Parametric Study on the Performance of a Counterflow Type Cooling Tower

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ABSTRACT: A design procedure for cooling towers was set up using the Merkel theory. In the past, the design data could be different depending on the characteristic curve that the engineer adopted. Therefore, consistent and reasonable criteria are required, which are based on the exact information of the cooling tower performance. In this study, analysis program for both the design and off-design for a counterflow-type cooling tower was developed and verified by comparing with experimental data. The off-design performance with various operating conditions was analyzed, as well.

Nomenclature

A : frontal area [m^2]
a : area of water interface per unit volume [m^2/m^3]
c_p : specific heat [kJ/kg·℃]
G : mass flow rate of air [kg/s]
h : enthalpy [kJ/kg]
K : overall mass transfer coefficient [kg/s·m^2]
L : mass flow rate of water [kg/s]
m : mass [kg]
q : heat transfer rate [kJ/s]
T : dry bulb temperature [℃]
t : water temperature [℃]
U : overall heat transfer coefficient [kJ/s·m^2·℃]
V : cooling tower volume [m^3]
W : absolute humidity

Superscripts

$'$: at bulk water temperature
$''$: at interface

Subscripts

a : air
G : between interface and air
L : latent heat
S : sensible heat
w : water
1, 2 : inlet and outlet of cooling tower

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1. Introduction

The heat released from HVAC systems and/or industrial process should be rejected to the atmosphere. For example, cooling media such as water are often used to remove heat from condenser or heat exchanger of the energy system.

In the past, cooling water was supplied from tap water or river, and rejected to the sewerage or the river again. Recently, conventional methods cannot satisfy either economic criteria or environmental regulation because the cost of supply and disemboguement of cooling water is increasing tremendously, and the thermal pollution is regulated severely as well.

Air-cooled heat exchanger can be an alternative, but it requires high initial investment cost and high fan power consumption. Cooling tower enhances its application due to the low power consumption and, especially, low water consumption down to 5% of the direct water-cooling system. Heat rejection is accomplished within the tower by heat and mass transfer between hot water droplets and ambient air.

The operation theory of cooling tower was suggested by Walker in 1923, however, the generally accepted concept of cooling tower performance was developed by Merkel in 1925. A simplified Merkel theory has been used for the analysis of cooling tower performance and Lichtenstein introduced a graphical method. Baker and Shryock tried to minimize the error due to the assumptions of Merkel theory.(1)

ASHRAE developed the cooling tower performance curves based on the Merkel theory in 1975, and several researchers have paid attention to the cooling tower performance by numerical analysis or experiments on the fluid flow phenomena and combined heat and mass transfer in cooling tower.(2-6)

Counterflow type cooling tower dominates the Korean market, and is widely used in the petrochemical industry, iron industry, and HVAC plant. However, the design of a cooling tower depends on the existing foreign data and/or the procedure is lack of consistency. Design and off-design performance analysis has not been completed yet, which is one of the key parameters in the cooling tower performance evaluation.

In this study, existing theories on cooling tower design were reviewed and summarized. Previous design methodology of the company is thought to be lack of the theoretical background in choosing the characteristic curve of the tower and, thus, the design point. In this sense, a program which computerizes the design procedure has been completed to keep consistency in the design.

The off-design performance analysis program has been developed to analyze easily the performance characteristics of a counterflow type cooling tower with various operating conditions. Through the experiment on various operating conditions, the off-design program has been verified.

2. Basic theory

2.1 Merkel equation

Heat transfer rate in the cooling tower is represented by the difference between the enthalpy of moist air at bulk water temperature and the enthalpy of moist air.

Merkel equation describes the heat transfer characteristics of a filler at the design condition. It needs several assumptions: (1) effect of evaporation does not exist, (2) thermal and mass diffusion coefficients of air/water system are the same. The analysis combines the sensible and latent heat transfer between air and water droplets in the tower.

Total heat transfer rate per unit volume of a filler (dV) from the interface to the air is the sum of sensible heat (dq_S) and latent heat (dq_L).

$$dq_S = U_G\, a\, dV(T'' - T) \tag{1}$$

$$dq_L = h_{fg}\, dm = h_{fg} K' a\, dV(W'' - W) \tag{2}$$

Energy conservation principle with the assumption that the interface temperature is same as the air temperature derives the following equation.

$$Lc_{pw}\, dt = Ka\, dV(h' - h) \tag{3}$$

Integration of Eq. (3) results in Eq. (4).

$$\frac{KaV}{L} = \int_{t_2}^{t_1} \frac{c_{pw}\, dt}{(h' - h)} \tag{4}$$

2.2 Counterflow type cooling tower

Left-hand side of Eq. (4) is a dimensionless parameter called NTU (number of transfer unit) which is the characteristic value of the filler and represents the heat transfer capacity, that is, the required heat transfer area. It is a function of air and water temperature, independent of the size of the tower or the shape of the filler. Counterflow cooling diagram shown in Fig. 1 is convenient to integrate Eq. (4). The curves indicate the drop in water temperature (Point A to Point B). The temperature difference between the water entering and leaving the cooling tower (A-B) is the range. The difference between the leaving water temperature and the entering air wet-bulb temperature (B-C) is the approach of the cooling tower.

The equations are not self-sufficient, therefore, Tchebycheff integration is applied to get the approximate value.

$$\int_{t_2}^{t_1} \frac{c_{pw}\,dt}{h'-h} \approx c_{pw}(t_1-t_2)\times\frac{1}{4}\sum_{i=0}^{4}\left(\frac{1}{h_i'-h_i}\right) \quad (5)$$

where h_i' is the air enthalpy at the interface with bulk water temperature, and h_i means the air enthalpy with the air stream temperature.

The enthalpy of point C and D in Fig. 1 can be represented as Eq. (6) based on the energy balance.

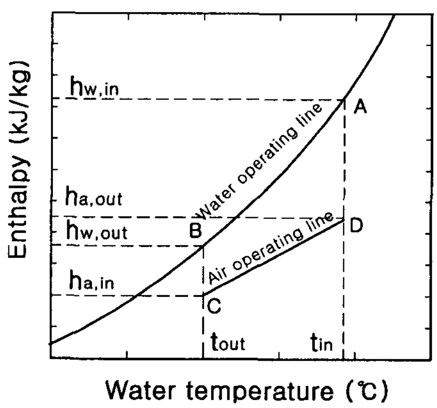

Fig. 1 Enthalpy-temperature diagram of air and water.

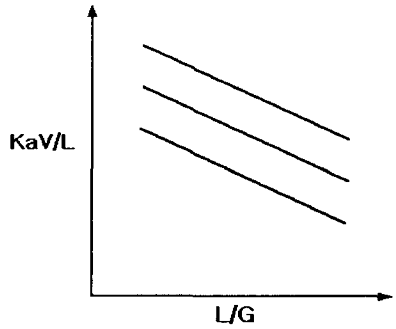

Fig. 2 Characteristic curve of a cooling tower.

$$h_2 = h_1 + c_{pw}\frac{L}{G}(t_2-t_1) \quad (6)$$

The slope of the air operating line CD equals L/G, the ratio of the water flow rate to the air flow rate.

Packing characteristic curve represents the heat transfer characteristics of the filler, which is shown in Fig. 2. It is a typical correlation of the performance characteristic of a cooling tower showing the variation of available KaV/L with L/G for a constant air velocity on logarithmic coordinates. If the air flow rate decreases with constant water flow, the heat transfer at the filler will diminish as in Fig. 2.

The cooling tower characteristic curve in Fig. 2 corresponds to the following relation from the experimental results.[7]

$$\frac{KaV}{L} = c\left(\frac{L}{A}\right)^m\left(\frac{G}{A}\right)^n \quad (7)$$

where A is the frontal area, and c, m, and n are experimental constants.

3. Design and off-design analysis

3.1 Design analysis

The design procedure of a cooling tower is as follows;

(1) Input design conditions: water inlet & outlet temperature, water flow rate, air inlet temperature.

(2) Assume the ratio L/G, and evaluate the exit air enthalpy using Eq. (6).

(3) Calculate required NTU from Eq. (4).

(4) Calculate characteristic NTU from Eq. (7).

(5) Iterate until the required NTU equals the characteristic NTU.

(6) Set design NTU.

3.2 Off-design analysis

Off-design performance analysis is required to check whether the equipment operate normally. Because the equipment does not always operate on the design condition in the field, the off-design performance analysis is inevitable to the efficient and energy saving operation.

The procedure of the off-design analysis of a cooling tower is as follows;

(1) Evaluate the ratio L/G at the off-design condition.

(2) Evaluate the exit air enthalpy by assuming inlet water temperature.

(3) Calculate outlet water temperature and approach.

(4) Calculate required NTU using Eq. (4).

(5) Evaluate characteristic NTU with characteristic curve of design stage.

(6) Iterate until the required NTU equals the characteristic NTU.

(7) Set corresponding L/G and characteristic NTU.

Table 1 Design data (base case)

Item	Unit	
Circulation water flow rate	m^3/hr	3.9
Hot (inlet) water temp.	℃	37
Cold (outlet) water temp.	℃	32
Inlet air wet bulb temp.	℃	27
Relative humidity	%	60
Nominal capacity	kcal/hr	19,500

3.3 Verification

Field test was run to verify the off-design performance analysis procedure. The temperature of the water reservoir is raised to a setting value. The heated water is drawn into the tower and cooled by air. Flow rate and inlet & outlet temperature of water, and temperature and humidity of inlet air are measured.

The design data used in the test are summarized in Table 1. The capacity of the tower is 19,500 kcal/hr, which is designed by the DHTech corporation (Model No. DCT-5R).

Both measured and calculated outlet water temperature are represented in Table 2, and it shows that the off-design analysis predicts the performance fairly well. By comparing the measured and predicted values, the design and off-design analysis procedure is verified.

Existing design data and the results of this study are compared in Table 3. Existing design data, hand calculated data using CTI Bluebook, and data from this analysis program are shown. CTI Bluebook is the handbook for the design of cooling tower, say, NTU by CTI (Cooling

Table 2 Off-design performance data (experiment and prediction)

	Design condition	Case I	Case II	Case III	Case IV
Water flow rate (m^3/s)	0.9×10^{-3}	3×10^{-3}	2.98×10^{-3}	3.02×10^{-3}	1.1×10^{-3}
Inlet air dry bulb temp. (℃)	32.8	27.2	29.3	25.4	26.7
Relative humidity (%)	70	64	40.3	34.7	50
Inlet air wet bulb temp. (℃)	28.1	22	19.6	15.6	19.3
Hot water temp. (℃)	40	38	39	30	34.5
Cold water temp. (Exp., ℃)	34	34.5	35.4	28.5	30.4
Cold water temp. (Cal., ℃)	34	36.1	35.8	27.8	30.9

Table 3 Comparison of the design data (current calculation, CTI bluebook, company's own design)

Item	Unit	Case I	Case II	Case III	Case IV	Case V
Circulation water flow rate	m^3/hr	680	600	772.5	800	220
Hot water temp.	℃	53	45	43	37	43
Cold water temp.	℃	35	35	32	32	32
Wet bulb temp.	℃	27	28	28	27	28
Cell quantity	ea	1	5	3	2	2
$(L/G)_{CAL}/(L/G)_{CTI}$		0.975	1.033	0.932	0.993	.932
$(NTU)_{CAL}/(NTU)_{CTI}$		0.969	0.944	1.006	0.962	1.006
$(L/G)_{CAL}/(L/G)$company		1.625	1.188	1.186	1.15	1.717
$(NTU)_{CAL}/(NTU)$company		1.409	1.245	1.275	1.268	1.53

Tower Institute) of U. S. A.

Results of this study are well consistent with the data of CTI Bluebook, and also predict the existing data with moderate error. The existing data are relatively subjective because the selection of the characteristic curve is dominated by the design engineer. Case I and V of the existing data are far away from the CTI Bluebook and this study. This seems to be due to the engineer's choice on the factors irrelevant to the thermal performance of a cooling tower such as the size of the tower and fan consumption.

The selection of the characteristic curve in Fig. 2 changes everything such as thermal performance, cost, and power consumption. This is the reason why the design procedure should be computerized to prevent the engineer's subjective criteria.

3.4 Off-design performance of a cooling tower

It is very difficult to maintain the actual operating conditions of a cooling tower at the design condition. Also the off-design performance on the various operating conditions should be provided to the customer. The importance of an off-design performance analysis cannot be overemphasized.

Through the validation procedure of the current study, the performance characteristic of a cooling tower with various operating conditions is reviewed in the following sections. The design data in Table 1 are used as the reference condition.

3.4.1 Variation of wet-bulb temperature

The influence of a wet-bulb temperature on the performance of a cooling tower is studied under constant water flow, air flow, and water inlet temperature. Water outlet temperature as a tower performance is represented in Fig. 3. Also air flow rate is changed by ±20% from the design point.

Even with the wide range of wet bulb temperature change more than 15℃, water temperature varies within a relatively small range, 5~6℃. Considering that the heat capacity of water is much higher than that of air in cool-

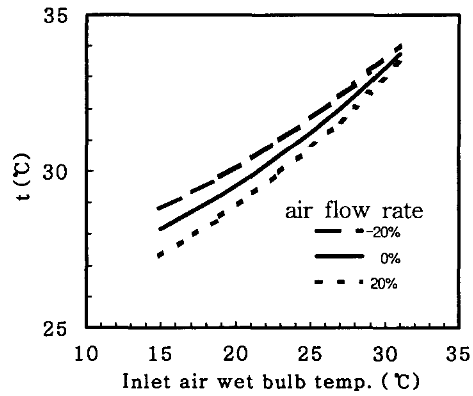

Fig. 3 Effect of wet bulb temperature on the exit water temperature.

ing tower operation, it can be predicted that the effect of a wet-bulb temperature on the water temperature is not so critical.

Water outlet temperature decreases and the effect of the wet-bulb temperature becomes more sensitive with increasing air flow. When the wet-bulb temperature is too high, little effect on the performance is seen even with 20% increase of air flow.

These trend will be different for each cooling tower and each operating condition, respectively, so it should be suggested to the customer that the off-design analysis be done to predict the extent of change. For example, it could be suggested that increasing air flow be not helpful on the performance if the wet-bulb temperature of inlet air is above a threshold value.

3.4.2 Variation of range of water temperature

Cooling performance with range of water is shown in Fig. 4. Larger range means higher water outlet temperature. This means that increasing cooling load can be met by the larger range for a given heat exchanger. If the range is changed, the user has to set the water inlet temperature to a different value for the required performance. Water outlet temperature decreases with increasing air flow.

3.4.3 Variation of water flow rate

The effect of a water flow on the performance is represented in Fig. 5. Even with ±20% variation of water flow, the outlet water temperature changes within 1℃. Cooling capacity becomes higher with increasing air flow, but it does not practically change when the water flow rate increases about 20%.

Sensitivity of such parameters on the cooling tower performance will be different for each cooling tower, therefore off-design analysis is inevitable and the feedback of actual performance data from the field is also necessary for the setup of a characteristic curve of a cooling tower.

4. Summary

(1) Cooling tower design procedure is computerized and the results are compared with existing design data. The procedure is necessary to prevent the subjective judgement of a design engineer and the appropriate selection of a characteristic curve is also important.

(2) Off-design analysis is setup and verified. This can be used for the evaluation of a cooling tower performance on every different operating conditions.

(3) The effects of some parameters such as wet-bulb temperature, water flow, range of wa-

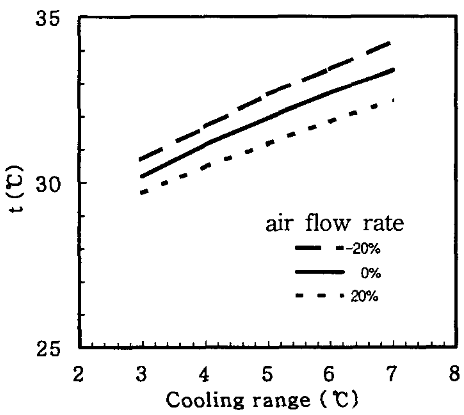

Fig. 4 Effect of cooling range on the exit water temperature.

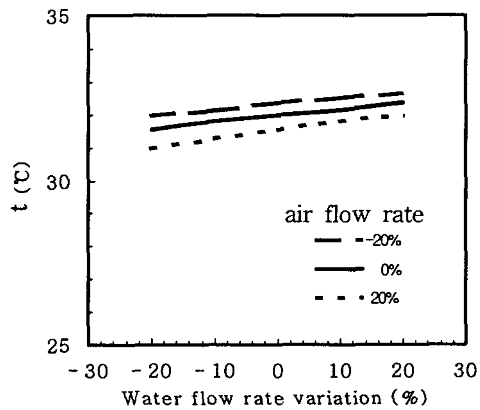

Fig. 5 Effect of water circulation rate on the exit water temperature.

ter temperature are studied by off-design analysis. The changes of inlet air wet-bulb temperature and range of water temperature affect the cooling tower performance considerably but the effect of water flow on the performance is not so high. Off-design performance should be carefully reviewed at the design stage because it will be different for every equipment and operating condition.

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