A Study of Air Velocity in a Cooling Tower that Affects the Diameter of the Droplet

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ABSTRACT

The study of air velocity inside the cooling tower gives an overview of the process of heat or mass transfer. This study developed mathematical modelling based on the principle of continuity and statistical thermodynamics to track changes in radius, velocity, density, and temperature of droplets and air along with the droplet trajectory or tower height. Before that, the droplet radius range is predicted in advance to get the accuracy of the calculation. Also, water capacity and fan rotation are varied to determine their effect on cooling tower performance. The calculation results showed that 18 Lpm capacity gives efficiencies above 50%, while for 0.5 Lpm capacity, it produces efficiencies in between 25% to 40%. The highest efficiency indicates that the evaporation process occurs most efficiently. Mathematical modelling in calculations can also describe the increase in air temperature, which usually uses numerical simulations.

Keywords: *heat or mass transfer; mathematical modelling; statistical thermodynamics; droplet trajectory; tower height.*

Introduction

A cooling tower is a large heat exchanger that has high effectiveness, in between 40% to 70% [1–5]. Investigation about the phenomena of the water

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and air that work in it is an enticing thing to do, such as the droplet evaporation [1, 6]. Observations were made to the level of droplets to get a high level of accuracy [6–12]. It described fluid interactions in the form of mathematical modelling obtained from governing equations, for example, the droplet surface temperature, the average water temperature, change in velocity of the falling droplet, and so on [13–16].

Qi [17] reported that exergy from the water supply was not absorbed entirely by air, but much was destroyed in the rain zone by irreversibility. The highest heat transfer occurs in the spray zone, where water first contacts with air in the tower. Whereas Calderon [18] and Xia [19] conducted numerical investigations using different methods of cooling tower design to solve the heat transfer problem in the rain zone and produced a model that was close to the original. They figured out droplet temperature charts along the cooling tower heights.

Based on a review by Sun [20] that different nozzles provide different spray patterns. The characteristics of spray patterns are affected by the corresponding flow rate, pressure, mean droplet size, and quantified droplet size distribution. According to Li [21], the study needs to give a windbreak wall to the large size of the cooling tower so that airflow is not disturbed, which causes a decrease in its performance. Wind blowing from the outside of it causes this disturbance and affecting the airflow inside it.

In our two previous studies, this study has analysed the phenomenon of drifting and evaporation processes. This study based all on the movement of the droplet. Not only when it comes out of spray nozzles [22] but also when it moves along the height of the tower [23]. However, the movement of air that the fan sucked into it got less attention. Therefore, in this study, the analysis is focused on obtaining air velocity along the trajectory. Also, increasing or decreasing the temperature of working fluids due to the air movement.

Methods

This study derived the prediction of air velocity inside a cooling tower from the continuity equation [1, 4, 6, 9]. From this, this study obtained the maximum and average speeds of air used to calculate air velocity [7, 10, 16, 20] along with the height of the tower using the principle of orifice area because the bottom of the cooling tower has a different shape to the roof ($L^2 > A$), as shown in Figure 1.

Then, this study achieved droplet diameter prediction from air and water spray velocities [4, 9, 10]. From statistical thermodynamics, we made mathematical modelling to calculate the temperatures of the working fluids [2, 3, 5, 14].

Aerodynamics elements

Based on the movement of fluid, the fan sucked across the orifice, the velocity obtained is the average velocity [4, 10, 14]. When it enters, the speed is low, while when it exits, the rate is high [7, 8, 20]. Based on this phenomenon, the air velocity u (m/s) [3, 9] is as:

$$u = Q_a / \left(\rho_a L^2 \right) \quad (1)$$

where Q_a (m^3/s) is the air capacity, ρ_a (kg/m^3) is the air density, and L (m) is the bottom diameter.

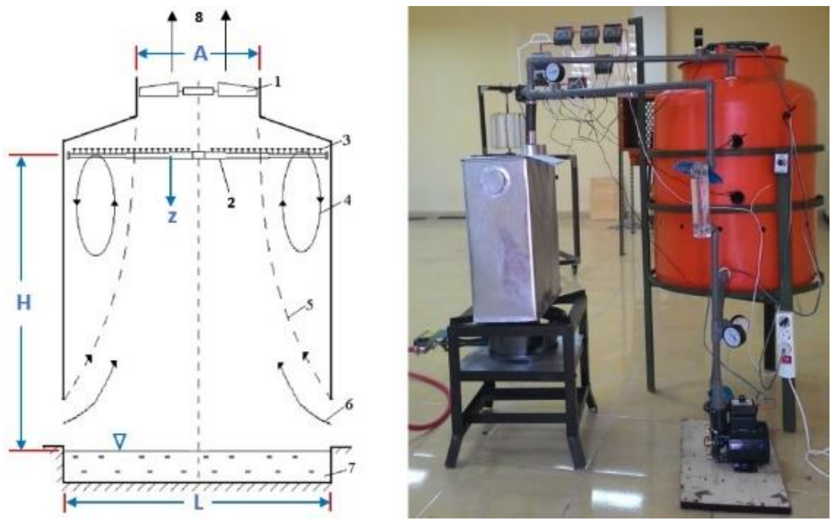

Figure 1: Scheme of the cooling tower: (1) Exhaust fan, (2) Delivery pipe, (3) Spraying nozzles, (4) Stagnation zone, (5) Line of stagnation zone, (6) Enter air, (7) Water basin, (8) Exit air.

Meanwhile, this study got the maximum velocity of air u_{max} (m/s) when it leaves the tower [6, 9] as:

$$u_{\max} = Q_a / \left(\rho_a A \right) \quad (2)$$

where A (m^2) is the roof cross-section area of the tower that is $A = \pi d_f^2 / 4$ and d_f (m) is the suction fan diameter.

This study received the velocity of droplet v (m/s) from continuity at the nozzle [8, 15, 20] as:

$$v = \left(Q_w / A_n\right) - u \tag{3}$$

where Q_w (m^3/s) is the water capacity and A_n (m^2) is the nozzle cross-section area that is $A_n = \pi d_n^2 / 4$ where d_n (m) is the nozzle diameter.

Because the bottom part of the roof tower resembles an orifice, it forms non-uniform airflow inside the cooling tower. This study based the velocity of air $u(z)$ (m/s) along the vertical z-axis on the principle of simple geometry [1, 9] as:

$$u(z) \cong u_{\max} \frac{\pi (H-h)^2}{2\left[H - h + z\left(L\sqrt{\pi/2A} - 1\right)\right]^2} \tag{4}$$

where H (m) is the height of the tower, h (m) is the height of the window, and z (m) is the position of observation.

Model of the interactions

The size of the droplet radius depends on the velocity that affects it. In the principle of continuity, the greater the rate, the smaller the radius. On the other hand, the temperature of the water that exits the nozzle also influences the droplet surface tension. Surface tension is directly proportional to the radius. From these two relationships, this study formulated the droplet radius R (m) [9, 10] as:

$$R \leq 2.3 \frac{\sigma}{\rho_a u^2} \tag{5}$$

where σ (N/m) is the water surface tension.

From the relationship in Equation (5), this study gained a range of radius values. This study achieved the minimum radius when the air velocity that moves upward and holds the droplet falling is maximal [4]. Whereas the maximum radius received is based on the speed of the droplet falling relative to the average velocity of the air upwards [10].

In line with the principle of flow is a droplet with a large radius that has a large surface area as well, so that the drag force caused by the airflow is also getting larger. As a result, air will carry the droplet out of the tower in the form of mass transfer because the droplet is still in the liquid phase. This study can see the range of droplet radius values, as shown in Figure 2.

Droplet velocity is much higher than air velocity, even when compared to the maximum speed [14, 15]. It is due to the effect of spraying on the nozzle, which causes high droplet velocity. Therefore, the possibility of droplet radius distribution is dominated by droplet velocity, as shown in Figure 3. From the distribution, the average value of the droplet radius is one-quarter [7] of its range, to make it easier.

The number of droplets N_d (dimensionless) that exit in the spraying process depends on the water capacity, velocity, and diameter [4, 10] as:

$$N_d(z) = \frac{3Q_w}{4\rho_w \pi R(z) v(z)} \tag{6}$$

where ρ_w (kg/m^3) is the liquid water density, $R(z)$ (m) is the droplet radius, and $v(z)$ (m/s) is velocity along the z-axis.

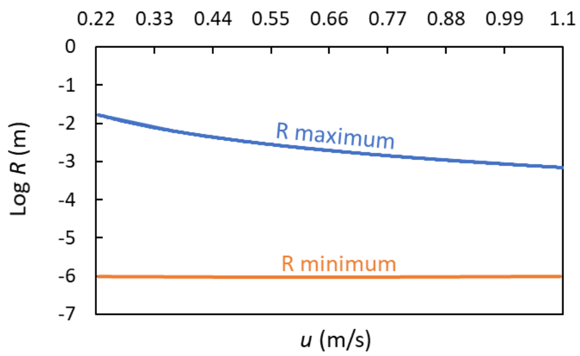

Figure 2: Droplet radius range values versus average air velocity.

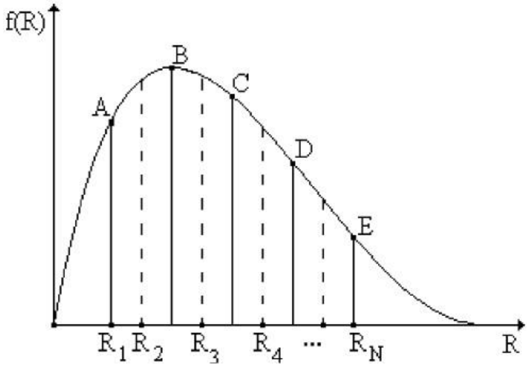

Figure 3: Probability distribution of droplet radius.

Some constants are related to fluid flow as follows: The Reynolds number Re (dimensionless), the heat exchange coefficient Nu (dimensionless), the mass exchange coefficient γ (m/s), and the drag coefficient C_d (dimensionless) as shown in Equation (7), Equation (8), Equation (9), and Equation (10), respectively [14, 15].

$$\mathrm{Re} = \frac{2\rho_a R(z)\left[v(z) - u(z)\right]}{\mu_a} \tag{7}$$

$$Nu = 2 + 0.5\,\mathrm{Re}^{0.5} \tag{8}$$

$$\gamma = \frac{D\left(2 + 0.5\,\mathrm{Re}^{0.5}\right)}{2R(z)} \tag{9}$$

$$C_d = \frac{24}{\mathrm{Re}}\left(1 + \frac{\mathrm{Re}^{2/3}}{6}\right) \tag{10}$$

where D (m^2/s) is the coefficient of diffusion for water vapor and μ_a (kg/m.s) is the air dynamic viscosity.

Then, the mathematical model that calculates interactions between water and airin the form of changes in droplet radius $R(z)$ (m), droplet fall velocity $v(z)$ (m/s), droplet temperature $T_w(z)$ (K), air temperature $T_a(z)$ (K), and droplet density $\rho(z)$ (kg/m^3) along the z-axis is presented by Equation

(11), Equation (12), Equation (13), Equation (14), and Equation (15), respectively [15, 16].

$$\frac{dR(z)}{dz} = -\frac{h_m\left[\rho_s\left(T_w(z)\right) - \rho(z)\right]}{\rho_w v(z)} \tag{11}$$

$$\frac{dv(z)}{dz} = \frac{g}{v(z)} - C_d \frac{\rho_a\left[v(z) - u(z)\right]^2}{2v(z)} \frac{\pi R(z)^2}{m} \tag{12}$$

$$\frac{dT_w(z)}{dz} = \frac{3\left\{h\left[T_a(z) - T_w(z)\right] - h_m\left[r - c_w T_w(z)\right]\left[\rho_s\left(T_w(z)\right) - \rho(z)\right]\right\}}{c_w \rho_w R(z) v(z)} \tag{13}$$

$$\frac{dT_a(z)}{dz} = \frac{4\pi}{\rho_a c_a} \frac{R(z) N_d(z)}{v(z) - u(z)} h\left[T_w(z) - T_a(z)\right] \tag{14}$$

$$\frac{d\rho(z)}{dz} = -4\pi \frac{R(z)^2 N_d(z)}{v(z) - u(z)} h_m\left[\rho_s\left(T_w(z)\right) - \rho(z)\right] \tag{15}$$

where ρ_s (kg/m^3) is the saturated water vapor density, c_w (J/kg.K) is the water specific heat, c_a (J/kg.K) is the air specific heat, and r (J/kg) is the latent heat of vaporization.

From Equation (7) to Equation (15), they are not independent but depend on each other. Therefore, to start the calculation needed boundary conditions in the form of initial values as also applied by researcher such as Fisenko and Brin [6] in their study in the simulation of a cross-flow cooling tower performance. The following are the initial values for each parameter but, keep in mind that the position $z = 0$ for water and air is different because this cooling tower is of counter flow type.

At $z = 0$ (the point of water exits the nozzles), the droplet radius:

$$R\big|_{z=0} = R_0 \tag{16}$$

the droplet velocity:

$$v\big|_{z=0} = v_0 \tag{17}$$

the droplet temperature:

$$T_w\big|_{z=0} = T_{w0} \tag{18}$$

At $z = H$ (the point of air enters the windows), the air temperature:

$$T_a\big|_{z=H} = T_{a0} \tag{19}$$

the water vapor density:

$$\rho\big|_{z=H} = \rho_0 \tag{20}$$

with these initial value definitions, this study formed a nonlinear boundary-value problem system fromordinary differential equations, which are Equation (11) to Equation (15).

The last thing to count is the performance of the cooling tower in the form of efficiency. As previously identified, the limitation of the system is the ambient air temperature entering it in the form of atmospheric temperature or temperature limit $T_{\lim}$. The efficiency η as mentioned, around 40%, by Brin and Petruchik [2] such as:

$$\eta = \frac{T_{w0} - T_{wf}}{T_{w0} - T_{\lim}} \tag{21}$$

where T_{wf} is the water average temperature in the water basin. This study also used the temperature limit to calculate air humidity in a cooling tower [2, 15] as:

$$\rho_s\left(T_a\right)\cdot\psi = \rho_s\left(T_{\lim}\right) \tag{22}$$

where ψ is the air relative humidity.

Results and discussions

This study presented cooling tower dimensions in the experiment, as shown in Table 1. The water capacity and fan rotation are varied to obtain variations in droplet and air velocities. Also, this study have determined the load calculated based on previous studies: 0.5 Lpm (minimum), 6.0 Lpm (equilibrium), and 18 Lpm (maximum).

Table 1: The cooling tower dimensions

Dimensions	Value	Units
Tower height (H)	0.56	meter (m)
Bottom diameter (L)	0.65	meter (m)
Windows height (h)	0.20	meter (m)
Fan diameter (d_f)	8.0	inch (in)
Nozzle diameter (d_n)	0.001	meter (m)
Water capacity	0.5 – 18	Liter per minute (Lpm)
Fan rotation	300 – 1500	rotation per minute (rpm)

Changes in the droplet radius, as shown in Figure 4, undergo the highest decrease for the lowest capacity. Even though, from the count, the smallest load has the largest radius. This statement is in line with Fisenko and Brin [6]. The same thing is also presented by the graphs of the change in velocity droplet, as shown in Figure 5, where the lowest capacity also has the tallest velocity change, while the initial velocity is the lowest.

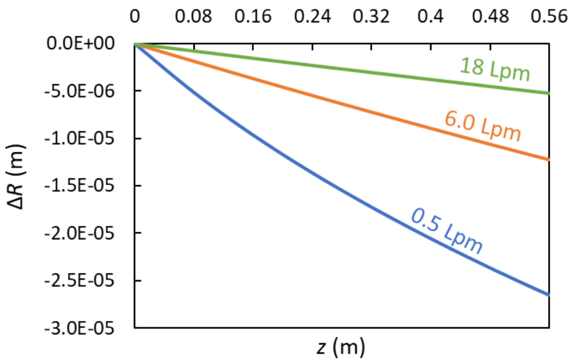

Figure 4: Droplet radius changes along its vertical trajectory.

Low water capacity has little momentum that airflow may carry some of the water in the form of a liquid phase because this is a counterflow. This study observed this reduction through the graphs of changes in vapor density in Figure 6. It appears that the lowest capacity has the highest reduction in the mass of the droplet while crossing the airflow. Because low water capacity has a low water mass, reduction of airflow causes significant mass loss so that the density of low water capacity drops to a low value.

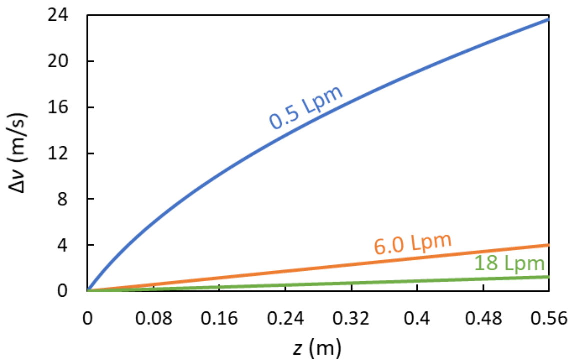

Figure 5: Changes in velocity of falling droplets along its trajectory.

Whereas for high capacity graphs, both 6.0 Lpm and 18 Lpm in Figure 6, the vapor density tends to remain. It indicates a mass reduction at high capacity relatively small. Since a high-water capacity has a high-water mass, the reduction in airflow has little effect on it so that the density graph remains high.

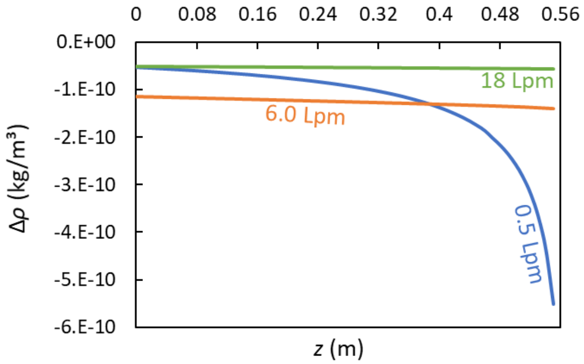

Figure 6: Reduction of vapor density along the droplet trajectory.

The highest droplet temperature reduction is achieved by the lowest capacity, as shown in Figure 7. Similarly, the highest increase in air temperature is also given by it, as illustrated in Figure 8. Both temperatures are the result of interactions within the tower.

High water capacity carries high mass water flow so that, with the same tower volume, it provides higher density, which causes lower temperature changes. With the same airflow capacity, it produces lower air temperature enhancements, as seen in Figure 8.

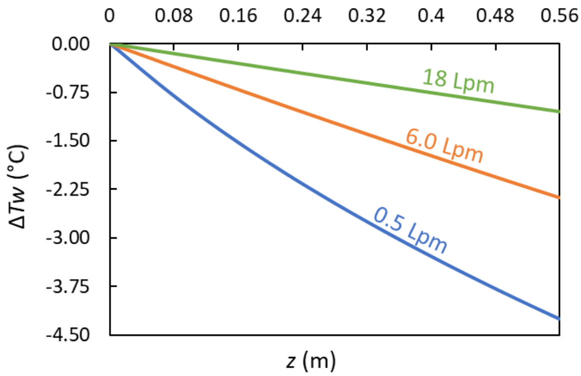

Figure 7: Decreased droplet temperature along its trajectory.

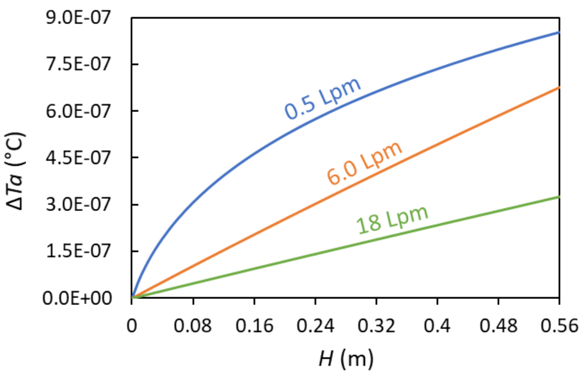

Figure 8: Increased air temperature along the tower height.

The same thing with air temperature is indicated by relative humidity, as shown in Figure 9. Humidity increases indicating that the water content in the air also increases. The lowest water capacity has the highest difference in humidity. It is in line with the highest water mass reduction experienced by the low water capacity, which causes a difference in the highest humidity. Also, it is in line with Calderon et al. [5] and Fisenko et al. [9].

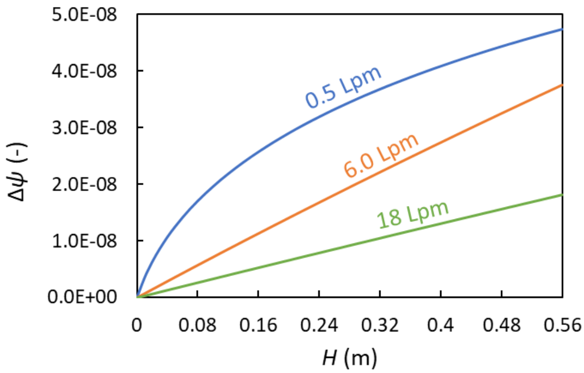

Figure 9: Increased relative humidity along the tower height.

Variations in fan rotation provide variations in the velocity of air across the tower. Figure 10 describes the variation in the form of it along with the tower height. When the fan sucked it in, the air has a horizontal velocity direction, then changes to a vertical direction when it reaches the tower roof so that the air velocity becomes very high when it exits the tower.

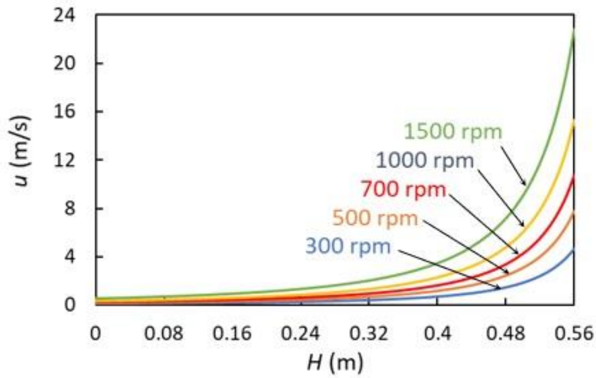

Figure 10: Air velocity along with tower height.

This study reflected the evaporation process in the performance graphs, as presented in Figure 11. From this graph, the highest capacity has the highest efficiency, which means that the heat transfer process occurs most efficiently at it. A high mass flow rate of water accelerates the distribution of droplets to move heat into the air. Conversely, a low water mass flow rate causes a high-water mass loss. It inhibits the droplet evaporation process and reduces efficiency. This statement is in line with Brin and Petruchik [2].

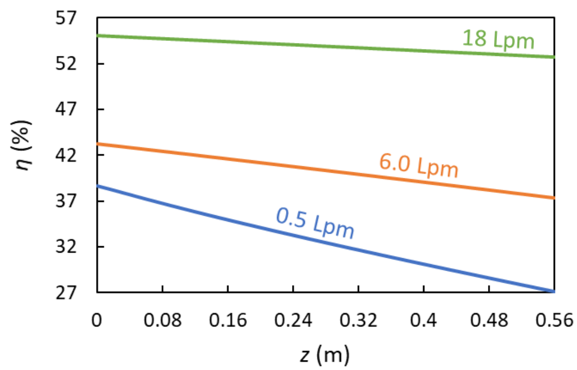

Figure 11: The cooling tower efficiency along the droplet trajectory depends on the water capacity.

Conclusions

The lowest water capacity produces the most substantial changes in droplet radius, velocity, density, and temperature, but it generates the smallest performance. It means the highest losses in the form of drifting for the droplet mass, which is still in a liquid phase. The air velocity reaches its maximum when it exits the tower, as well as its temperature and humidity.

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