THEORETICAL AND EXPERIMENTAL STUDY OF A CROSS-FLOW INDUCED-DRAFT COOLING TOWER

by

Mohamed Mahmoud ABO ELAZM and Ahmed Farouk ELSAFTY

Original scientific paper
UDC: 66.045.53:66.011
DOI: 10.2298/TSCI0904091A

The main objective of this study is to find a proper solution for the cross-flow water cooling tower problem, also to find an empirical correlation's controlling heat and mass transfer coefficients as functions of inlet parameters to the tower. This is achieved by constructing an experimental rig and a computer program. The computer simulation solves the problem numerically. The apparatus used in this study comprises a cross-flow cooling tower.

From the results obtained, the "characteristic curve" of cross-flow cooling towers was constructed. This curve is very helpful for designers in order to find the actual value of the number of transfer units, if the values of inlet water temperature or inlet air wet bulb temperature are changed. Also an empirical correlation was conducted to obtain the required number of transfer units of the tower in hot water operation. Another correlation was found to obtain the effectiveness in the wet bulb operation.

Key words: *cooling tower, number of transfer units, effectiveness, cross-flow*

Introduction

Cooling towers are heat exchangers that are used to dissipate large heat loads to the atmosphere. All cooling towers operate on the principle of removing heat from water by evaporating a small portion of the water that is re-circulated through the unit. The heat that is removed is called the latent heat of vaporization. Each one kilogram of water that is evaporated removes approximately 2270 kJ in the form of latent heat [1].

Cooling towers are used in a variety of settings, including process cooling, power generation cycles, and air conditioning cycles. All cooling towers that are used to remove heat from an industrial process or chemical reaction are referred to as industrial process cooling towers (IPTC). Cooling towers used for heating, ventilation, and air conditioning are referred to as comfort cooling towers (CCT) [2].

There are two types of cooling towers – natural draft and mechanical draft. This study deals with the cross-flow mechanical draft cooling tower type. Cross-flow cooling towers have a fill configuration through which air flows horizontally across the downward flow of the water.

There are some important factors affecting cooling tower selection and performance. Methods for calculating standard design parameters such as wet-bulb temperature, dry-bulb temperature and/or relative humidity, heat load flow, range and approach remain unchanged. But although cooling tower technology has stayed relatively stable, certain trends are allowing owners and operators as well as manufacturers to view some aspects of towers construction and operation in a new light. These areas of focus fall into three primary categories: environmental, materials of construction, and controls [1].

The main objective of this study is to find a proper empirical correlation controlling heat and mass transfer coefficients as function of different operation and design parameters for cross-flow induced-draft cooling towers.

Experimental and theoretical investigations

To achieve the objective of this study, experiments were conducted using an experimental rig, especially designed and constructed for this purpose. A computer program was written to simulate the cross-flow cooling tower heat transfer problem using commercial programming language software. The computer simulation solves the problem numerically while the experimental rig used for determination of the input parameters. [3, 4]

Theoretical modeling and numerical approach

In a cross-flow tower, water enters at the top of the tower and air enters from its side. Setting water heat loss equal to air heat gain where the cross section is divided into unit volumes in which (dV) becomes (dxdy) and considering the transfer from the interface to the air-stream will lead to [2]:

$$\dot{m}_{\mathrm{w}} C_{\mathrm{w}} (t_{\mathrm{w\,in}} \quad t_{\mathrm{w\,out}})\mathrm{d}x \quad (h_{\mathrm{a\,in}} \quad h_{\mathrm{a\,ut}})\dot{m}_{\mathrm{a}}\mathrm{d}y \quad k_{\mathrm{m}} a (h_{\mathrm{i}} \quad h_{\mathrm{a}})\mathrm{d}x\mathrm{d}y \tag{1}$$

From eq. (1) it could be found that:

$$\dot{m}_{\mathrm{w}} C_{\mathrm{w}} (t_{\mathrm{w\,in}} \quad t_{\mathrm{w\,out}})\,\mathrm{d}x \quad k_{\mathrm{m}} a (h_{\mathrm{i}} \quad h_{\mathrm{a}})\mathrm{d}x\mathrm{d}y \tag{2}$$

Then:

$$\frac{k_{\mathrm{m}} a \mathrm{d}x\mathrm{d}y}{\dot{m}_{\mathrm{w}}\mathrm{d}x} \quad \frac{C_{\mathrm{w}} (t_{\mathrm{w\,in}} \quad t_{\mathrm{w\,out}})}{h_{\mathrm{i}} \quad h_{\mathrm{a}}}$$

thus

$$\frac{k_{\mathrm{m}} a \mathrm{d}y}{\dot{m}_{\mathrm{w}}} \quad \frac{C_{\mathrm{w}} (t_{\mathrm{w\,in}} \quad t_{\mathrm{w\,out}})}{h_{\mathrm{i}} \quad h_{\mathrm{a}}} \quad \Psi \tag{3}$$

The first term in eq. (3) represents the number of transfer units (*NTU*) in the vertical direction (Y direction), and could be considered as an increment to find the water temperature distribution in the vertical direction of the cooling tower volume. Considering that the cooling tower volume is divided into a number of elements where: *mx* is the number of elements in the horizontal direction, *my* – the number of elements in the vertical direction, I – the raw number, and J – the column number.

So eq. (3) could be written in the numerical form:

$$\Psi \quad \frac{C_{\mathrm{w}} [t_{\mathrm{w(I\,J\;\;1)}} \quad t_{\mathrm{w(I\,J)}}]}{h_{\mathrm{i(I\,J)}} \quad h_{\mathrm{a(I\,J)}}} \tag{4}$$

In order to obtain the value of $t_{\mathrm{w(I\,J)}}$ from the above equation there are three unknowns that must be found before applying this equation. Those unknowns are the values of the increment (Ψ), the interface enthalpy ($h_{\mathrm{i(I\,J)}}$), and the air enthalpy (h_{a}). The value of the increment can be found from:

$$\Psi \quad \frac{NTU}{my \quad 1} \tag{5}$$

After the value of y is calculated, then it is necessary to obtain the value of the inlet air enthalpy to the element, as follows:

$$\dot{m}_\mathrm{w} C_\mathrm{w} (t_\mathrm{w\,in} \quad t_\mathrm{w\,out})\mathrm{d}x \quad \dot{m}_\mathrm{a} (h_\mathrm{a\,out} \quad h_\mathrm{a\,in})\mathrm{d}y \tag{6}$$

Rearranging eq. (6):

$$\frac{\dot{m}_\mathrm{w}\mathrm{d}x}{\dot{m}_\mathrm{a}\mathrm{d}y} \quad \frac{\Delta h_\mathrm{a}}{C_\mathrm{w}\Delta t_\mathrm{w}} \quad \lambda \tag{7}$$

Equation (7) could be considered as an increment:

$$\lambda \quad \frac{\dot{m}_\mathrm{w}}{\dot{m}_\mathrm{a}} \frac{mx}{my} \tag{8}$$

If the same number of elements is used in both X and Y directions, then:

$$\lambda \quad \frac{\dot{m}_\mathrm{w}}{\dot{m}_\mathrm{a}} \tag{9}$$

λ representing the change in air enthalpy across the element and is found by rewriting eq. (7) in numerical form:

$$\lambda \quad \frac{h_{\mathrm{a(I\ \ 1,\ J)}} \quad h_{\mathrm{a(I\ J)}}}{C_\mathrm{w} (t_{\mathrm{w(I\ J)}} \quad t_{\mathrm{w(I,\ J\ \ 1)}})} \tag{10}$$

From eq. (10), the value of the exit water temperature from each element $t_{\mathrm{w(I\ J)}}$ could be found, then it is considered as the inlet water temperature to the next element at the same column. After the value of the air enthalpy of each element is found, the air dry bulb temperature is found. This can be obtained using a routine which considers the relation between the air enthalpy and the air temperature as a polynomial of the 3rd order.

From the assumption that the amount of heat transfer from water to the interface is equal to the amount of heat transfer from the interface to the main air stream, then:

$$\frac{\Delta t_\mathrm{a}}{\Delta h_\mathrm{a}} \quad \frac{t_\mathrm{i} \quad t_\mathrm{a}}{h_\mathrm{i} \quad h_\mathrm{a}} \tag{11}$$

Equation (11) could be written in numerical form:

$$\frac{t_{\mathrm{a(I\ J)}} \quad t_{\mathrm{a(I\ \ 1\ J)}}}{h_{\mathrm{a(I\ J)}} \quad h_{\mathrm{a(I\ \ 1\ J)}}} \quad \frac{t_{\mathrm{i(I\ J)}} \quad t_{\mathrm{a(I\ \ 1\ J)}}}{h_{\mathrm{i(I\ J)}} \quad h_{\mathrm{a(I\ \ 1\ J)}}} \tag{12}$$

The previous relations are used in constructing a computer algorithm.

Experimental setup

Figure 1 shows the overall view of the experimental test rig, while fig. 2 shows the schematic diagram of the used cross-flow cooling tower.

Figure 1. Overall view of the experimental apparatus

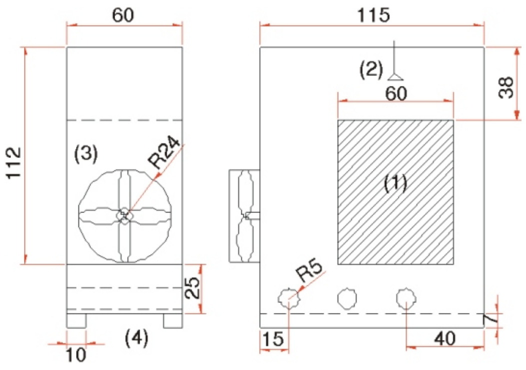

Figure 2. Schematic diagram for the experimental cooling tower
(1) Heat transfer media (the fill), (2) Nozzles, (3) Fan, (4) Casing

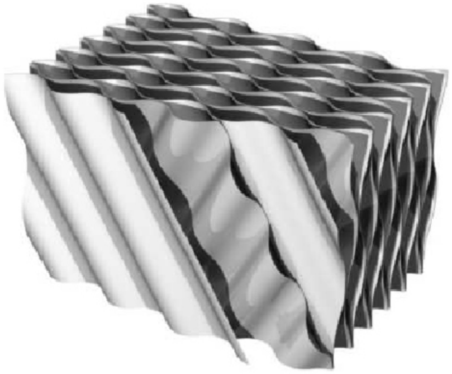

Figure 3. The fill packing of the cooling tower

Apparatus description

The apparatus used in this study comprises a "cross-flow cooling tower". The main parts of the experimental tower are shown in fig. 2. The casing material of the cooling tower is of hot-dip galvanized steel to provide adequate corrosion protection at low cost.

Heat transfer media (the fill)

The packed volume (the fill) of the apparatus is shown in fig. 3, its dimensions are 60 cm width, 60 cm length, and 74 cm height. The fill is made from polyvinyl chloride. It is of "mixed corrugated type fill".

Air flow system

The type of the apparatus used is "the induced draft cross-flow tower". A fan placed in the outlet of the tower sucks the air out after it passes across the fiber packing. The fan is driven by an electric motor of 0.37 kW. The motor is connected directly to the fan using key and keyway drive.

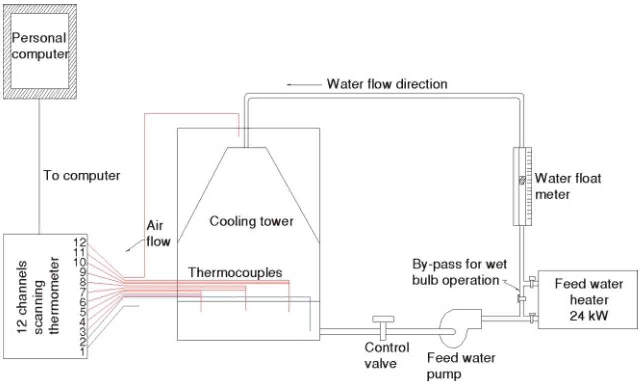

Figure 4. Schematic diagram for the full experimental test rig with the measuring instrumentations

Water flow system

The hot water is supplied from a heat exchanger that heats the water by means of electric heater. The electric heater capacity is 24 kW. The water is supplied directly to the tower as shown in fig. 4.

The water is pumped to the apparatus using a centrifugal pump that is driven by an electric motor of

0.37 kW power, and 2.7 m^3 per hour maximum discharge. A valve on the delivery side controls the water flow rate. The water is distributed before entering the packed volume through four nozzles each of 1.25 cm diameter. The hot water passes vertically down through the fill and is cooled by the air streams passing horizontally.

The cooled water is collected in a basin beneath the fill of the tower. The basin is provided with a make up feed, an overflow, and a drain.

Theoretical and experimental results

Figure 5 shows the experimental relation between the available *NTU* and the water/air mass flow ratio (m_w/m_a) in the wet bulb operation.

Figure 6 shows the experimental relation between the available *NTU* and m_w/m_a in hot water operation.

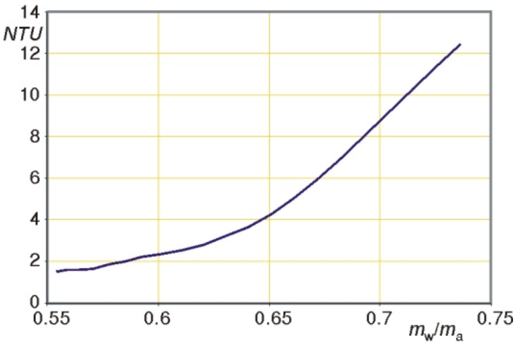

Figure 5. Relation between m_w/m_a and available *NTU* obtained from experimental work at wet bulb operation

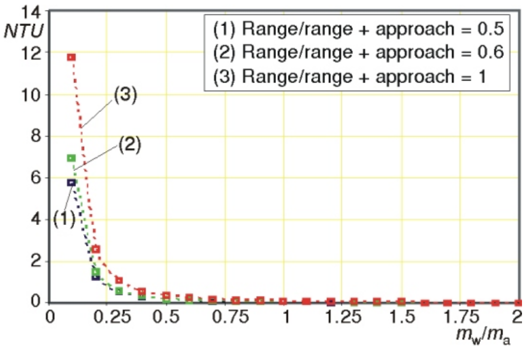

Figure 6. Relation between *NTU* and m_w/m_a obtained from experimental work in hot water operation

The values of *NTU* and ka obtained from feeding the values of the experimental work to the computer program. From these values a relation was found to obtain the required of the tower in hot water operation. This relation is shown in eq. (13), also this relation is plotted on fig. 6:

$$NTU \quad 0.076 \; \frac{\dot{m}_w}{\dot{m}_a}^{2.19} \; \frac{\text{Range}}{\text{Range} \quad \text{Approach}}^{1.03} \tag{13}$$

Another relation was found for the effectiveness in the wet bulb operation. This relation is shown in eq. (14) and is plotted in fig. 7:

$$\varepsilon = 1 - e^{-\lambda NTU} \tag{14}$$

where ε is the effectiveness and λ – the witting ratio.

Results of the numerical approach

Results from 11 runs for the apparatus with different wetting ratios, and also 4 runs for wet bulb operation where the water is allowed to circulate without heating and also with different wetting ratios are presented to develop the model.

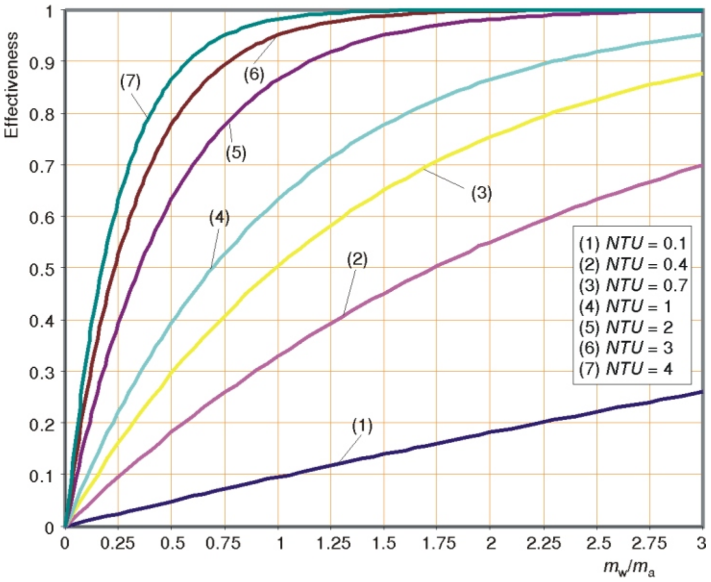

Figure 7. Relation between effectiveness and m_w/m_a obtained from experimental work in wet bulb operation

When running the program at different values of air inlet wet bulb temperatures, it was found that, when the air inlet wet bulb temperature decreases by 1 °C, the value of the effectiveness ε also decreases by $7\cdot10^{-3}$. Also it was found that, when the value of water inlet temperature $t_{w\,in}$ is decreased by 1 °C, the value of effectiveness ε is also decreased by $3.1\cdot10^{-3}$. The relation between the effectiveness and the *NTU* is shown in fig. (8).

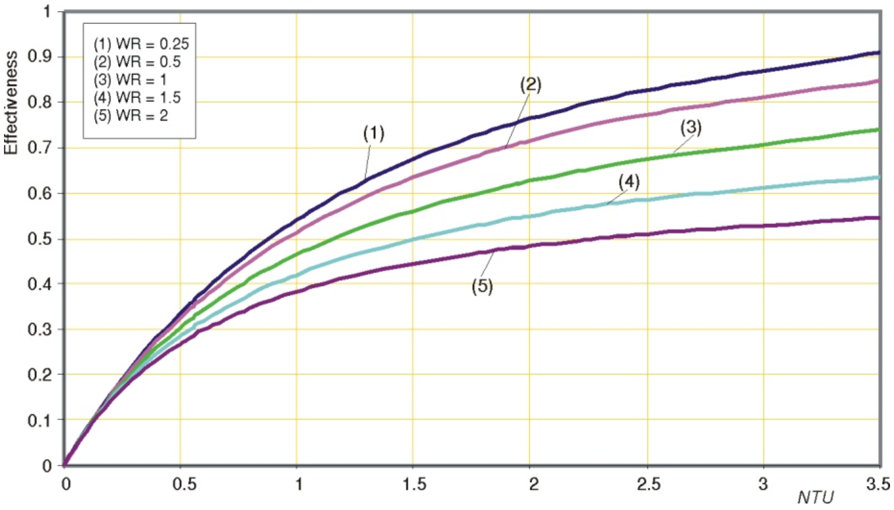

Figure 8. Relation between effectiveness and *NTU*

From the previous results, the "characteristic curve" shown in fig. 9 was constructed. This curve is very helpful for designers in order to find the actual value of the number of transfer units, if the values of inlet water temperature $t_{w\,in}$ or inlet air wet bulb temperature t_{wbin} are

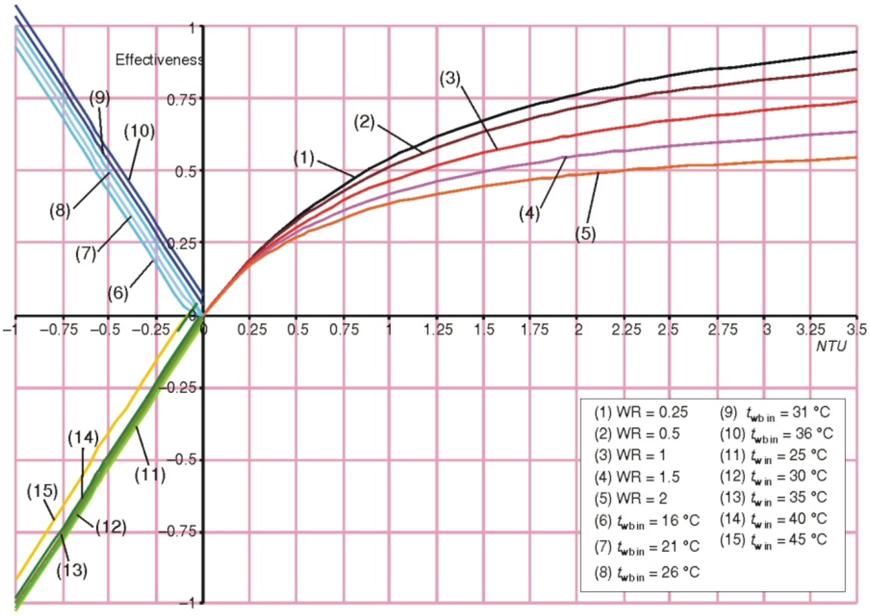

Figure 9. Effectiveness *vs.* *NTU* over wide range of wetting ratio with the effect of $t_{\mathrm{wb\ in}}$ and $t_{\mathrm{w\ in}}$ (color image see on our web site)

changed, *e. g.* If the value of *NTU* is found to be 1 and wetting ratio (WR) of 1 then the effectiveness will be found 0.48. As well as if the inlet wet bulb temperature is 21 °C and the water inlet temperature is 35 °C, the effectiveness will be 0.5 which is increased due to the effect of the inlet wet bulb temperature and the water inlet temperature.

Conclusions

The numerical results shown, give a good analysis for the cross-flow cooling towers over wide ranges of operation, where the experimental investigation could not cover all these ranges. The numerical method described in this investigation appears to be valid to obtain the required number of transfer units (*NTU*). The results of numerical work show deviation between our solutions with that which assumes that the interfacial temperature is equal to bulk water temperature. It could be said that, taking the film resistance into consideration leads to minimize the temperature potential and humidity driving force. These effects of film resistance decrease the rate of heat and mass transfer and need more *NTU*. Also the separation between sensible and evaporative mechanisms of cooling gives a good indication to bulk air temperature distribution and interfacial temperature and humidity.

The *NTU* obtained from the computer program is called the required number of transfer units, which may be considered as a system relation (system curve).

To sum up, the coefficients of mass transfer, heat transfer of air side and heat transfer of water side are functions of both water and air mass velocities. But the coefficient of mass transfer is affected by the inlet bulk air temperature (dry bulb temperature). But this parameter does not affect the coefficient of heat transfer of airside.

As a general conclusion, the combination between the required and the available *NTU* creates the complete solution. The intersection between the available *NTU* and the required number of transfer units curves obtains the design condition, which is the main aim of the designer.

Nomenclature

a – extended water surface area per unit volume, $[\mathrm{m^2m^{-3}}]$
C_w – water specific heat, $[\mathrm{kJkg^{-1}K^{-1}}]$
h_a – bulk air enthalpy, $[\mathrm{kJkg^{-1}}]$
h_i – interfacial film enthalpy, $[\mathrm{kJkg^{-1}}]$
k_a – air thermal conductivity, $[\mathrm{Wm^{-1o}C^{-1}}]$
k_m – mass transfer coefficient, “interface to air” $[\mathrm{kgs^{-1}m^{-2}}]$ $[\mathrm{=kg_v kg_a^{-1}}]$
$\dot{m}_\mathrm{a}$ – air mass flow rate, $[\mathrm{kgs^{-1}}]$
$\dot{m}_\mathrm{w}$ – water mass flow rate, $[\mathrm{kgs^{-1}}]$
t_a – bulk air dry bulb temperature, [°C]
t_i – interfacial film temperautre, [°C]
$t_\mathrm{w\,in}$ – water inlet temperature, [°C]
$t_\mathrm{wb\,in}$ – inlet air wet bulb temperature, [°C]
$t_\mathrm{w\,out}$ – water outlet temperature, [°C]

Greek letters

ε – cooling tower effectiveness
λ – change of the air enthalpy across the volume element
ψ – increment value

Non-dimensional numbers

NTU – number of transfer units

References

[1] Katzel, J., Trends in Cooling Towers, *Plant Engineering, 54* (2000), 1, pp. 38-43
[2] Wang, S. K, Handbook of Air Conditioning and Refrigeration, McGrew Hill, New York, USA, 2001
[3] Haik, Y., Engineering Design Process Brooks/Cole, Pacific Grove, Cal., USA, 2003
[4] Tamburini, D. R. The Analyzable Product Model Representation to Support Design-Analysis Integration. Ph. D. dissertation, Georgia Institute of Technology, Atlanta, Geo., USA, 1999

Authors affiliations:

M. M. Abo Elazm
Mechanical and Marine Engineering Dept.
College of Engineering and Technology
Arab Academy for Science, Technology and Maritime Transport (AASTMT)
Alexandria, Egypt

A. F. Elsafty (**corresponding author**)
Mechanical and Marine Engineering Dept.
College of Engineering and Technology
Arab Academy for Science, Technology and Maritime Transport (AASTMT)
P. O. Box 1029 Alexandria, Egypt
E-mail: aelsafty@aast.edu

Paper submited: May 2, 2008
Paper revised: August 7, 2008
Paper accepted: December 28, 2008