Journal of Advanced Engineering Research
ISSN: 2393-8447
Volume 2, Issue 1, 2015, pp.1-10

Modelling Heat and Mass Transfer in a Cooling Tower under Hot and Humid Conditions

Dang Tran Tho* and Dang Quoc Phu

School of Heat and Refrigeration Engineering, Hanoi University of Science and Technology, Vietnam

*Corresponding author email: tho.dangtran@hust.edu.vn, Tel: 0084.912 260 610

ABSTRACT

A model for estimate of outlet water temperature under hot and humid condition in a mixed counter-flow cooling tower was developed. With an assumption that the cooling tower reacted as an adiabatic continuous and stable system, the water outlet temperature was theoretically estimated as function of climate conditions and structure of the cooling tower. A complete set of experimental data on the water outlet temperature in a lab-scale cooling tower operating under the same climate conditions were taken for comparison that have shown a good agreement with the predicted results.

Keywords - Cooling, Cooling tower, hot and humid, heat and mass transfer, modeling**.**

1. INTRODUCTION

Cooling tower (CTW) is widely used in many applications, especially in refrigerating and air conditioning systems, where there is a need to release the heat from a hot water flow into a cooler atmosphere. As a mixed heat exchanger, the heat transfer taking place in a CTW is obviously associated with the mass transfer between the hot water and cool air moving inside the CTW. As a result, the cooling tower efficiency depends on the evaporation of water into the air, which in turn varies not only with the climatic conditions under which the CTW is employed but also its own structure [1]. So far, attempt to study energy performance of CTW was made by many researchers worldwide. However, most work were conducted in cold and dry climate. Under these conditions, heat exchange effectiveness of CTW is normally high. Main operating variables investigated are the natural evaporation in a CTW without packed-bed [2]; the height and structure of a CTW used in power plants [3]; the air flow direction [4]; the wind direction and wind shedding objects [5]; the life span of CTW shell [6]. In addition, improvements of thermal analysis and calculation method for CTW performance were also attempted based upon Merkel's theory [7,8,9].

In hot and humid climate, ambient temperature and air relative humidity are normally high, a relatively low heat capacity and cooling efficiency of CTW used under such conditions are normally observed. This paper deals with modelling of a CTW performance by taking into consideration the effect of some operating parameters (i.e air humidity and temperature, water-to-air flows ratio) as well as its own structure (i.e. specific surface area, height of the packed bed of the CTW). Comparison between the modelling results and the experimental ones which were earlier carried out on a lab-scale CTW is then made that shows a pretty good agreement.

2. THEORY

2.1 Building differential equation system describing heat and mass transfer in cooling tower

Heat and mass transfer in a CTW is influenced by mixing between the cooling air and hot water inside the CTW. Once the air reaches its saturated state, heat exchange between the air and the water would decrease. The amount of water evaporated into the air at this stage is negligible. As a result, cooling efficiency of a CTW depends on how heat exchange process takes place when the air is still at under saturated state [10, 11].

Let's denote dA a surface area element of a CTW (see Fig 1). Assuming that the CTW reacts as an adiabatic system and heat and mass transfer taking place in the CTW is of continuous and stable process [10,11], if $t_w > t_a$, heat and mass transfer taking place in dA can be represented by some fundamental equations as below:

- Heat transfer by convection from water to air in dA:

$$dQ_{cv} = \alpha.(t_w - t_a).dA = \alpha.\Delta t.dA \qquad (1)$$

- Heat transfer by evaporation between water and air:

Let's denote β a mass transfer coefficient which is defined as amount of water evaporated into the air per unit time per unit area if a difference in the differential pressure of the evaporation surface and that of air is 1 Pascal. The amount of evaporated water into air can be thus calculated as follows.

$$dG_w = \beta.(p_{vplt} - p_{vp}).dA = \beta.\Delta p.dA = G_a.d(d) \quad (2)$$

Here:

- p_{vplt} is the differential vapor pressure of the air on the water-to-air interface and at water temperature t_w. Of course, $p_{vplt} = p_s(t_w)$, in Pa.
- p_{vp} is the differential vapor pressure of the air at air temperature t_a, in Pa.
- d(d) is differential variation of moisture content in air, in kg water/kg dry air.

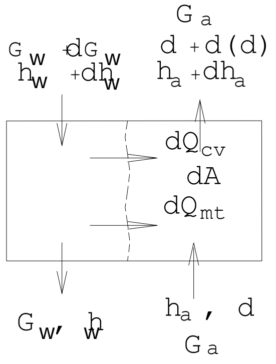

Fig 1. Heat and mass transfer in dA

From Equation (2), heat exchange between water and air by mass transfer can be estimated as below.

$$dQ_{mt} = dG_w.r_{lt} = \beta.\Delta p.r_{lt}.dA \quad (3)$$

here r_{lt} is the latent heat of water vapor which is determined by the latent heat of water vapor at 0°C and its specific heat C_{pvp}.

$$r_{lt} = C_{pvp}.t_w + r_0 \quad (4)$$

Assuming air is still at under-saturated state, the energy balance equation has the following form:

$$dQ = |dQ_w| \qquad = |dQ_a| \quad (5)$$

- From the water side:

$$dQ_w = G_w.dh_w + h_w.dG_w \quad (6)$$

- From the air side:

$$dQ_a = G_a.dh_a \quad (7)$$

Combining Equations (3), (4), (6) and (7), the energy balance equation for dA is as follow:

$$\begin{cases} dQ_k = dQ_{dl} + dQ_{tc} \\ dQ_n = dQ_{dl} + dQ_{tc} \end{cases} \quad (8)$$

By replacing Equations (1), (2), (3), (4) into Equation (8) and with some mathematical modifications, a system of two differential equations describing heat and mass transfer process in under-saturated air zone can be obtained as below.

$$\begin{cases} \dfrac{dt_a}{dt_w} = \dfrac{G_w}{G_a}\left[\dfrac{\left(\dfrac{\alpha.\Delta t}{\beta.\Delta P} + C_{pvp}.\Delta t\right).C_w}{\left(\dfrac{\alpha.\Delta t}{\beta.\Delta P} + r_{lt} - i_w\right).(C_{pda} + d.C_{pvp})}\right] \\ \dfrac{d(d)}{dt_w} = \dfrac{G_w}{G_a}\left[\dfrac{C_w}{\dfrac{\alpha.\Delta t}{\beta.\Delta P} + r_{lt} - i_w}\right] \end{cases} \quad (9)$$

The equations system (9) expresses the variation of air temperature and that of air moisture content as function of water temperature. To solve this differential equation system, apart from its initial and boundary conditions, it is necessary to define some intermediate parameters as follows.

2.2 Determine intermediate parameters

2.2.1 Variation of moisture content in air

Moisture content in air can be estimated as below

$$d = 0{,}622\ .\frac{\varphi.p_{sa}(t_a)}{p - \varphi.p_{sa}(t_a)}, \text{ kgwater/kg dry air} \quad (10)$$

here $P_s(t_a)$ is the saturation pressure of water vapor in moist air.

2.2.2 Water to air flow ratio

As water evaporation always takes places inside a CTW during its operation, the ratio G_w/G_a changes with variation of moisture content in air. Based upon the mass balance for the element dA, this ratio can be defined as below.

$$\frac{G_w}{G_a} = \frac{G_{w2}}{G_a}.[1 + \frac{G_a}{G_{w2}}.(d - d_1)] \quad (11)$$

2.2.3 Characteristic coefficient of cooling tower $\dfrac{\alpha.\Delta t}{\beta.\Delta P}$

The estimate of heat and mass transfer coefficients for mixed heat exchangers appears complicated as coefficients α and β depend on many factors. By applying Lewis Theorem, relationship between these two coefficients can be expressed as below [14].

$$\frac{\alpha}{\beta} = C_{pa} \qquad (12)$$

The above expression can be however appropriate only under adiabatic conditions. On the other hand, by assuming heat conduction and diffusion processes being of the same nature, relationship between heat and mass transfer coefficients can be represented as follows [15]

$$\frac{\alpha}{\beta.C_{pa}} = 0{,}9085.\frac{\xi - 1}{\ln \xi} \qquad (13)$$

In this study, by combining Equations (1) and (7), heat transfer by convection can be expressed as below.

$$dQ_{cv} = \alpha.(t_w - t_a)dA = \alpha.\Delta t.dA = G_a.C_{pa}.dt_a \qquad (14)$$

Also, heat transfer by evaporation can have another expression as fololows

$$dQ_{mt} = G_a.d(d).r_{lt} =$$
$$= G_a.[d.C_{pvp}.dt_a + (r_0 + t_a.C_{pvp}).d(d)] \qquad (15)$$

By combining Equations (4) and (15) one can get

$$d.C_{pvp}.dt_a = (C_{pvp}.t_w - t_a.C_{pvp}).d(d) = C_{pvp}.\Delta t.d(d) \quad (16)$$

$$\text{or: } \frac{dt_a}{d(d)} = \frac{\Delta t}{d} \qquad (17)$$

Similarly, by combining Equations (14) and (3), one can obtain:

$$\frac{\alpha.\Delta t}{\beta.\Delta P} = C_{pa}\frac{dt_a}{dd} \qquad (18)$$

By combining Equations (17) and (18) we have:

$$\frac{\alpha.\Delta t}{\beta.\Delta P} = C_{pa}\frac{\Delta t}{d} \Rightarrow \frac{\alpha}{\beta} = C_{pa}.\frac{\Delta P}{d} \qquad (19)$$

By substituting Equation (19) into Equation system (9), we finally receive a new differential equations system as follows:

$$\begin{cases} \dfrac{d(t_a)}{d(t_w)} = \dfrac{G_w}{G_a}.[\dfrac{C_w.\Delta t}{(C_{pa}.\Delta t + (r_{lt} - i_w).d)}] \\ \dfrac{d(d)}{d(t_w)} = \dfrac{G_w}{G_a}.[\dfrac{d.C_w}{C_{pa}.\Delta t + (r_{lt} - i_w).d}] \end{cases} \qquad (20)$$

In some cases, moisture content in air at the outlet of a CTW (d_2) is known. From Equations (9) and (17), we obtain the system of differential equations to estimate the water and air temperature as functions of moisture contents in air.

$$\begin{cases} \dfrac{d(t_a)}{d(d)} = \dfrac{\Delta t}{d} \\ \dfrac{d(t_w)}{d(d)} = \dfrac{G_a}{G_w}.[\dfrac{C_{pa}.\dfrac{\Delta t}{d} + r_{lt} - i_w}{C_w}] \end{cases} \qquad (21)$$

The above differential equation systems (20) and (21) can be solved by numerical methods.

3. EXPERIMENTAL WORK

3.1 Experimental set-up

An experimental work was carried out on T123D laboratory equipment currently available at Hanoi University of Science and Technology [1]. Its schematic diagram is presented in Figure 2 [14].

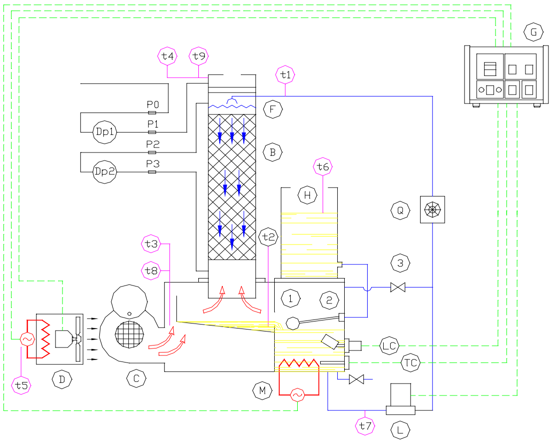

Fig 2. Schematic diagram of the experimental set-up

<u>Legend and notes</u>:

B: Cooling tower: The tower has a square cross section, tower shell is made of organic glass. Configuration of the packed-bed inside the tower can be changed during experiment;

C: Centrifugal fan with a flow control valve; D: the air heater;

F: Over-flow trough-type distributor of water. Hot water is pumped into the distributor where it runs off through small holes and squirt all over the packed-bed;

G: Control panel where major experimental data are displayed;

H: Make-up water tank; I: Hot water tank that includes water tray, water collector, float valve to adjust the water level inside the tank, and an electric water heater; L: Water circulating pump with a maximum flow rate V_{max} of 3.26 m^3/h; Q: Flow meters;

t_1, t_2: water temperature at the inlet and outlet of tower, respectively;

t_3, t_4: dry air thermometer temperature at the inlet and outlet of the tower, respectively;

t_8, t_9: wet bulb air thermometer temperature at the inlet and outlet of the tower, respectively;

t_5, t_6, t_7: ambient temperature, temperature of the water tank, and temperature of the water collector, respectively;

P_1, P_2: static pressures inside the packed-bed of CTW;

Dp2: pressure drop through the packed-bed of CTW

3.2 Experimental procedure and instrumentation

Hot water from the hot water tank I is pumped up into the over-flow distributor F located on top of the CTW. From there, water is sprayed onto the packed-bed surface. By flowing downwards, water is cooled by a flow of air that moves upwards from a fan (C). A mixed heat and mass transfer from the water to air then takes place on the packed-bed surface. The cooled water is collected at the bottom of the CTW, preheated in the hot water tank I and again is pumped back on the top of CTW. Make-up water is regularly made due to a loss of water evaporated during the water-to-air heat and mass transfer process. Under static conditions, a reduction in the volume of water in the make-up water tank should equal to the amount of water evaporated in the CTW that leads to an increase in humidity of the air going out from the CTW.

For this study, the following are main operating parameters with their respective selected values.

- Water temperature at the inlet of the CTW, t_{w1}: 35°C, 40°C, 45°C;
- Air temperature in the CTW, t_{a1}: 25 °C, 30 °C, 35 °C;
- Air humidity in the CTW, φ_1: 55%, 60%, 65%, 70%, 75%, 80%, 85% and 90 %;
- Specific area surface of the packed-bed that is estimated as the ratio of surface area of the packed bed to its entire volume, f: 0 m^2/m^3, 25 m^2/m^3, 64 m^2/m^3, 125 m^2/m^3, 160 m^2/m^3, 250 m^2/m^3 and 300 m^2/m^3;
- Height of the packed-bed, H: 150mm, 300mm, 450mm, 600mm and 750 mm.

For each experiment, only one operating parameter is varied at a time while the others are kept unchanged. During each experiment, measurement of water and air temperatures and flow, pressure drop in the packed bed and air humidity were carried out with the help of TESTO 400 (German product) and Dwyer (USA product) with high accuracy.

4. COMPARISON BETWEEN THE EXPERIMENTAL AND PREDICTED RESULTS

In this work, the Runge-Kutta numerical method was used to solve the differential equation systems (20) and (21) with the boundary conditions being stated in accordance with the range of the experimental work [1]. On the other hand, a total of 181 runs were conducted on the above described CTW set-up. Detailed experimental data and results were analyzed in [1] while the effects of some main operating variables on the energy performance of the CTW were eraborated in [15].

All the experimental and predicted results of the water temperature at the outlet of the CTW are given in Table 1.

Figure 3 shows a comparion between the experimental and predicted results. From this figure, the positions of the points tw2-ex are fluctuated around and focus on the main diagonal, with the largest and average deviations being 4.65% and 1.4%, respectively.

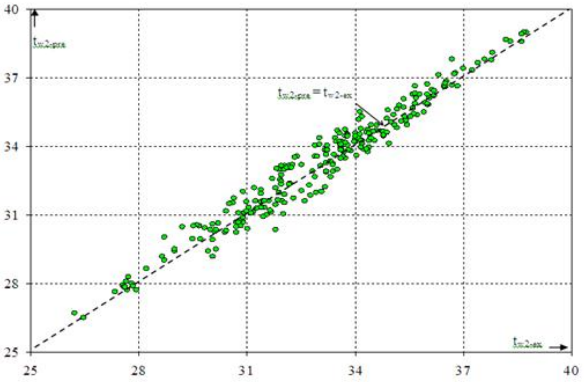

Fig 3. Comparison between the experimental and predicted results

Table 1. Experimental and predicted results for the water temperature at the outlet of the cooling tower

t_{w1} [^oC]	μ	f [m^2/m^3]	H [mm]	t_{a1} [^oC]	φ_1 [%]	t_{a2} [^oC]	φ_2 [%]	t_{w2ex} [^oC]	t_{w2pre} [^oC]
35.00	1.20	300.00	600.00	25.00	55.00	26.54	94.08	28.20	28.63
					65.00	27.26	94.87	29.00	29.42
					70.00	27.28	97.22	29.20	29.96
					80.00	28.06	98.63	29.80	30.42
					90.00	28.46	99.39	30.10	30.60
				30.00	60.00	30.90	86.84	30.10	29.91
					70.00	31.14	88.65	30.80	31.08
					80.00	31.72	91.34	31.30	31.57
					90.00	31.88	93.83	31.80	32.19
				35.00	60.00	32.00	92.80	31.50	31.01
					65.00	32.82	93.93	32.00	31.60
					70.00	33.34	94.53	32.50	32.06
					80.00	34.00	96.46	33.40	33.24
					90.00	34.46	98.64	33.90	33.79
40.00				25.00	60.00	29.00	97.93	30.70	31.73
					65.00	29.24	98.54	30.90	31.25
					75.00	30.22	96.79	31.40	31.75
					85.00	30.86	97.41	31.70	32.05
					90.00	31.48	98.30	32.10	32.45
				30.00	68.50	32.14	96.07	32.20	33.07
					75.00	32.20	97.63	32.40	33.57
					80.00	32.26	99.47	32.90	34.04
					85.00	32.70	99.16	33.70	34.43
					90.00	33.22	99.03	34.10	35.16
				35.00	65.00	35.38	92.89	34.00	33.60
					70.00	35.60	94.08	34.40	33.77
					75.00	35.68	96.69	35.00	34.12
					80.00	36.10	97.36	35.40	35.14
					90.00	36.54	98.82	36.00	35.90
45.00				25.00	55.00	31.40	93.36	32.50	32.25
					60.00	31.98	94.81	33.80	33.55
					75.00	32.70	94.87	34.50	34.25
					80.00	33.08	94.37	34.80	34.55
					90.00	33.96	94.85	35.10	34.85

				30.00	60.00	34.72	90.23	35.20	35.78
					70.00	35.46	92.26	35.80	36.28
					85.00	36.34	93.76	36.30	37.14
					90.00	36.62	94.17	36.70	37.79
				35.00	60.00	37.28	90.86	36.00	35.81
					65.00	37.66	91.90	36.50	36.65
					75.00	38.18	94.43	37.30	37.33
					90.00	38.72	95.47	38.30	38.57
35.00	0.90	300.00	600.00	30.00	70.00	31.04	90.56	30.00	29.17
	1.10					31.38	91.57	30.80	30.22
	1.30					31.64	92.70	31.00	30.41
	1.60					31.94	93.42	31.40	30.92
	1.80					32.12	94.54	31.70	31.14
40.00	1.00					33.06	91.15	32.20	32.70
	1.30					33.94	91.41	33.20	33.63
	1.60					34.08	93.00	34.00	34.32
	2.00					34.32	93.68	34.40	34.72
	1.00			35.00	65.00	35.12	90.55	33.20	32.86
	1.25					35.60	91.51	33.70	33.45
	1.50					36.00	92.70	34.20	33.88
	1.75					36.24	92.48	34.80	34.64
	2.00					36.34	94.14	35.00	34.92
45.00	1.00					37.18	90.86	35.70	35.39
	1.25					37.88	90.10	36.50	36.85
	1.50					38.12	90.86	37.40	37.64
	1.75					38.68	91.41	37.80	38.09
	2.00					38.78	92.52	38.20	38.65
40.00	1.20	0.00	600.00	20.00	60.00	26.52	92.40	33.82	33.83
					70.00	26.60	92.87	34.18	34.77
					80.00	26.62	94.71	34.92	35.58
					90.00	26.62	94.86	35.68	36.65
				25.00	60.66	28.60	88.24	34.20	34.23
					70.46	28.90	89.02	34.90	35.21
					80.13	28.90	89.73	35.70	36.13
					90.00	29.00	93.35	36.00	36.72
				30.00	60.23	30.80	86.68	35.10	34.92
					70.00	31.00	90.13	35.60	35.67
					75.00	31.20	91.82	36.20	36.22
					80.00	31.42	92.95	36.50	36.60

					90.00	31.64	95.34	37.02	37.41
				35.00	60.00	34.52	85.76	35.92	35.49
					70.20	34.90	87.09	36.68	36.69
					80.00	35.10	91.31	37.80	37.78
					90.00	35.30	96.54	38.62	38.58
	1.20	25.00	600.00	20.00	60.00	26.52	93.16	33.20	33.27
					70.00	26.70	94.26	33.60	33.92
					75.00	26.90	94.58	34.12	34.38
					80.00	27.04	95.36	34.46	34.94
					90.00	27.96	94.85	34.92	35.60
				25.00	60.00	29.38	91.52	33.42	33.63
					70.25	29.56	91.85	33.98	34.21
					75.00	29.66	93.00	34.50	34.64
					80.34	29.86	93.03	34.62	34.92
					85.00	30.08	92.34	35.16	35.62
					90.00	30.08	96.78	35.36	35.69
				30.00	60.00	31.68	88.50	34.54	34.24
					70.74	31.70	94.64	35.16	34.82
					75.00	31.62	93.40	35.68	35.87
					80.00	31.84	93.97	36.16	36.17
					90.00	31.72	95.07	36.76	37.18
				35.00	60.00	35.10	88.12	35.28	35.08
					70.00	35.42	90.34	35.54	35.32
					80.04	35.32	93.92	36.86	36.64
					90.75	35.56	97.08	37.60	37.81
35.00	0.90	64.00	600.00	25.00	70.00	29.16	95.70	26.46	26.50
	1.10					30.36	95.80	27.72	28.27
	1.30					30.50	98.40	27.92	27.71
	1.50					31.18	98.60	28.72	29.03
	1.70					32.18	96.10	30.52	31.49
	1.90					32.98	93.40	29.62	30.55
40.00	1.20			30.00	60.00	35.30	87.70	30.92	31.08
					70.00	36.80	94.70	33.72	34.75
	2.00				60.00	36.08	93.90	32.84	32.92
					70.00	36.70	95.70	33.60	33.49
	1.20	125.00	600.00	20.00	60.00	28.92	97.39	30.12	30.28
					70.00	29.12	97.10	30.62	31.52
					80.00	29.20	96.66	31.26	33.08
					85.00	29.24	96.37	32.15	33.84

					90.35	29.60	96.98	33.24	31.34
				25.00	60.02	29.66	96.54	31.04	31.60
					70.00	30.44	96.67	31.62	32.47
					75.00	31.00	95.28	31.95	33.14
					80.00	31.02	95.14	32.24	32.89
					85.00	31.02	96.84	32.47	33.12
					90.00	31.10	98.27	33.02	34.08
				30.00	60.21	31.22	104.68	32.02	31.03
					70.00	32.72	96.66	33.68	33.57
					75.00	33.02	94.90	33.78	34.04
					80.00	33.02	96.13	34.78	34.64
					85.00	33.52	96.30	35.06	35.39
					90.00	34.08	95.80	35.36	36.07
				35.00	60.00	34.94	92.32	34.32	33.88
					70.00	35.04	93.76	34.88	34.60
					75.00	35.42	94.06	35.64	35.43
					80.00	36.02	93.35	36.12	36.48
					90.00	36.30	96.59	36.78	37.19
	1.20	160.00	600.00	25.00	60.00	30.00	91.35	30.70	31.35
					65.00	30.32	92.95	31.00	31.65
					70.00	30.54	94.68	31.20	32.17
					80.00	31.20	95.02	32.00	32.97
					90.00	31.70	96.46	32.32	32.97
				30.00	60.00	32.42	92.67	31.92	33.53
					70.00	32.80	93.39	32.50	33.18
					80.00	33.30	95.74	32.90	33.54
					85.00	33.94	96.86	33.70	33.76
					90.00	34.36	97.42	34.32	34.62
				35.00	60.00	35.10	93.25	33.50	32.99
					65.00	35.60	94.08	34.40	33.97
					70.00	35.60	96.03	34.80	34.44
					80.00	36.10	97.36	35.40	35.31
					90.00	36.50	99.34	36.00	35.82
40.00	1.20	250.00	600.00	30.00	75.00	34.70	95.60	31.86	31.63
	1.40					35.70	94.40	31.94	32.32
	1.60					36.56	96.20	33.40	33.18
	1.80					36.26	96.50	33.34	33.35
	1.20				85.00	35.12	98.70	32.74	32.32
	1.30					36.00	95.00	32.16	33.15

	1.60					36.52	92.40	33.00	34.37
	1.80					36.58	94.90	32.28	32.93
35.00	1.40	300.00	150.00	25.00	70.00	26.30	96.13	30.72	30.46
						26.20	95.36	30.42	30.31
40.00	1.50			30.00	75.00	30.00	99.27	36.00	35.84
						29.64	99.71	36.00	35.88
45.00	1.60				75.00	31.30	99.15	38.76	38.98
						31.44	99.01	38.62	38.89
35.00	1.60	300.00	300.00	26.00	80.00	30.30	94.30	30.80	30.74
						30.30	94.44	30.78	30.69
40.00				30.00	75.00	33.00	99.45	34.40	34.24
						33.12	99.17	34.44	34.37
45.00					65.00	33.92	99.59	36.02	36.26
						34.28	99.46	36.08	36.13
35.00	2.00	300.00	450.00	25.00	80.00	31.30	93.51	30.20	30.63
						31.06	96.60	30.14	30.35
40.00	2.00				70.00	34.30	96.39	33.64	34.18
						34.32	96.26	33.72	34.16
45.00	1.10					31.98	97.63	33.58	34.20
						31.76	99.72	33.60	34.09
35.00	1.30	300.00	600.00	25.00	60.00	29.78	95.10	27.34	27.65
						28.88	97.49	27.66	28.09
40.00				30.00	70.00	33.50	98.23	31.90	31.99
						33.68	97.83	31.80	31.43
35.00	1.30	300.00	750.00	25.00	80.00	31.22	98.44	27.68	27.70
						31.10	99.29	27.84	27.88
40.00						33.82	99.46	31.26	31.27
						34.16	99.59	31.46	31.61
45.00				30.00		37.44	99.87	34.14	34.51
						37.62	99.74	34.20	35.31

5. CONCLUSION

The mixed heat and mass exchange process in a CTW under hot and humid condition appears complicated. The efficiency of this process depends on the evaporation process from water into the air flowing inside the CTW. In this study, a mathematical model was developed to comprehensively describe such exchange process taking place inside the CTW. A good agreement between the experimental and predicted results has shown that developed mathematical model would be a reliable tool for the designing, operating and performance evaluation of the CTW.

Temperature and humidity of air have a great influence to the cooling efficiency of CTW. Normally, CTW produced in the temperate zone, weld zone and cold countries operated in hot, humid conditions then its working heat capacity only achieve 40% capacity as designed (reduces 60%).

In CTW heat transfer by mass transfer mainly, with hot and humid climate conditions, heat transfer by this mechanism is more than 80% of the total heat exchange.

NOMENCLATURE

Symbol	Name	Subscripts	
C [kJ/kgK]	Specific heat capacity	1	In
d [kgh/kgk]	Humidity ratio	2	Out
A [m^2]	Area	ev	Evaporation
m [kg/s]	Mass flow rate	cv	Convection
H [m]	Height of cooling tower packing	vp	Vapor
h [kJ/kg]	Enthalpy	a	Air
Q [W]	Heat flux	lt	Limit
t [^{o}C]	Temperature	pre	Predicted
r [kJ/kg]	Latent heat of evaporation	w	Water
α [W/m^{2}K]	Heat convection coefficient	av	average
β [kg/m^{2}sPa]	Mass transfer coefficient	mt	Mass transfer
φ [%]	Relative humidity of the air	ex	Experimental
μ [kgW/kgA]	Ratio of water and air flows	wb	wet bulb
		sa	Saturation
		da	Dry air

REFERENCES

[1] Dang Tran Tho, *Theoretical and experimental study on heat and mass transfer in cooling towers of refrigerating and air-conditioning systems,* PhD’s Thesis, Hanoi University of Science and Technology, Vietnam, 2008.

[2] S.P. Fisenko, A.I. Petruchik and A.D. Solodukhin, Evaporative cooling of water in a natural draft cooling tower, *International Journal of Heat and Mass Transfer*, 45 (23), 2002, 4683-4694.

[3] R. Witasse, J.F. Georgin and J.M. Reynouard, Nuclear cooling tower submitted to shrinkage, behaviour underweight and wind, *Nuclear Engineering and Design,* 217, 2002, 247-257.

[4] M.A. Al-Nimr, Dynamic thermal behaviour of cooling towers, *Energy Conversion and Management*, 39, 1998, 631-636.

[5] Maurizio Orlando, Wind-induced interference effects on two adjacent cooling towers, *Engineering Structures,* 23 (8), 2001, 979-992.

[6] DD. Derksen, T. J. Bender, D. J. Bergstrom and K. S. Rezkallah, A study on the effects of wind on the air intake flow rate of a cooling tower: Part 1. Wind tunnel study, *Journal of Wind Engineering and Industrial Aerodynamics*, 64, 1996, 47-59.

[7] Jameel-Ur-Rehman Khan, Bilal Ahmed Qureshi and Syed M. Zubair, A comprehensive design and performance evaluation study of counter flow wet cooling towers, *International Journal of Refrigeration*, 27, 2004, 914-923.

[8] Jorge Facao and Armando Oliveira, Heat and mass transfer correlations for the design of small indirect contact cooling towers, *Applied Thermal Engineering,* 24, 2004, 1969-1978.

[9] M.S. Soylemez, On the optimum performance of forced draft counter flow cooling towers, *Energy Conversion and Management,* 45, 2004, 2335-2341.

[10] Dang Tran Tho, *A study of the effects of hot and humid climate on heat and mass exchanger efficiency of cooling towers*, Master’s Thesis, Hanoi University of Science and Technology, Vietnam, 2003.

[11] Poppe, *Wärme-und Stoffübertragung beider Verdungstungs- kühlung in Gegen- und Kreuzstrom*, VDI-Forschungsheft, Düsseldorf 56. Germany, 1973.

[12] W. Lewis, In *The Evaporation of a Liquid into a Gas*. Engineering, New York 55. USA 1933.

[13] F. Bonjakovic, *Technische thermodynamik*, Dressden, Germany, 1971.

[14] T123D catalogs: *Bench top cooling towers study unit*, Didacta, Italia, 2006.

[15] Dang Quoc Phu and Dang Tran Tho, A study of energy effectiveness in a cooling tower, *Proceedings of the International Conference and Utility Exhibition 2014 on Green Energy for Sustainable Development (ICUE 2014),* Thailand, 19-21 March 2014.