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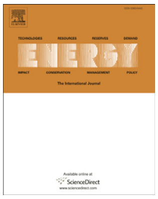

Innovative correlation for calculating thermal performance of counterflow wet-cooling tower

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an innovative correlation associating the effectiveness (ε) of the cooling tower with its number of transfer unit (NTU) and vice versa. The new correlations can be used simply to predict the performance of wet counterflow cooling tower. Those correlations are based on solving heat and mass-transfer equation "enthalpy potential method" coupling with energy equations simultaneously. The validity of the correlations was checked by experimental data reported in the available literature. The results obtained from those new correlations showed a very good agreement with deviation less than 10% with those obtained from the literature for a temperature difference between the inlet water temperature and inlet air wet-bulb temperature $(\mathrm{Tw}_i - \mathrm{Wbt}_i)$ equal to or less than 10 K. The main advantages of those correlations are: (1) its simplicity to be implemented through simple calculations of input parameters; (2) it provides helpful guidelines for optimization of cooling tower performance during its operation coupling with the thermal system at which the tower is connected.

1. Introduction

Cooling towers are widely used in thermal systems such as refrigeration and air-conditioning systems, power generation system, and chemical/petrochemical plants to reject heat to the atmosphere. Heat rejection of cooling towers is accomplished through evaporation of some of the water into an air stream. The principle of cooling tower operation is based on heat and mass-transfer processes between ambient air and process water. As known, the cooling tower connects the heat source (refrigeration system, power plant, etc.) with the heat sink (ambient environment). The variations occurred in the environmental conditions which are imposed on the cooling tower would be translated to alterations in the thermal performance of the heat sources systems. Therefore, the need to interrelate the thermal performance of the cooling tower to the imposed operating conditions is crucial for either the cooling tower designer or the system operator. The simpler accurate relationship describes the cooling tower's performance, the more attractive tool to be used in the practical site or in the theoretical analysis particularly for carrying-out an optimization exercise for the cooling tower performance. There are several researches in the available literature were conducted to describe the thermal performance of the cooling tower. Merkel [1] was the first one to develop a model to predict the performance of the cooling tower in counterflow. To simplify the model, Merkel combined the partial differential equations, describing the rate of change in properties of the water and air, into one simplified equation. The equation is commonly known as the Merkel equation and it describes simultaneous heat and mass transfer from a surface in terms of a coefficient, area and enthalpy driving potential. The Merkel equation is one-dimensional and can be solved with by hand. Zivi and Brand [2] developed and solved the Merkel model for a crossflow cooling tower. This crossflow model is two-dimensional and is solved numerically using a computer. The more common model used for crossflow towers is an effectiveness-NTU method. Jaber and Webb [3] adopted the e-NTU method, commonly used for heat exchangers, to be applied to cross- and counterflow wet-cooling towers. The method can be solved one dimensionally for both cross- and-counterflows with equal effort. Braun et al. [4] developed "effectiveness models" for cooling towers, which utilized the assumption of a linearized air saturation enthalpy and the modified definition of number of transfer units. The models were useful for both design and system simulation. However, Braun's model needs iterative computation to obtain the output results and is not suitable for online optimization. Bernier [5] reviewed the heat and mass-transfer process in cooling towers

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List of symbols

$A_{c.s}$	area cross-section of cooling tower, m^2
a_v	area per unit volume, m^2/m^3
b	slope of saturation air enthalpy line, kJ/kg K
c_w	water specific heat, kJ/kg K
Cro	specific heat ratio, b/cw
dbt	air dry-bulb temperature, °C
h_a	specific air enthalpy, kJ/kg
h_s	specific saturated air enthalpy, kJ/kg
K	convective mass-transfer coefficient, $kg/(m^2\ S)$
G	air mass flow rate, kg/s
L	water mass flow rate, kg/s
NTU	number of transfer unit, Ka_vV/L
Q	heat transfer, W
T_w	water temperature, °C
V	volume, m^3
wbt	air wet-bulb temperature, °C
Greek symbols	
ε	effectiveness
Subscripts	
a	ambient
i	inlet
m	mean
out	outside
s	saturated
w	water

at water droplet level and analyzed an idealized spray-type tower in one-dimension, which is useful for cooling tower designers, but not much information is provided to plant operators. Poppe and Rögener [6] developed a model that does not make the same simplifying assumptions as Merkel and can be used for prediction of air outlet conditions. The model consists of four partial differential equations which are functions of each other and solved simultaneously. Soylemez [7] presented a quick method for estimating the size and performance of forced draft countercurrent cooling towers and experimental results were used to validate the prediction formulation. Unfortunately, this model also need iterative computation and not suitable for direct optimization. Lu and Cai [8] used the formula of e-NTU of dry counter heat exchanger and empirical correlation NTU to the ratio of water flow rate to the flowing air flow rate. They used Taylor's series expansion to solve the problem of nonlinearity of the e-NTU correlation and to be formulated in a polynomial function using least square-fitting method to determine the coefficients of the model. Research conducted by Wanchai and Supawat [9] developed new calculation method to predict the cooling tower performance. The new method is based on iterative computational calculation between the calculated NTU from Merkel model and that was calculated using the empirical correlation as functions in demanding load. Picardo and Variyar [10] combined Merkel equation and standard empirical mass-transfer correlation to calculate the packed height of the counterflow cooling tower. The results of this study show that the tower height is to be independent of the water flow rate and tower diameter, and dependent only on the excess air flow. Most recent study conducted by Hernández-Calderón et al. [11] adopted an orthogonal technique to solve the poppe method equations for heat and mass transfer in counter flowing wet-cooling towers. They introduced the air humidity ratio as a finite power series at water temperature. The air enthalpy is expressed as a function of the water temperature and unknown coefficients of the expansion from the humidity ratio. They applied this methodology to eight examples, and their results were compared to the results obtained when the governing equations are integrated with the Dormand–Prince method.

It can be summarized from this survey that the determination of the cooling tower performance was done by complicated numerical or analytical computation or using e-NTU correlation for dry counter heat exchanger. In this work, new simplified correlations for e-NTU of counterflow cooling tower, based on Merkel theory, are presented. Those correlations are handy to be used by the process engineer or cooling tower designer.

2. Cooling tower model

A schematic diagram of a counterflow cooling tower considers an increment of a cooling process as in control volume dv of Fig. 1 where water mass flow rate L and air mass flow rate G flow uniformly of plane area. All horizontal sections through the tower are assumed to be the same, in which both streams move in an opposite and vertical direction (water moves downward while air moves upward).

The major assumptions that are used to derive the basic modeling equations may be summarized as [12,13]:

1 Heat and mass-transfer in a direction normal to the flows only and in one-dimension.
2 Constant water and air specific heats.
3 Constant heat and mass-transfer coefficients throughout the tower.
4 Constant water and air flow rates along the cooling tower.
5 Uniform cross-sectional area of the tower.
6 Constant value of Lewis number of unity throughout the tower;
7 Constant physical properties of the solid material.
8 Linear dependency of saturation enthalpy of air on temperature.

The amount of heat transferred in the incremental volume of dv (Fig. 1) can be written for water and air, respectively, as

$$\delta Q = G(h_{aj} + dh_a - h_{aj}) \tag{1}$$

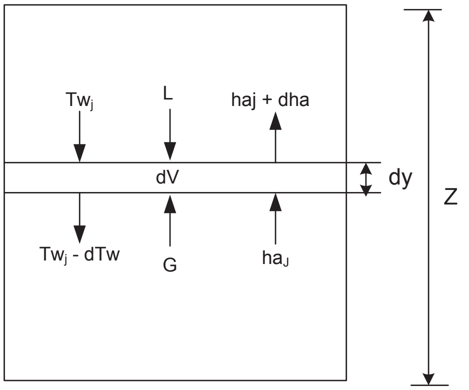

Fig. 1. Control volume for counterflow cooling tower.