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Prediction of Thermal Performance of Cooling Tower of a Chiller Plant Using Machine Learning

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Abstract. Chiller plants (CP) are accountable for regulating the comfort levels of most indoor environments. The CP uses water as the working medium and acts as a centralized cooling system for the controlled cooling of products, in the different production environments, machine tool industries, 3D printing, packaging, heat exchanging systems and to preserve agricultural produce, dairy products, and other edible items. The CP under study is used for providing cooling to sixteen storeyed hostel building at VIT Chennai. The refrigerant used in this system is Tetra fluoro ethane (R134a). The chilled water (ChW) from the evaporator is circulated to the rooms in the hostel through the secondary circuit and the air handling unit exchanges chillness from the chilled water and finally supplies to the hostel rooms. The chilled water from the hostel returns to the evaporator in a closed loop. The cooling water (CW) from the condenser of the refrigeration system rejects heat to the cooling tower (CT). Thus the performance of the CT is directly linked to the performance of the cooling provided to the hostel rooms. The objective of this research is to predict the temperature at the outlet of the CT integrated with the CP using machine learning algorithms. The predicted values are compared with the measured values and with the values calculated theoretically. The results are analyzed using the standard metrics and are observed to be appreciable.

Keywords: Machine Learning, Linear Regression, Cooling Tower, Thermal Performance Prediction, Chiller Plant.

1. Introduction

Temperature regulation is an important requirement for almost every industrial and agricultural process. The purpose of a CP is to transfer heat from one system (control volume) to another (or ambient) using water as working medium. Their applications range from cooling of products in cold storage, comfort cooling under indoor conditions and also other industrial processes & environments. A CP's highest cooling capacity varies according to its operating environments [1]. The CP can use air, water or brine solution as working medium. Chiller Plants using water has advantage over air-cooled as they are not vulnerable to outdoor environmental conditions such as rain, sunshine; dusty winds etc. and hence have a longer lifespan. They are also quiet while operating since flow of water through ducts and vents are not noisy. To meet the energy efficiency goals of the plant, it is required to conduct frequent checks for leakages and perform scheduled preventive maintenance [2]. In the centrally air-conditioned high rise buildings greater than 50% of the overall energy consumption is consumed by the chiller plant. It is very important to optimize the operating parameters of the chiller plant to augment its operating efficiency, reduce the energy source depletion and stimulate the exergy preservation of chiller plants and its associated systems [3]. The properties of the refrigerant are listed in Table 1 [4]. The primary focus of this article is on operation of the CT which is an integral part of CP, the CT under study is of induced draft type. The operation of cooling tower is dependent upon the principle thermal energy exchange from hot water in direct exposure to comparatively cool and arid air [5]. The performance characteristics of a cooling tower can also be influenced by on the size of the dewdrops in the spray area along with other parameters such as temperature, humidity and wind velocity [6]. The effectiveness of a cooling tower can be improved by atomisation of water droplets into fine size [7]. In another study, it has been observed that for 5-10°C rise in the dry bulb temperature, the evaporation losses are increases by 20% [8]. It is quite challenging to model the performance of a cooling tower quite precisely and accurately using classical modelling techniques that cope with the solution of complex differential equations [9]. Henceforth Supervised Machine Learning algorithm has been used to train the dataset and the outlet water temperature of the CT was predicted. The properties of the refrigerant R134a are listed in Table 1 and the specification of the chiller is mentioned in Table 2.

Table 1. Properties of R134a

Properties	Values
Boiling Point	-26.1°C
Auto Ignition Temperature	770°C
Ozone Depletion Level	0
Solubility in water at 25°C	0.11% wt
Critical Temperature	122°C
Global Warming Potential	1200

Table 2. Chiller Plant Specifications

Model	30XW1712P	Refrigerant	R-134a
Voltage	415 V	Max Power Input	446 kW
Frequency	50 Hz	Max Current	674 A
Phase	3 ϕ	Weight	9368 kg
Pressure (Min/Max)	0-15 bar	Pressure Setting	14.5 bar

2. The Chiller Plant

The CP taken for study is a system which exchanges heat from atmospheric air with ChW liquid through a vapour compression refrigeration (VCR) cycle/system. The CP operates with three sections namely air conditioning section, chiller section, and cooling tower section which have been schematically illustrated in the following Figure 1.

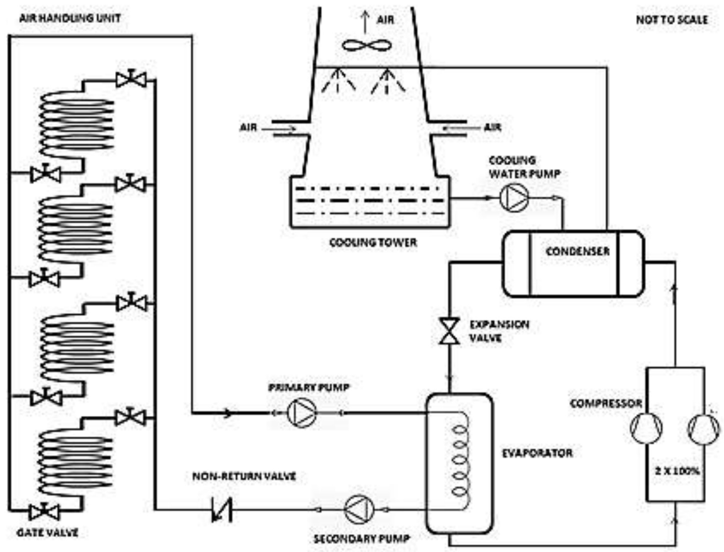

Figure 1. Schematic diagram of Chiller Plant

Air conditioning section is located in the hostel which contains pipelines and it receives the ChW from evaporator section of CP. After the thermal exchange between the air and ChW, the warm ChW returns back to the chiller (evaporator of VCR system). VCR system consists of four major components viz., compressor unit, condenser unit, throttling valve, and evaporator coil. The VCR system uses the refrigerant R134a as working medium in the primary circuit. The warm ChW leaving from the air conditioning unit transfers heat to the refrigerant of the VCR system at its evaporator section. The heat exchange medium in the cooling tower is CW from the condenser of CP and atmospheric air. This CW dissipates thermal energy to the atmospheric air after receiving the heat from the refrigerant at the condenser section of the CP. The chiller is made by *Carrier Corporation* and its specifications provided in Table 2. . In order to be efficient the chiller section should operate with reduced/increased refrigeration capacity with the decrease/increase in cooling load [10].

3. Data Reduction

The various performance parameters of the cooling tower and its mathematical relations are provided in this section. The performance parameters depend on the CW outlet temperature.

(i) Theoretical value of CW outlet temperature($T_{2\,theo}$)

The theoretical outlet temperature of cooling water from CT was calculated using the energy balance,

Heat lost by CW = Heat gained by air + Heat lost due to evaporation

$$m_1 \times C_{p1} \times (T_1 - T_{2\,theo}) = m_2 \times C_{p2} \times (T_4 - T_3) + m_3 \times H_v \tag{1}$$

Where

m_1 , m_2 - Mass flow rate of CW, air (kg/s)

Cp_1 , Cp_2 - Specific heat of water, air (kJ/kgK),

T_1, T_2 - Inlet and outlet temperature of CW (°C)

T_3, T_4 - Inlet and outlet temperature of air (°C)

m_3 - Mass of water evaporated (kg/s)

H_v - Latent Heat of evaporation (kJ/kg)

(ii) Range, R= T_1-T_{2act} (°C) (2)

(iii) Approach = T_{2act}-T_{wb} (°C) (3)

Where T_{wb} – Wet bulb temperature (°C)

(iv) Effectiveness = $\frac{Range}{(\text{Range + Approach})}$ (4)

(v) Cooling Capacity = $m_1 \times C_{p1} \times (T_1 - T_{2act})$ (kW) (5)

(vi) Blowdown loss, B = $\frac{E}{(\text{CoC} - 1)}$ (m^3/s) (6)

E - Evaporative flow loss = 0.00085×1.8×R×Q_1 (m^3/s) (Evaporative Loss is calculated for a Range of 2.3 °C and kept constant throughout.)

CoC - Cycle of Concentration = 3

(vii) Drift Loss, $D = \frac{0.2 \times Q_1}{100}$ (m^3/s) (7)

Q_1 - Volume flow rate of water (m^3/s)

(viii) Make-up Water Requirement, M = E + B + D (m^3/s) (8)

4. Prediction Using Machine Learning Algorithm

a. Linear Regression:

Let the input vector x ∈ {x_1, x_2, . . . , x_m} represent the input features (otherwise called as independent variables or predictor variables) and the output or response or dependent variable, y represents the required output. Linear regression works by creating a regression line equation involving all training data using least square method. The impact of every input feature towards the predicted output is observed and calculated using least square method. These weights that are computed for all input features are defined to be the coefficients, β1, β2, …, βm. The common bias of the data is observed and stored as β_0 (called as intercept) of the system. The representation can be understood by the following equation.

$$y = \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m + c$$

The parameters $\beta_1, \beta_2, \ldots, \beta_m$ and intercept 'c' is calculated using least square method to ensure minimal difference between predicted and actual values.

b. Dataset creation:

The following are observed to be the input parameters viz., CW inlet water temperature, Dry bulb & Wet bulb temperature of air entering, exit air temperature, mass flow rate of air & water and the output variable will be the CW outlet temperature of CT. The control unit of chiller plant is observed over a period of 46 days continuously at regular intervals of 1 hour to capture the defined inputs making a total of 414 experiences. The dataset is collected from a live environment using the electronic gadgets and hence prone to have some errors. Hence, pre-processing becomes mandatory before using the dataset for training the model.

Feature wise, the data is verified to have any missing values. If some values are missing, they are filled with mean of the values of corresponding feature. The dataset is then normalized. This is done since the measuring units are different for various features. Hence, feature values are standardized using min-max normalization to fall in the standard range from 0 to 1.

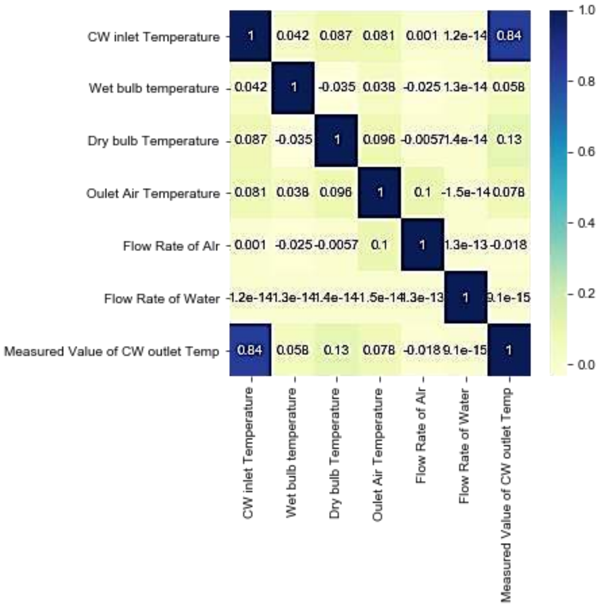

Figure 2: Correlation between features

Once completed, the dataset is checked for linearity to justify the usage of linear regression. The linearity check is performed using correlation analysis. A positive (+0.8 to +1) or negative (-0.8 to -1) correlation is witnessed to suit well with regression application whereas the correlation value near to zero indicates absence of relation between independent and dependent feature. The correlation values are presented in Fig.2.

c. Creation of Machine Learning model
The pre-processed dataset is splitted into training and testing data in the ratio of 80-20. The model is implemented in *Python* using *Jupyter notebook* as the platform.

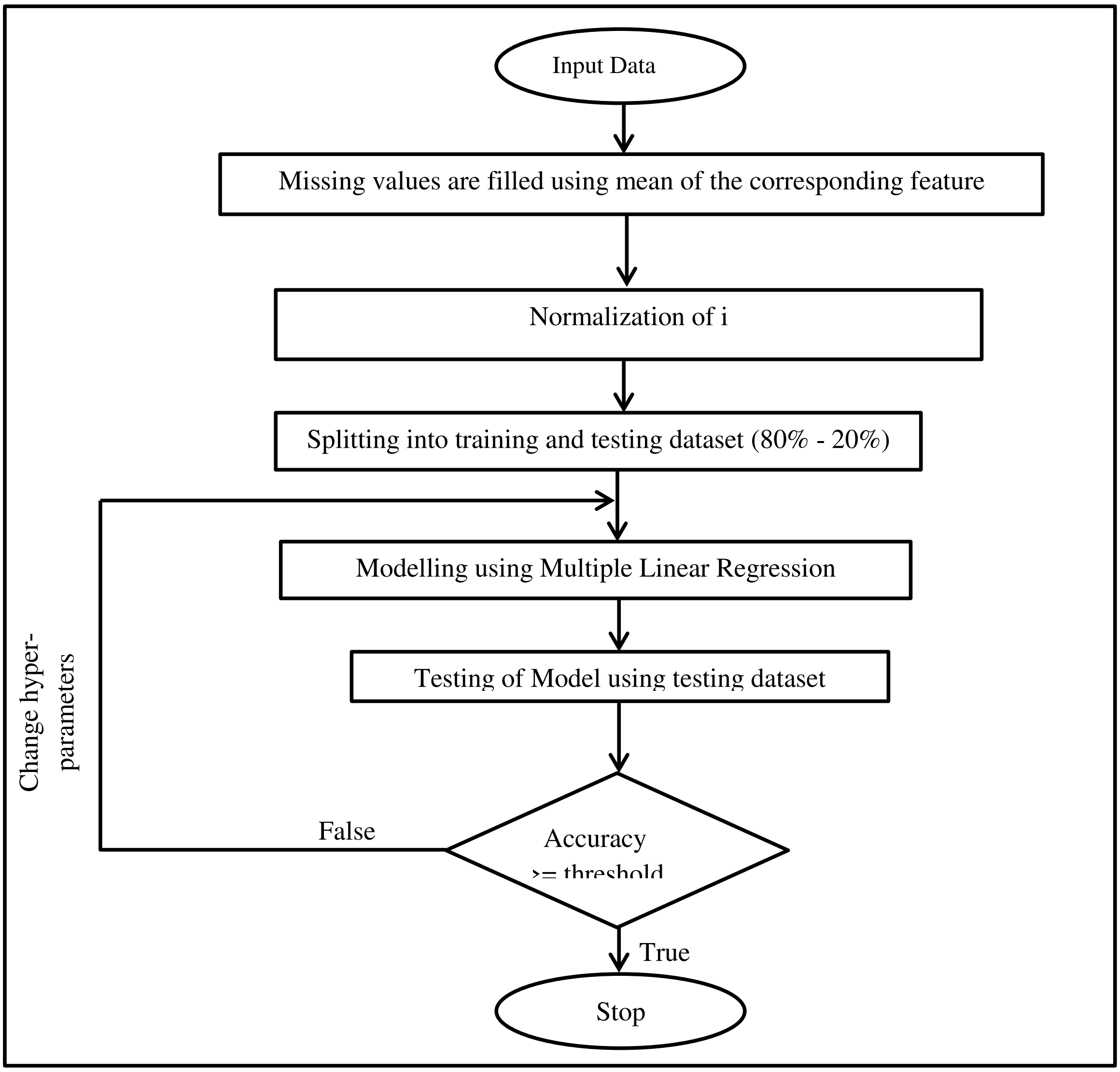

Figure 3. Process flow diagram of Predictive Model

A predictive model for determining the CW outlet temperature is illustrated in Figure 3 in the form of a flow chart. 80% data chosen at random is used for training the ML model and is resulted with the following regression line.

$$outlet\ temp = 0.5864738 * x_1 + 0.03087691 * x_2 + 0.06456786 * x_3 + 0.0056633 * x_4 - 0.07553096 * x_5 + 0 * x_6 + 10.4933341$$

Where, {x1, x2, . . . , xm} are the values residing in training dataset. From the equation it is evident that the feature titled x6 doesn't have any correlation with output and the impact or coefficient becomes zero. The computed coefficients and intercept are tested using the testing dataset. The input data is passed to equation and output is calculated for the separated 20% data. The difference between actual value and the predicted value is known as the error. To remove sign imbalance in the result, calculated differences are squared and taken average and is called as mean square error.

A sample dataset with measured and predicted values is shown in Table 3.

Table 3. Sample Dataset (Temperature in °C and flow rate in kg/s)

S.No.	CW Inlet Temperature	Wet Bulb Temperature	Dry Bulb Temperature	Outlet Air Temperature	Flow Rate of Air	Flow Rate of Water	CW Outlet Temperature	
							Measured	Predicted
0	30.1	24	30	40.2	33.067623	55.111944	28.5	28.554
1	30.2	24	30	40.2	32.710661	55.111944	29	28.64
2	30.5	23.5	29.7	40.2	31.802032	55.111944	28.5	28.85
3	30.9	22.5	30	40.2	32.029189	55.111944	29.5	29.056
4	32	24	30	40.2	33.132525	55.111944	30	29.664

5. Results and Summary

The accuracy of the trained model is tested using standard metrics, Root Mean Square Error (RMSE), and R2 value. The model results in RMSE value of 0.96 and R2 score of 0.71 indicating a minimal error rate. Figure 4a represents the relation between actual and predicted values of outlet temperature against the inlet temperature. Figure 4b illustrates the 3d view of outlet water temperature (Measured and Predicted) distribution against inlet water temperature and wet bulb temperature of incoming air. From these figures 4a and 4b, it can be inferred visually that, the deviation of predicted outlet temperature is very small.

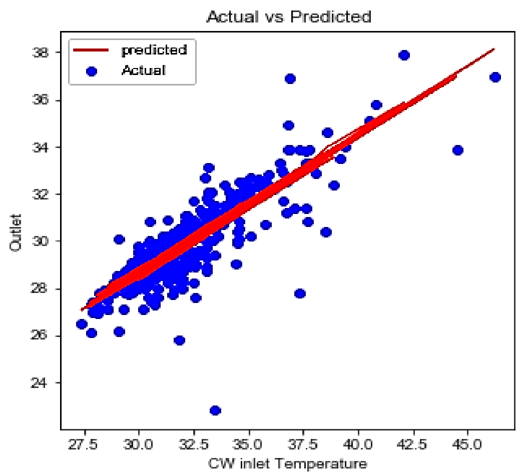

Figure 4a. Actual V/s Predicted values

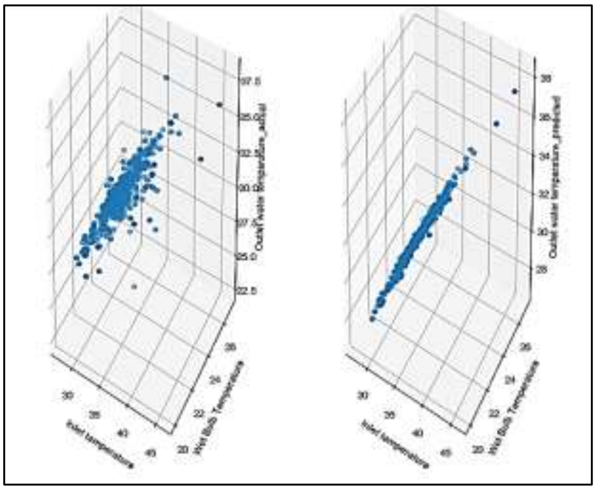

Figure 4b. Actual vs Predicted

6. CONCLUSION

The results of the predictive model using ML algorithm are compared with measured values and it is convincing. In any heat exchange system the energy loss is inevitable and its performance decreases as the system's life time increases. Once the decrease in performance is alarming then the cause of the problem is identified and suitable solution is provided. However, continuous performance monitoring of the CP is possible by comparing the predicted CW outlet temperature and the measured CW outlet temperature. If the deviation is too much then the cause can be identified and suitable control measures or preventive measures for energy loss can be carried out instantly. Hence, the performance of the CP can be at its best, throughout the period of operation in its life span. This allows optimum circulation of cooling water to achieve optimum heat transfer, thereby minimizing the pumping losses & thermal energy losses and ultimately sustainability of the environment is achieved.

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