. The prediction error by the previously proposed Stull's formula was 0.69 °C. The COP of the water Carnot cooling refrigeration cycle was 1.9 times higher than that of the air-cooling refrigeration cycle.

Keywords:
Cooling tower; Kuala Lumpur weather data; relative humidity

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1. Introduction

A cooling tower is used to cool the condenser of an air conditioning system of a building or a factory [1,2]. The outlet water temperature of an ideal cooling tower is the wet-bulb temperature (T_w) [3,4]. Although, the dry-bulb temperature (T_d) and the relative humidity (R_h) are accessible from the weather database (e.g. Malaysia historical weather data is available by Kuala Lumpur International Airport [5]), the wet-bulb temperature (T_w) is not available in such database. The wet-bulb temperature is obtained by solving Eq. (1) to Eq. (3) using the bisection method [6,7] at the research level and software such as Matlab [8] or EES [9] is commonly used to solve the set of equations. However, it would be convenient if the wet-bulb temperature could be obtained using a spreadsheet program. Under such background, in 2011 Stull proposed an algebraic formula to calculate the wet-bulb temperature (T_w) from the dry-bulb temperature (T_d) and the relative humidity (R_h) [10]. Such a formula had not been proposed until then [11,12]. However, the prediction accuracy of T_w by Stull's formula is around 0.6 °C and more accurate prediction formula is required. One of the

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objectives of this project is a more precise algebraic-prediction-formula in order to calculate the wet-bulb temperature (T_w) from the dry-bulb temperature (T_d) and the relative humidity (R_h). In addition, our objective is to demonstrate that the COP of a Carnot refrigeration cycle [13], where the condenser is cooled by water from a cooling tower, is superior to that of a cycle where the condenser is cooled by air [14].

2. Methodology

Using the weather station, HD52.3D417 2axes ultrasonic static anemometer with Barometer, temp & R_h made by Delta-Ohm [15], which was equipped at the top of the building F in UTM-KL campus, the dry bulb temperature, the relative humidity and the barometer were measured every 1 minute. The saturated water vapor pressure, P_s can be obtained using the following equation which is approximated from the saturated water vapor pressure [16].

$$P_s = \exp\{25.7545 - 5275.67\left(\frac{1}{T_d}\right)\} \tag{1}$$

From the weather data collected, we found out that the T_d in KL ranges from 22°C - 40°C. Meanwhile the R_h percentage in KL ranges from 20% to 100%. The water vapor partial pressure, P_v in the air is by Moran *et al.,* [17].

$$P_v = P_s \times R_h \tag{2}$$

There is the following correlation between the wet bulb temperature, T_w and the water vapor partial pressure in the air, P_v. The wet bulb temperature was obtained by the bisection method and Eq. (3) is called Sprung's formula [18].

$$P_v = \exp\left\{25.7545 - 5275.67\left(\frac{1}{T_w}\right)\right\} - 0.000662P_a(T_d - T_w) \tag{3}$$

In order to calculate the COP of Carnot Refrigeration cycle, the following equation was derived [13].

$$COP_R = \frac{Q_C}{W} = \frac{Q_H - W}{W} = \frac{Q_H}{W} - 1 = \frac{1}{1-\frac{T_C}{T_H}} - 1 = \frac{T_C}{T_H - T_C} \tag{4}$$

where T_H is the maximum hot temperature while T_C is the coldest temperature during the cycle. The flowchart for the following research is as below.

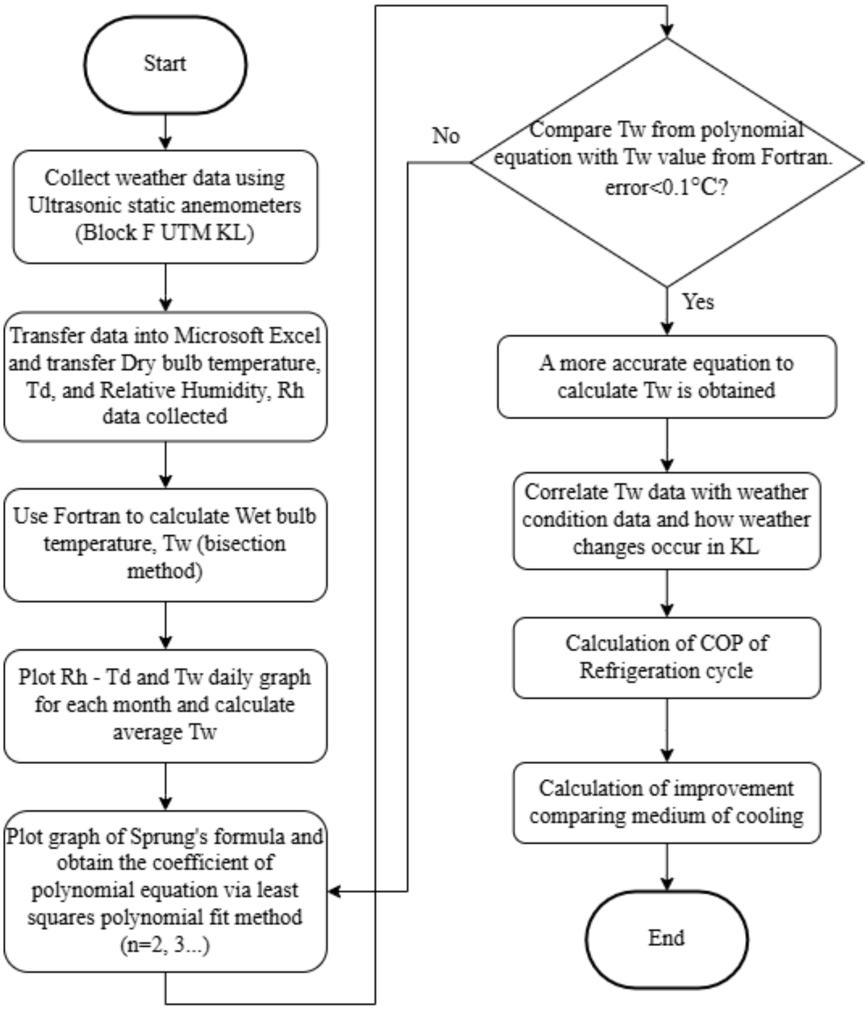


Fig. 1. Flowchart

3. Result

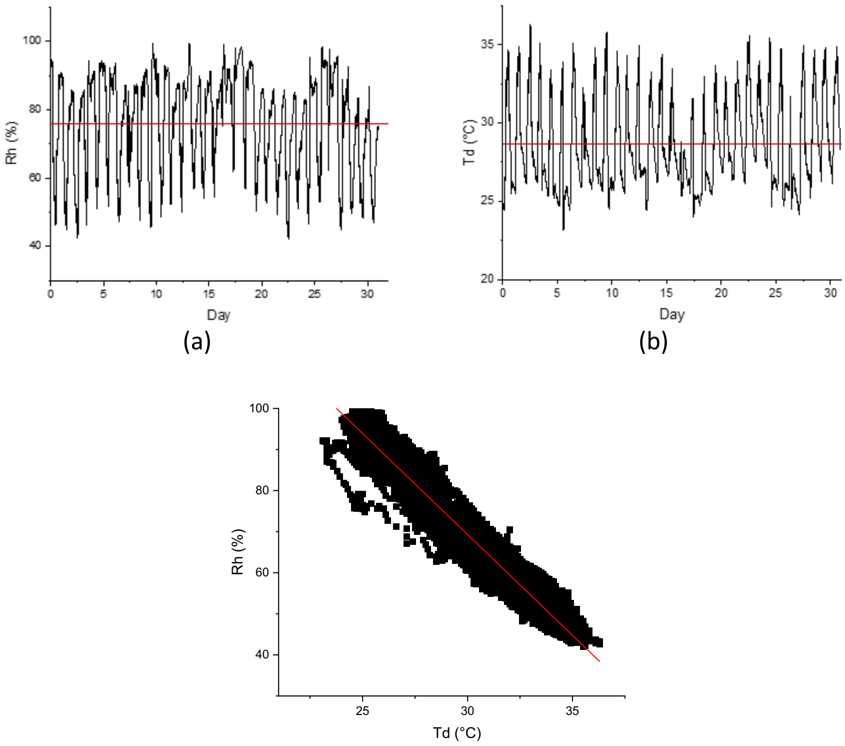
Based on the conducted data analysis, many discoveries have been identified that will assist us in accomplishing the primary research objectives. The bisection approach [6,7] was employed utilizing Eq. (2) and Eq. (3) in order to compute T_w from the acquired T_d and R_h data. The calculations were performed using the Fortran G95. Table 1 displays the observed data and computed T_w collected during the initial 15 minutes on the first day of May 2021.

Table 1
Weather data of Kuala Lumpur in May 2021

Hour	Dry Bulb Temperature, T_d	Relative Humidity, R_h	Wet Bulb Temperature, T_w
00:00:00	24.8	0.933	24.0
00:01:00	24.8	0.932	23.9
00:02:00	24.8	0.931	23.9
00:03:00	24.8	0.931	23.9
00:04:00	24.8	0.930	23.9
00:05:00	24.8	0.929	23.9
00:06:00	24.8	0.928	23.9
00:07:00	24.8	0.927	23.9
00:08:00	24.8	0.926	23.9
00:09:00	24.8	0.926	23.9

00:10:00	24.8	0.926	23.9
00:11:00	24.9	0.925	24.0
00:12:00	24.9	0.925	24.0
00:13:00	24.9	0.925	24.0
00:14:00	24.9	0.925	24.0
00:15:00	24.9	0.924	23.9

Figure 2(a) displays the measured T_d in May 2021, collected at 1-minute intervals. The temperature ranges from 24 °C to 36.5 °C, with the average value, indicated by the red line, being 0.76 °C higher than the median value. Figure 2(b) displays the relative humidity for May 2021, ranging from 40% to 97%. Figure 2(c) displays the R_h % and T_d collected at 1-minute intervals for the same month. The x-axis shows the T_d, measured in degrees Celsius, while the y-axis represents the Relative humidity, R_h, measured as a percentage. Based on the data presented in Figure 2(c), it is evident that these two factors exhibit a substantial correlation.



(a) (b)

(c)

Fig. 2. Data collected in May 2021 (a) Daily T_d (b) Daily R_h (c) R_h vs T_d

Based on the computed T_w data, it was determined that the mean T_w was 25 °C, depicted in Figure 3 as the solid red line. The standard deviation was found to be 0.64, as illustrated in the accompanying figure. The vertical axis represents the wet bulb temperature, while the horizontal axis represents the days on which the data was collected. The ±3σ red dotted lines indicate that 99.7% of T_w values [19] are within the range of 24.1 to 26.9 °C.

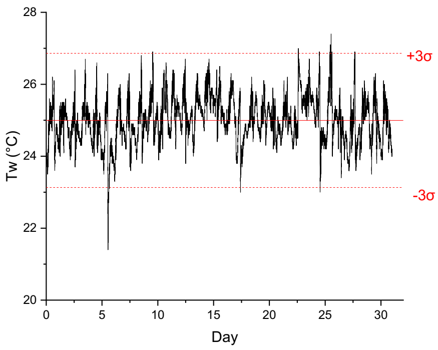


Fig. 3. T_w in May 2021

Subsequently, by utilizing all recorded T_d and R_h values in May 2021 and performing calculations based on Eq. (1) to Eq. (3), it is possible to plot the Iso-wet bulb temperature line. This line is depicted in Figure 4, using the aforementioned T_d and R_h data from May 2021. The range of the Iso-wet bulb temperature lines is from 22 °C to 28 °C, with an interval of 1 °C.

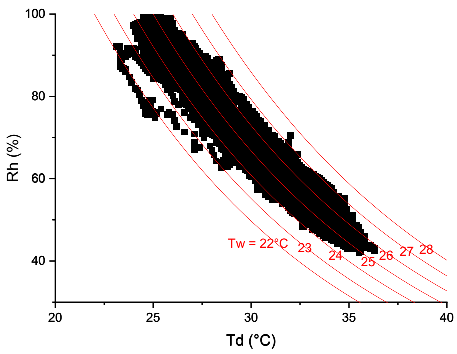


Fig. 4. Iso-wet bulb temperature lines with all measured T_d and R_h in May 2021

Based on the provided graphs, we have demonstrated that the weather data in KL shows a consistent pattern. Both the dry bulb temperature and relative humidity fluctuate throughout the month, which in turn affects the wet bulb temperature. Specifically, when the T_d decreases and the R_h percentage increases, the T_w also increases and vice versa. Thus, it can be inferred that the T_w values in KL do not undergo significant changes and only vary within the temperature range of 22 °C to 28 °C.

In addition to that, we observe the consistent weather pattern throughout the entire year. Figure 5 displays the mean T_w (wet bulb temperature) for the entirety of 2021, with an average value of 24 °C. The figure demonstrates a consistent rise in temperature in KL from January to May, with May seeing the highest temperature. Subsequently, the temperature decreased to a specific level and remained constant for the rest of the year. In addition, the red line on the graph reflects the average T_w values plus three standard deviations (+3σ), indicating the highest T_w data in 2021 with a 99.7% probability [19], which is around 26.7 °C.

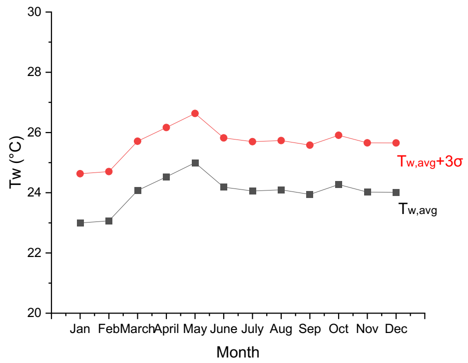


Fig. 5. Monthly average T_w and T_w +3σ for each month in year 2021

In order to get the value of T_w, it is necessary to solve Eq. (2) and Eq. (3). However, Microsoft Excel alone cannot provide the parameter until a macro is loaded. Hence, it would be highly advantageous to have a prediction function in Excel that can accurately predict the value of T_w based on the T_d and R_h data. The Stull's formula [10] was employed to carry out this phase. The Stull's formula can be used for T_d values ranging from -20 °C to 50 °C and for relative humidity values between 5% and 95%. This results in the procedure encountering an inaccuracy of approximately 0.69 °C. However, as depicted in Figure 4, it is adequate to compute the T_w values in KL within a limited range of 22 °C to 28 °C. Linear interpolation can be used to compute T_w values from T_d and R_h, given that the Iso-wet bulb temperature lines are evenly spaced. Subsequently, the estimated values of the relative humidities, $R_{h,22}$ and $R_{h,28}$ which correspond to the temperatures T_w of 22 °C and 28 °C respectively, were determined as a function of T_w. This was achieved by employing a polynomial fit [20] to derive a cubic equation for $R_{h,22}$ and $R_{h,28}$.

$$R_{h,23} = 497.67884 - 30.18266T_d + \ 0.6664538T_d^2 - 0.006885811T_d^3 \tag{5}$$

$$R_{h,28} = 701.86169 - 40.75944T_d + \ 0.880737_2T_d^2 - 0.006885811T_d^3 \tag{6}$$

As seen in Figure 4, the interval of the iso-wet bulb temperature lines is almost constant, we can apply the linear interpolation for T_w as.

$$T_w = (28 - 22)\frac{R_h - R_{h,22}}{R_{h,28} - R_{h,22}} + 22 \tag{7}$$

where the maximum error of Eq. (7) is only 0.15 °C in the T_d range from 20 °C to 40 °C. These values shown an improvement compared to the maximum error of the T_w calculated using Stull's formula which is 0.69 °C in the same T_d ranges.

Lastly, the COPs of the Carnot refrigeration cycle is obtained for two cases where the condenser is cooled by cooling tower water and air. As an example, the condenser temperature, T_H is 28 °C when the condenser is cooled by cooling tower water T_H is 35 °C when the condenser is cooled by air. Both minimum temperatures, T_C are set to be 20 °C. Thus,

$$COP_{R,1} = \frac{293}{8} = 36.625 \tag{8}$$

$$COP_{R,2} = \frac{293}{15} = 19.533 \tag{9}$$

Therefore, it can be said that using cooling tower water is more efficient compared to air as the medium for cooling purpose in the refrigeration cycle by up to 1.9 times.

4. Conclusion

These data indicate that the average T_w value in Kuala Lumpur ranges from 24 °C to 24.5 °C and does not reach 27 °C, even when the highest value is increased by 3σ. In addition, the temperature in KL maintains a consistent pattern throughout the year, with uniform fluctuations in both Dry-bulb temperature and Relative humidity. Thus, the value of T_w likewise exhibits a consistent and proportional increase and decrease within the temperature range of 21-28 °C. Moreover, a more precise equation for estimating the value of Wet bulb temperature in KL, based on Dry bulb temperature and Relative Humidity, has been derived. Finally, this demonstrates that the coefficient of performance (COP) of a refrigeration cycle, where the condenser is cooled by water from a cooling tower, is superior to that of a cycle where the condenser is cooled by air.

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