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Development of a New Nomograph for Dry-Cooling Tower

Kanthaporn Lathulee and Wanchai Asvapoositkul*

Department of Mechanical Engineering, King Mongkut's University of Technology Thonburi,
126 Pracha Uthit Rd., Bang Mod, Thung Khru, Bangkok, Thailand, 10140
* Corresponding Author: wanchai.asv@kmutt.ac.th

Abstract

A method for construction of a nomograph for dry-cooling tower was presented. This new nomograph was developed based on dry-cooling system demand/supply curves for estimating the performance of an existing dry-cooling tower. It represents the relationship among water temperatures at the inlet and the outlet, air dry-bulb temperature, and a ratio of water-to-air loading for a given dry-cooling tower. The chart is presented in a simple format that is easy to use and understand. It was validated and showed good agreement with experimental measurements. It can be used in dry-cooling tower analysis as well as by cooling tower manufacturers and users for the practical application of the towers. Its implementation and application are simple and straightforward since the working conditions are obtained directly from the chart without complex calculation. The purpose of this study is to create a chart that shows the working conditions thoroughly on a wide variety of situations in one diagram.

Keywords: Dry-cooling tower, nomograph construction, cooling tower performance, cooling tower working conditions, cooling tower prediction

1. Introduction

Dry-cooling tower (or air-cooled heat exchanger) is another type of cooling tower that involves no direct contact between the cooling water and the air. The heat flows from the water, through tube walls of coils, to the atmosphere. The operation of a cooling tower is greatly influenced by ambient conditions. Therefore, estimating the performance of an existing cooling tower, at other than design conditions, is often required. It can be evaluated by Logarithmic Mean Temperature Difference (LMTD) method or effectiveness-Number of Transfer Units (ε-NTU) method [1]. Reviews of the methods are given by many authors (e.g. Incropera [2], and Thomas [3]). LMTD method is simple in terms of formulation and requires less computational effort than ε-NTU method when heat exchanger inlet and outlet temperatures are known. However, the application of the LMTD method is not straightforward when either of the temperatures is unknown since the method undergoes iterations to find a solution. In this case, the effectiveness-NTU method is preferred [4]. In fact, both methods are mathematically equivalent to each other [5]. A summary of various computational techniques for the analysis and design of cooling towers, principally dry-cooling towers, was prepared by Kröger [6], and Choi and Glicksman [7]. Asvapoositkul and Kuansathan [1] developed an empirical model based on the effectiveness-NTU approach for a dry-cooling simulation to evaluate the thermal performance of air-cooled heat exchangers (or dry-cooling towers). Its performance was presented in an analogous form to the conventional expression for the wet-cooling tower characteristic curve. The method was applied to evaluate the thermal performance for a hybrid (wet/dry) cooling tower, in which dry- and wet-cooling towers are designed to work in combination by Asvapoositkul and Kuansathan [8].

Cooling towers of an air-cooled performance may be depicted graphically in a format analogous to that of wet type that is commonly used in the Cooling Technology Institute (CTI) cooling tower characteristic curve [9]. Figure 1 shows a dry-cooling tower characteristics curve. This indicates that the performance of a given cooling tower is governed by the ratio of water to air (L/G) and the ambient conditions. Once a cooling tower is installed the problem often arises of determining what cold water temperature one can expect under conditions differing from those for which the tower was designed. For problems involving various climatic conditions, this chart is not generally convenient since it cannot be read directly and instead is rather difficult to determine and hard to understand. It requires a specialist who clearly understands cooling tower characteristics. To allow rapid determination of wet cooling tower operations involving those parameters, Fijita and Tezuka [10] has developed a method and created charts representing a practical compromise between simplicity and absolute accuracy. The charts which are appropriate for different wet-bulb temperatures are usually limited to a single ratio of water-to-air (L/G) and to a particular inlet water temperature. The method has been applied to meet a wide range of service requirements by Asvapoositkul and Treeutok [11]. For practical use, inlet water temperatures are limited within +/- 2 °C, water flow rates are within +/- 5% and inlet wet-bulb temperatures are within +3 °C /-17 °C from the design conditions [10]. Because of the practical limitations of existing charts, it was desired to develop a single chart that would offer cooling tower data over a wide range of working conditions.

This work is part of a wet/dry-cooling tower analysis. The principle goal of the work is the determination of variations in atmospheric temperatures upon a dry-cooling tower performance. The second objective was that cooling range and approach should be determinable directly from the observed dry-bulb temperatures, and L/G. The third objective was the direct solution of problems involving the interchange of heat between air and water.

These objectives required the use of temperature versus L/G as the primary coordinates while other useful variables such as ambient conditions, cooling range and initial temperature difference (ITD) were superimposed to as great an extent as was possible. A group of curves is presented in nomograph form, which permit rapid, accurate determination of the dry-cooling tower for any working conditions.

2. Cooling Tower Characteristic Curve

There are many parameters which have an effect the cooling tower design and operation. Prediction of either wet- or dry-cooling tower performance at various conditions is important in an optimization of hybrid (wet/dry) cooling towers, in which dry- and wet-cooling towers are designed to work in combination. This study will be limited to and discuss only dry-cooling towers.

2.1 Dry-Cooling Demand Curves and Dry-Cooling Tower Characteristics

The solution of simulation problems using dry-cooling performance curves is given by Asvapoositkul and Kuansathan [1]. The plots of dry-cooling tower effectiveness versus L/G are presented in two forms, the dry-cooling system demand curve and the supply curve. These two forms are analogous to wet-cooling tower demand curves and the supply curve, respectively. The procedure to determine cooling system operating point is explained below.

The dry-cooling demand curve on which the required effectiveness (ε), for a given inlet air dry-bulb temperature (T_{db}) and range (R), is plotted versus L/G with the approach (A) as a parameter is shown in Fig. 1. The calculation is based on the effectiveness-NTU approach.

Dry-cooling tower characteristics of a specified cooling tower can be expressed in an analogous form to the conventional expression for the wet-cooling tower by the following relationship:

$$\varepsilon = C\left(\frac{L}{G}\right)^n \tag{1}$$

This is also taken as the dry-cooling tower operating curve and superimposed on each dry-cooling tower demand curve to determine its operating point. In a similar manner to the wet-cooling tower simulation calculation procedure, when either air or water flow rate is changed (e.g. L/G is changed), not only is the approach affected, but the tower effectiveness is also changed. A change in the inlet water temperature does not affect the tower effectiveness, but does change the approach and can change the range.

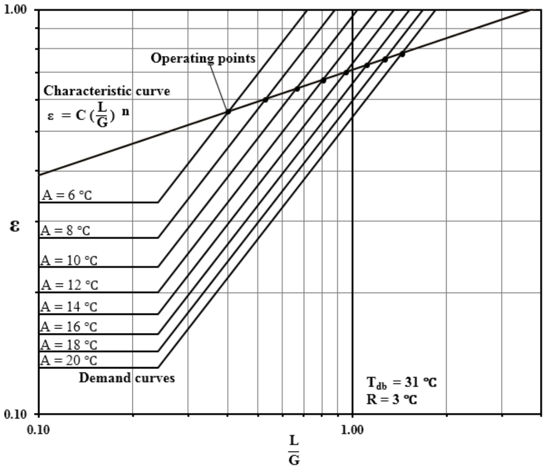

Fig. 1 Dry-cooling tower characteristic curves and demand curves

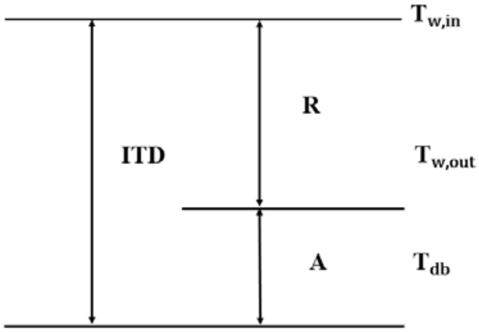

Fig. 2 Temperature relation

2.2 Air/Water Temperatures

Figure 2 shows the relationship of the hot water ($T_{w,in}$), cold water ($T_{w,out}$) and dry-bulb (T_{db}) temperatures of a dry-cooling tower. These temperature measurements are used in the cooling tower characteristic curve. For a given cooling tower, its characteristics are described by Eq. (1) in which ε will remain unchanged as long as the ratio of water-to-air loading (L/G) is constant. Weather conditions, on the other hand, will affect the range and the approach of the cooling tower as follows

$$R = T_{w,in} - T_{w,out} \tag{2}$$

$$A = T_{w,out} - T_{db} \tag{3}$$

$$ITD = T_{w,in} - T_{db} = R + A \tag{4}$$

3. Simulation Calculations

For the dry-cooling tower being considered for the duty, the tower characteristic curve of Eq. (1) may be obtained with known values of C and n from manufacturers or experiments. The dry-cooling demand curves can be calculated and plotted by computer over a large span of temperature and operating conditions.

Details of these calculations are given in Asvapoositkul and Kuansathan [1, 8]. The intersection of these two curves is its operating point for the proper dry-bulb and range. In estimating the performance of the cooling tower, at other than design conditions, there are a number of possible answers which required specified knowledge of cooling tower calculations. This can be done simply by plotting the results in familiar parameters, which permits rapid, accurate determination of the cooling tower for any working conditions. The technique will be illustrated in this paper.

4. How to Create a Nomograph

The thermal performance capacity of a cooling tower at various ambient temperatures would be important information to have for the cooling tower evaluation. Such data can be extracted from the cooling tower demand and characteristic curves. The set of such curves is displayed in Fig. 1. For a given ambient temperature, say, T_{db} = 31 ºC and range = 3 ºC, Fig 1 shows the operating points where the cooling tower supply line intersects at various approach temperature lines of the cooling demand curves. These data of dry-cooling tower were used as basic data in the construction of the chart. Figure 3 shows inlet water temperature on the x-axis and ITD temperature on the y-axis with T_{db} as a parameter. The lines were determined from Eq. (4). Figure 4 shows L/G on the x-axis and ITD temperature on the y-axis with range (R) as a parameter. It should be noted that the values of ITD, R and A are the balance point of the given cooling tower as shown in Fig. 1. Following a similar process for the other balance points, we can develop a chart as shown in Fig. 4. For a fixed water mass flow rate (L), the required air mass flow rate (G) is obtained from the known value of L/G. The relation between L/G and G for a given L is shown in Fig. 5.

In order to create the dry-cooling tower nomograph, data from Figs. 3 – 5 must be read according to its operation. The chart is arranged into three areas (e.g. A1, B1 and B2) as shown in Fig. 6 with alternate lines omitted for clarity. The charts A1, B1 and B2 are Figs. 3, 4 and 5, respectively. These charts signify the relation of three variables which has been specified through straight lines for all the variables of the cooling tower, as shown in Fig. 6.

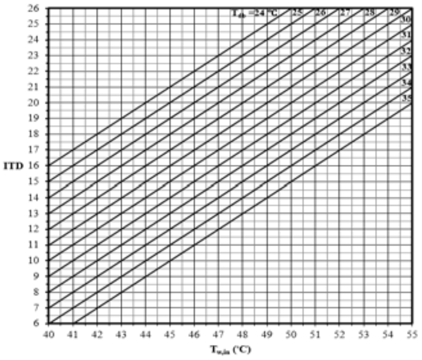

Fig. 3 The relation between $T_{w,in}$ and ITD

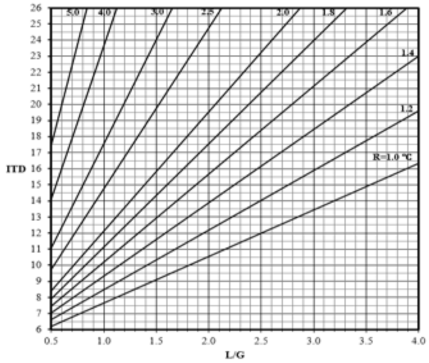

Fig. 4 The relation between L/G and ITD

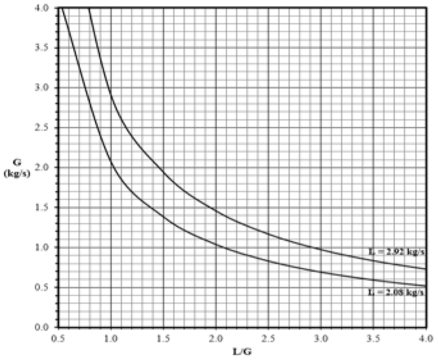

Fig. 5 The relation between L/G and G

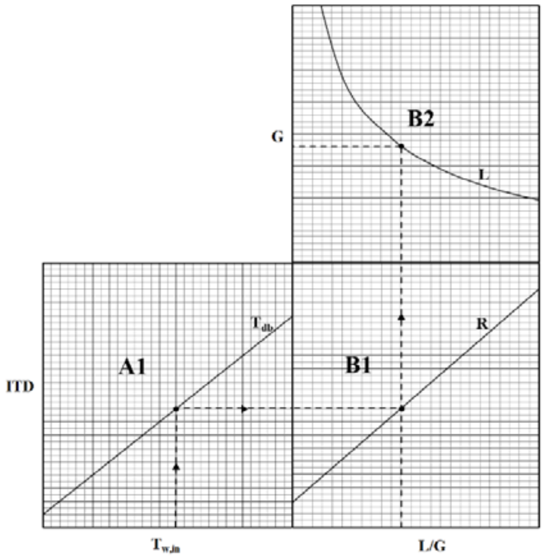

Fig. 6 The example of use method for the nomograph

5. The Dry-Cooling Tower Nomograph

The Nomograph chart for the dry-cooling tower is shown in Fig. 7 where data were extracted from the dry-cooling tower demand and characteristic curves as shown in Fig. 1. The values of the dry-bulb temperature line in Fig. 7 represent different climate conditions throughout Thailand [12]. We can see that

ITD for dry-cooling tower is between 6 – 26 ºC. The temperature scale range is only 1 ºC to 5 ºC. From the figure, at $T_{w,in}$ = 50 ºC, T_{db} = 35 ºC and L/G = 1, the range is found to be 2.56 ºC and ITD = 15 ºC. Therefore, the outlet water temperature $T_{w,out}$ = 47.44 ºC and approach temperature = 12.44 ºC. For water mass flow rate L = 2.92 kg/s, the air mass flow rate is found to be 2.92 kg/s. Once all working conditions are known, the heat transfer rate (Q) can be calculated as in Eq. (5)

$$Q = Lc_{pw}R \tag{5}$$

6. Experimental Validation

To validate the nomograph, it is here applied to a number of comprehensive set of experimental results for dry-cooling towers, which were measured in detail by Asvapoositkul and Kuansathan [1, 8, 13]

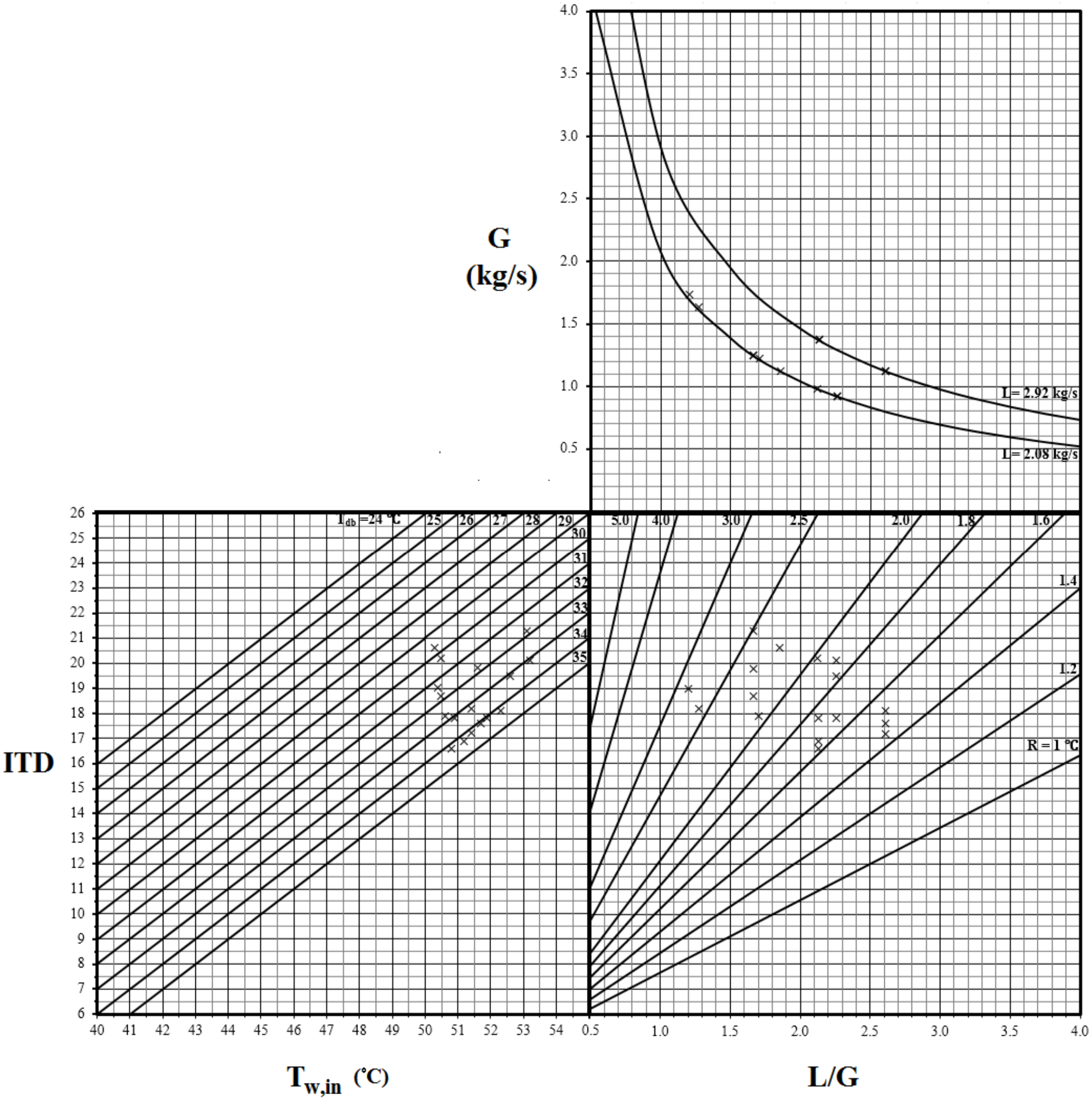

Fig. 7 The nomograph for the dry-cooling tower

The experiments were conducted in a hybrid (wet/dry) cooling tower that performs both dry and wet operations. Only the experimental results from the dry-cooling tower were used in this study. The tower width, length and height were 1000 mm × 1000 mm × 3350 mm, respectively. The dry-cooling tower thermal performance in Eq. (1) was found with C = 0.71 and n = 0.26. The nomograph can be constructed as described and is shown in Fig. 7. From the list of parameters in the chart, the working variables must be specified through straight lines for all the variables. The possible set of working variables may be $T_{w,in}$, T_{db}, L/G and L or ITD, T_{db}, R and L. For a case study, we selected $T_{w,in}$, T_{db}, L/G and L as known working conditions. The values of ITD, R, and G can be determined from the chart. The $T_{w,out}$, A, and heat transfer rate can be determined from Eqs. (2), (3) and (5), respectively. The test measured values are also indicated in Fig. 7 with a cross mark (×).

Comparisons between the corresponding predicted and measured values of R, Tw,out, and G are presented in Figs. 8, 9 and 10, respectively. It is noted that the nomograph reads R with the maximum error of +0.002 °C /-0.05 °C, that of $T_{w,out}$ with the maximum error of +0.06 °C /-0.02 °C, and that of G with the maximum error of +1.84%. There is some uncertainty in the measurements. The uncertainty of R, in the experiment, is ±0.212 °C, that of Tw,out is ±0.193 °C, and that of G is 2%. Details of the uncertainty analysis of the dry-cooling tower may be seen in [1]. Thus, all predicted parameters are within these limits. Because of this validation, the nomograph can be used to predict dry-cooling tower performance under changing operation conditions.

7. Evaluation of Dry-Cooling Tower Performance

The nomograph can be applied to determine a tower's characteristics at any particular working conditions. Specific working parameters can have a significant impact on the performance of the tower. The deviation in performance was to focus on variations, such as $T_{w,in}$, T_{db}, and L/G. To implement this, specific working conditions were obtained from the chart. The ITD is determined from the point where it is intersected by the dry-bulb temperature line (T_{db}) to the given $T_{w,in}$. The horizontal line of ITD is then drawn in the chart, and extended to intersect the vertical line of L/G. A read value of R is determined from the point by interpolating vertically between the two adjacent R lines.

From Fig. 7, we can see that the effect of an increase or a decrease in T_{db} on ITD can be compensated by an increase or a decrease in $T_{w,in}$ by the same value. For example, the chart is given R = 3 °C at T_{db} = 31 °C for $T_{w,in}$ = 50 °C and L/G = 1.12. When T_{db} increases with 1 °C (to 32 °C), the range will drop by 0.16 °C. In order to keep the R = 3 °C with the same L/G, the $T_{w,in}$ should be increased with 1 °C (to 51 °C). It should be noted that in this case the outlet water temperature also increased with the same value (1 °C, from 47 to 48 °C). Another way, to get the same R and outlet water temperature of 47 °C, is to decrease L/G to 1.03. When T_{db} decreases with 1 °C (to 30 °C) the range will increase by 0.16 °C or the outlet water temperature will drop by 0.16 °C (from 47 to 46.84 °C). In order to get the same R and outlet water temperature of 47 °C, the L/G should be increased to 1.19. This gives a clear demonstration that the chart is convenient to use.

The effect of L/G on R can also be determined from the chart. As the L/G increases, the range R decreases. With L/G higher than 1.5, the decrease in R may be slight. From the standpoint of economy, the higher L/G means less air and/or a smaller tower. The power required by a cooling fan in general increases with an increase in G. Therefore, L/G is the most important factor in designing a cooling tower and related to the construction and operating cost of a cooling tower. Figure 11 shows the effect of L/G for $T_{w,in}$ = 50 °C with a different inlet air dry-bulb temperature on R. These data are extracted from Fig. 7. Heat rejection through the cooling tower is proportional to the mass flow rates L and R. Thus heat transfer capacity increases with an increase in R and decreases with an increase in dry-bulb temperature.

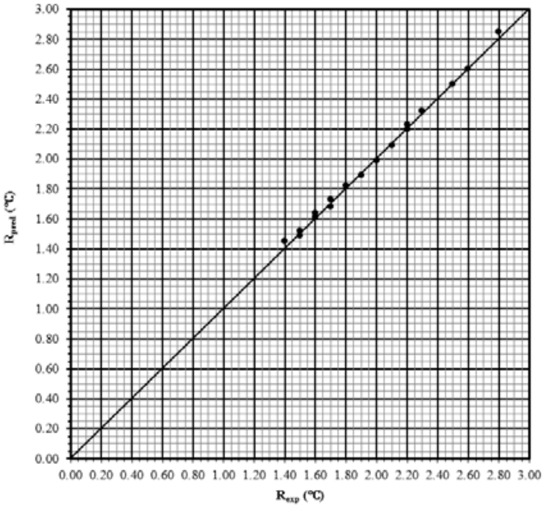

Fig. 8 Comparison of cooling range between the experiment data and the nomograph predicted values of the dry-cooling tower

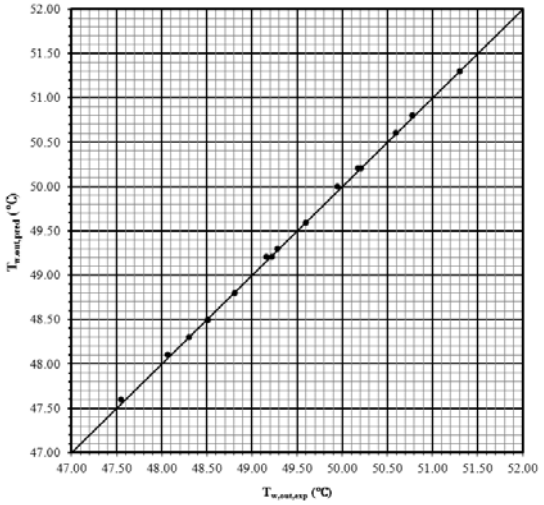

Fig. 9 Comparison of exit water temperature between the experiment data and the nomograph predicted values of the dry-cooling tower

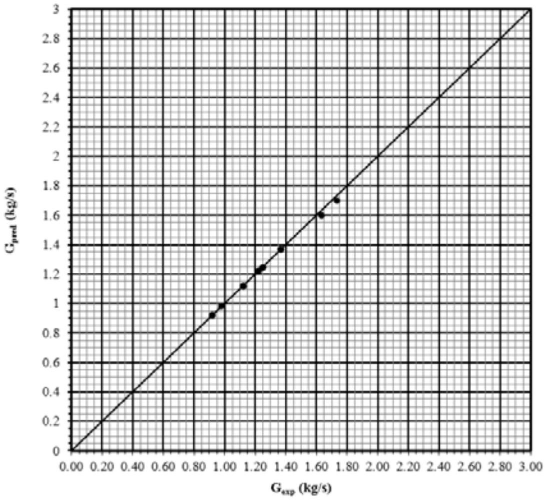

Fig. 10 Comparison of air mass flow rate between the experiment data and the nomograph predicted values

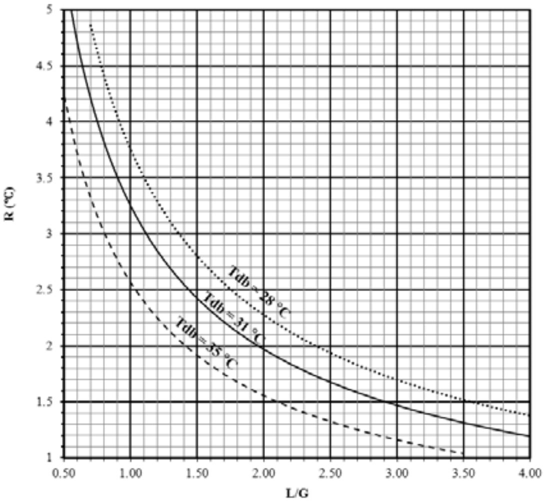

Fig. 11 Effects of change in L/G and R when $T_{w,in}$ = 50 ºC

8. Conclusions

A new nomograph for dry-cooling tower was developed based on cooling tower demand and characteristic curves. The chart was validated and could be used for predicting dry-cooling tower characteristics. The operation of the dry-cooling tower was adversely affected by an increase in dry-bulb temperature and inlet water temperature. A major objective of a cooling tower is to keep the outlet water temperature sufficiently low for normal productive operations. The outlet water temperature is determined by R which can be successfully handled by L/G. One way of evaluating the proper value of L/G is by using a dry-cooling tower's nomograph. Although the chart is an indirect form of effectiveness-NTU approach, our main development is to create a chart that shows the working conditions thoroughly on a wide variety of situations in one diagram. Subsequently, the results can be used in exergy analysis on the performance of the cooling system easily. Currently work is underway to this goal.

9. Acknowledgement

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