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Increasing the thermal performance of cooling tower by utilizing swirling jets

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ABSTRACT

Cooling towers are generally utilized in heating, ventilation, and air conditioning systems, electric power plants and manufacturing applications. The main problem for cooling towers is evaporation loss. The evaporation loss is decreased with utilizing fans, drift eliminators for more water saving. This work is mainly focused numerical analysis of cooling tower for reducing evaporation loss and increase the efficiency of the tower by utilizing two crosswise swirling jets that reduce the inlet hot water temperature in the outlet of the cylindrical channel to the not harmful to ambient conditions temperature. The model is computed for various parameters; air inlet temperatures (10, 22, 32, 40 °C) and Reynolds number for jets inlet velocities (Re= 3900, 5200, 7800, 8500). This model was studied numerically by utilizing ANSYS Fluent CFD software. In this work, it is achieved that increasing Reynolds number causes an increase on evaporation loss. The higher air inlet temperature causes higher evaporation loss. When the air inlet temperatures are reduced from 40 °C to 10 °C, the evaporation loss is decreased as 62% and 81%, respectively. When Reynolds number is decreased from 8500 to 3900, the evaporation loss decreased as 30%. By utilizing this new design, the outlet water temperature could be reduced of 19 °C. Moreover, the numerical findings were validated by some researches available in the literature.

1. Introduction

Cooling towers are widely used for heat rejection into the atmosphere. Cooling towers used in HVAC system, for cooling the process hot water in manufacturing, electric power plant for cooling the condenser and chemical plants. Heat rejection of the tower is accomplished with evaporation air and hot water or steam. In cooling towers, water evaporates due to content of the moisture in air which occurs when the air is fewer than saturated of the water temperature. Hereby, energy transfer occurs among water and air so water cools and air become hot. Cooling towers are designed and manufactured in various types for specific condition such as ambient wet bulb temperature, intended temperature and flow rates. So, we can classify cooling towers with heat transfer method, build, air draft and air flow pattern. There are two types of cooling tower considering to heat transfer method, dry and wet systems. Wet cooling tower, most commonly using tower which operated with principle of evaporation for cooling the hot water or steam. The hot fluid is cooled with ambient air that comes to the cooling tower. Dry cooling tower has a closed-circuit system which separates the air and hot

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water or steam. This pipe system protected the cooled water from environment. Evaporation does not occur between the air and hot water. There are three types of cooling towers depends on air draft. The atmospheric type of towers very cost effective and very inefficient. There is no mechanical work for driving to air. Natural draft cooling tower shape is hyperbolic structure and natural air flow is accomplished cooling with using own hyperbolic structure. The air inflow into the tower is a result of the density difference between hot and air inside the cooling tower. Mechanical cooling towers are used forced draft and induced draft fan. Forced draft fan blow the air into the cooling tower and it is located beside of the cooling tower. The fan is in outside of the cooling tower so in cold weather condition freezing may occur in fan. The inlet air velocity is higher than outlet air velocity. Induced draft fan is located on the cooling tower so the fan is absorbed to air vapor mixture to the atmosphere from into the cooling tower. The outlet air velocity is higher than air inlet velocity. There are two types cooling tower based on air flow. Cross-flow tower the direction of air flow is upright to the water flow direction. Thus, the cooling tower has a fill design to allow cross flow at the inlet side of the air. Counter-flow tower the direction of water is vertically downward to bottom and air flow is vertically upward through. It needs more fan power because the fill design causes pressure loss. In large capacity, cooling tower pressure loss can be decrease by increasing surface area.

There are some researches about cooling tower to estimate the evaporation loss and effectiveness. Merkel [1] presented the thermal calculations of cooling towers in 1925. Merkel made three assumptions in calculation. These are: The Lewis factor is equal to 1. The outlet of air is saturated with water vapor and it is designated only enthalpy. The decline of water level by evaporation is unheeded in the energy balance. In Merkel method is very accurate and simplicity when calculating the outlet temperature of air and heat rejection if the outlet air is supersaturated with water vapor. Jaber and Webb [2] developed NTU effectiveness method for cooling tower. E-NTU are completely logical with the fundamental definitions used in heat exchanger design. Using the definitions, can be analyzed easily heat exchanger and also cooling tower in counterflow, crossflow forms. Poppe and Rögener [3] investigated the Poppe model for cooling tower calculation. This model more accurate when calculating Merkel number because Poppe model is considered the assumption which is not considered by Merkel. They obtained if the outlet water temperature is significant, the less accurate Merkel and e-NTU methods can be used. Poppe method can predict lower outlet water temperature under warm dry ambient situations. Kloppers and Kröger [4] investigated the differences between the Merkel, Poppe, and e-NTU methods. They expanded Poppe method equations give detailed representation of the Merkel number. They obtained pope method is convenient for analyzing in cooling tower as the case of the outlet air is accurately decided. And also [5] investigated the Lewis factor effecting on the performance estimate of the cooling tower fill performance using Lewis factor. The Poppe method is considered in heat and mass transfer analysis. They obtained to increasing Lewis factors, the heat rejection rate increases, the water outlet temperature decreases and the water evaporation rate decreases. Wang et al. [6] easily calculated the analytical solution of outlet water temperature, for calculate performance, the assumption is the enthalpy of the saturated air is a linear function of the water surface temperature on the counter flow wet cooling towers. Yılmaz [7] obtained an analytical method and compared with LMED and corrected LMED method in inlet and outlet temperatures for water between 10-90 ºC and for different cooling ranges between 4 and 16 ºC. Mansour et al. [8] developed an innovative correlation employing the basic laws of mass and energy balance contact with the heat and mass transfer equations for e-NTU of cooling towers. Those new correlations showed that deviation less than 10%. The advantages of NEM correlations are easily use simple calculation of input parameters and help to optimization of cooling tower when it is working. Deziani et al. [9] developed a system which reduces the evaporation loss in cooling tower by using an air heat exchanger with fan that the minimum dry bulb temperature difference between inlet air and outlet air was reduced to 3 °C so, using this model could be save water about 35% evaporation. Ayoub et al. [10] are worked thermodynamic flow equation for describe the heat and mass transfer for analyzing cost occurs in wet type cooling tower. The purpose of the model is to predict the effects of excessive air conditions on cooling tower efficiency. They showed that considerable efficiency drops could be expected at high ambient temperature and humidity, with a smaller but important effect of the makeup water temperatures. Smrekar et al. [11] showed how the efficiency of a cooling tower can be develop by optimizing the heat transfer along the cooling tower packing using a suitable water distribution from inside the plane area of the cooling tower. They obtained mathematical model which gives optimization of the cooling tower performance regulating a fan power to changing ambient conditions. The mass flow rate of air can be adjusted by remote control robot unit in induced draft due to hot fluid temperature through cooling tower and also the outlet temperature is decrease that is increase the efficiency.

Fisenko et al. [12] developed a model for the differential equation system indicating the boundaryvalue problem, describing a change in the velocity, radius and temperature of the droplets, and a change in the temperature and density of the water vapor in the cooling tower. By means of this model, the cooling tower performance can be set of the fan power. Gao et al. [13] found temperature difference and efficiency can be increased by cross wind condition comparison to windless condition in experiment. When the Froud number increase to 0.174 by increasing crosswind condition. In experimental results, it is obtained that temperature difference and efficiency are affected by the cross-wind, and temperature difference and efficiency can reduce by 6% and 5%. Hajidavalloo et al. [14] they are used to conventional mathematical model for see thermal behavior of cooling tower with cross flow at variable wet bulb temperatures. They investigated when the wet bulb temperature increases, the evaporation loss can increase. They obtained the evaporation rate is increased when the dry bulb temperature increases and the increasing rate is almost constant at different wet bulb temperatures. Also, impact separator can be used for decrease the number of suspended solids in the air without evaporation loss in the cooling tower performance. Lu et al. [15] used swirling plume method which increase the overall tower updraft capacity in dry and wet cooling towers. In CFD analysis they found that cooling tower temperature decrease when using swirling plume driven by fan blower. They analyzed 20 m height and 12 m diameter wet cooling tower with swirling plume which improve the air flow rate and the decreased cooling water temperature by at minimum 53.6% and 3.57 °C (39.3%). Rahmati et al. [16] investigated experimentally when changing parameter of cooling tower such as hot water temperature, water flow rate and air flow rate how affect the thermal performance of cooling tower. They showed the efficiency is concerned with air mass flow rate, hot water temperature. They obtained to cooling tower performance can be increased by lower water flow rate and higher values of hot water temperature and air mass flow rate. Klimanek et al. [17] examined the cooling tower with flue gas under wind conditions. They showed the effect of increased air flow on leaving water temperature. They worked with ANSYS CFD model. It has also been shown that, under high wind conditions, the centrally introduced flue gas can flow close to the tower shell due to the inflow of cold air and the bending of the gas flow. Therefore, the risk of wear of the tower shell may increase and a corrosion-resistant layer is required in the cooling tower. Li et al. [18] they are subjected to air flows at the top of the cooling tower and this flow poorly effected to cooling tower performance. In experiment outlet water temperature is can be increase up to 3℃ due to incursion of air flow to the cooling tower. So, inlet air temperature can be carefully select in designing for small cooling tower. Imani-Mofrad et al. [19] experimentally investigated cooling tower performance using four Nano fluids including ZnO-H2O, SiO2-H2O, Al2O3-H20 and graphene-water as process fluid. In experiment they are used Nano fluid separately and find parameters such as effectiveness and evaporation rate. Finally, after experiments they obtained graphene-water Nano fluid parameters provided the best thermal performance. Mahmud et al. [20] studied experimentally about the direct contact cross flow cooling tower for different air and water velocities how effect on cooling capacity, effectiveness and evaporation loss. They worked about six air velocity and three water velocity. As a result, when the increasing air velocity, effectiveness is increase also evaporation loss is increase. In low water velocity effectiveness is high.

The literature suggests that there are many researches about cooling tower performance calculation method such as Merkel, Poppe and effectiveness-NTU methods. According to literature, applying Merkel and effectiveness -NTU methods assumed to assumptions which occurs simple calculation in analysis. Poppe method there is no assumptions so it is very accurate but in calculation is relatively more complex than the Merkel and e-NTU methods. Also, researcher studied to how to decrease evaporation loss in cooling tower by using some configurations in system.

Different from the literature, present study is mainly focused on numerical analysis of a new cooling system which works as a cooling tower for decreasing evaporation loss and increase the efficiency of the tower by using two crosswise swirling jets to decrease the inlet temperature of hot water and also to prevent thermal pollution to the environment. The cooling of the hot water is provided by using direct contact cooling method with two swirling jets which increase the contact surface area between water and air. Swirling jets was chosen to take advantage of both mechanical and thermal effects. The model is calculated for different parameters; Reynolds number for jets inlet velocities (Re= 3900, 5200, 7800, 8500) and air inlet temperatures (10℃, 22℃, 32℃, 40℃). This model was studied numerically and by using ANSYS Fluent Computational Fluid Dynamic program. By using this model, the outlet water temperature was reduced by 19℃ and the effectiveness is also increased 21% when compared to the experimental studies of Smrekar et al. [11]. Also, the numerical results were validated by some studies in the literature.

2. Numerical Model and Data Reduction

The study is mainly focused on numerical research of cooling tower performance using swirling jet for decrease of outlet air-vapor mixture and condensed water temperature, and evaporation loss. The model has an 80 mm radius and a 240 mm length. Two swirling jets are placed opposite to each other. The hydraulic diameters of the rotating jets are 0.016 mm. In this numerical analysis, the k-ε turbulence model of ANSYS Fluent computational fluid dynamics package program was used. The inlet velocity of air is in turbulence region and the k-ε turbulence model was chosen because it gives better results in these ranges for confined jet flows. The geometry of the numerically examined model is shown in Figure 1.

The aim of the experiment is to decrease the evaporation loss with using swirling jet that provide to obtain more cooling, compared to mechanical draft fans in cooling tower and saving the water in the system. There are three method in analyzing cooling tower these are; merkel, poppe, and e-NTU methods. In the present study, calculations were made by using e-NTU method. This model provides simple and precise results in cross flow and counter flow models. This model can be used in cooling tower calculations as well as in heat exchangers.

In analyzing of cooling tower, we applied to dry air, water mass balance and energy balance for find to air mass flow rate [21];

Dry mass balance:

$$m_{inlet\ air} = m_{outlet\ air} \quad (1)$$

Water mass balance:

$$m_{steam} + m_{inlet\ air}\omega_{inlet} = m_{condensed\ water} + m_{outlet\ air}\omega_{outlet} \quad (2)$$

Energy equation:

$$\sum_{in} mh = \sum_{out} mh \quad (3)$$

So, the equations give the mass flow rate of air:

$$m_{air} = \frac{m_w(h_{inlet\ water} - h_{outlet\ water})}{(h_{inlet\ air} - h_{oulet\ water}) - (\omega_{inw} - \omega_{outw})h_{outlet\ water}} \quad (4)$$

Where ω is the humidity ratio find from psychometric chart or correlation formulas. Enthalpy of dry air and water also find correlation formulas show in below [22]:

$$\omega = \frac{1.00416(T - T_{wb})}{[2501.6 - 1.8577(T - 273.15) - 4.184(T_{wb} - 273.15)]} \quad (5)$$

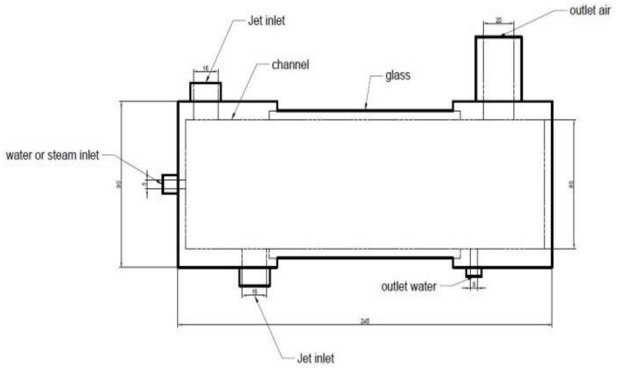

Figure 1. Analysis domain of cooling tower

The enthalpy of air inlet and outlet temperature evaluated by using below formula:

$$h = c_p T_w + \omega(h_{fgw} + c_p T_w) \quad (6)$$

Humidity ratio is also calculated inlet and outlet condition from this formula is;

$$\omega = \frac{0.622P_v}{P - P_v} \quad (7)$$

P is the atmospheric pressure and Pv is the calculated from relative humidity and saturation pressure of air inlet and outlet temperature which shown in below equation:

$$P_v = \phi P \quad (8)$$

$$\phi = \frac{\omega P}{(0.622 + \omega)Pg} \quad (9)$$

The makeup water represents the how much water is evaporated in cooling tower. Also, makeup water is equal to evaporation loss. The makeup water is found with a formula showed below:

$$m_{make\ up} = m_{air}(\omega_1 + \omega_2) \quad (10)$$

Using these equations, we can find how much required air flow rate come through from cooling system to obtain outlet temperature. For finding effectiveness of cooling tower need to evaluate the heat transfer rate Qmax and Qactual that is calculated from this equation given below:

$$Q_{actual} = m_w cp_w (T_{wi} - T_{wo}) \quad (11)$$

To find the Qmax , evaluate the correction factor λ for improving the accuracy of the enthalpy of air regarding to water temperature from using the equation given below:

$$\lambda = \frac{(h_{maswo} + h_{maswi} - 2h_{maswm})}{4} \quad (12)$$

The correction factor used to obtain Qmax is defined as:

$$Q_{max} = C_{emin}(h_{maswi} - \lambda - h_{mai}) \quad (13)$$

Following these equations, we can find effectiveness calculated from this equation given below:

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \quad (14)$$

Finally, we obtain the effectiveness-NTU equation for cooling tower. This equation is given below:

$$\varepsilon = \frac{1 - exp\,[-NTU(1 - C_e)]}{1 - C_e exp\,[-NTU(1 - C_e)]} \quad (15)$$

So, Evaporation loss is equals to;

$$Evaporation\ loss = \frac{m_{air}(h_{outlet\ air} - h_{inlet\ air})}{hr} \quad (16)$$

Boundary conditions used at this study are shown below;

Table 1. Boundary conditions

	U (m/s)	V (m/s)	W (m/s)	T (K)	K (J/kg)	E (J/kg.s)
Inlet	$U = 0$	$V = -V_i$	$W = 0$	$T = T_i$	$(T_i w_{jet})^2$	$(C_\mu C_d)^{3/4} k^3 / L$
Wall	$U = 0$	$V = 0$	$W = 0$	$q'' = 0$	$k = 0$	$\partial\varepsilon/\partial z = 0$
Outlet	$\partial U/\partial z = 0$	$\partial V/\partial z = 0$	$\partial W/\partial z = 0$	$\partial T/\partial z = 0$	$\partial k/\partial z = 0$	$\partial\varepsilon/\partial z = 0$

2.1 Verification of Numerical Results

In this numerical analysis, the k-ε turbulence model of ANSYS Fluent computational fluid dynamics program was used. 130973 mesh was used in the modeling study. In the inflation process, smooth transition model was applied. In the modeling, the number of mesh in the jet and water inlets was increased.

3. Results and Discussion

In this study; effect of jet velocities on evaporation loss and efficiency values at different Reynold numbers (Re = 3900, 5200, 7800, 8500) and different air inlet temperatures (10 °C, 22 °C, 32 °C, 40 °C) were investigated numerically. Efficiency-NTU method was used as it was more practical in the calculations.

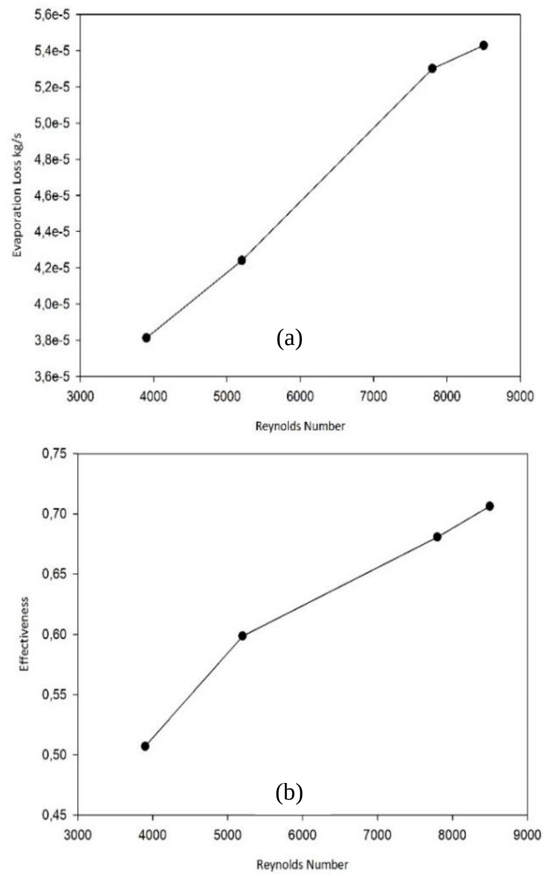

Figure 2. Effects of Reynolds numbers on a) evaporation loss and b) on effectiveness of cooling system

3.1 Effect of Different Reynold Numbers (Re = 3900, 5200, 7800, 8500) On Evaporation Loss and Efficiency

Increase in Reynolds number causes an increase on evaporation loss. Because high jet velocities can take away of more water vapor. For designing a system, air velocity should be selected to decrease evaporation loss. It was found that evaporation loss decreased by 30% when Reynold number decreased from 8500 to 3900 and which decreased by 28.5% of the effectiveness of the cooling system. Figure 2 shows the effect of the Reynolds number on evaporations loss and effectiveness. Temperature contours and streamlines for different Reynolds numbers (Re=3900, 5200, 7800, 8500) are shown in Figure 3.

3.2 Effect of different air inlet temperatures on evaporation loss and efficiency

Increasing the air inlet temperature causes and increase on evaporation loss. The reason is that the water holding capacity of air increases with increasing air temperature. Because of environmental conditions, temperature of air inlet is selected in 10°C, 22°C, 32°C, 40°C. In this model, evaporation loss decreased by 62% when the air temperature was decreased from 40 °C to 10 °C and when increasing the air inlet temperature from 10 °C to 40 °C, the effectiveness decreases of 62.3%. Result are shown in Figure 4.

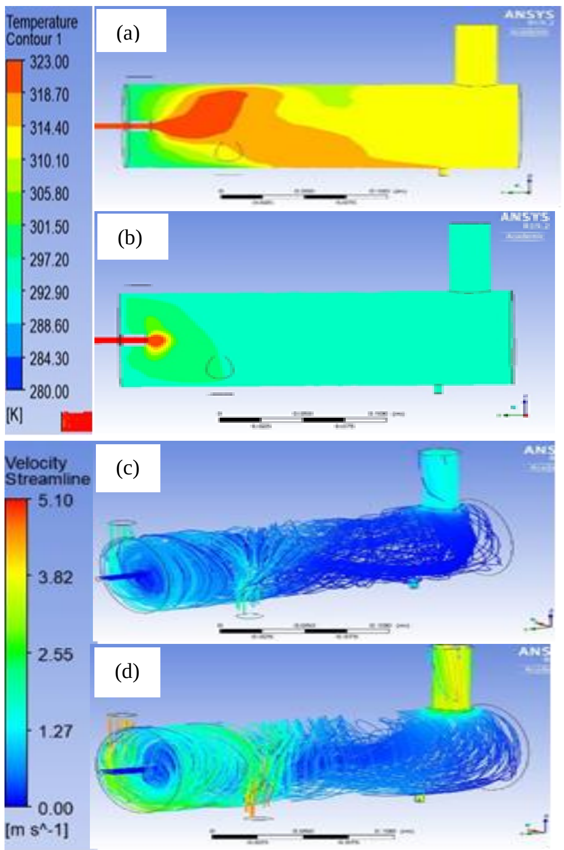

Figure 3. Temperature contours at 22 °C air temperature at different Reynolds numbers a) 3900 b) 8500 and air flow streamlines c) 3900 d) 8500

Temperature contours and streamlines for different inlet temperature ($T_{airinlet}$= 10°C and 40°C) are shown in Figure 5.

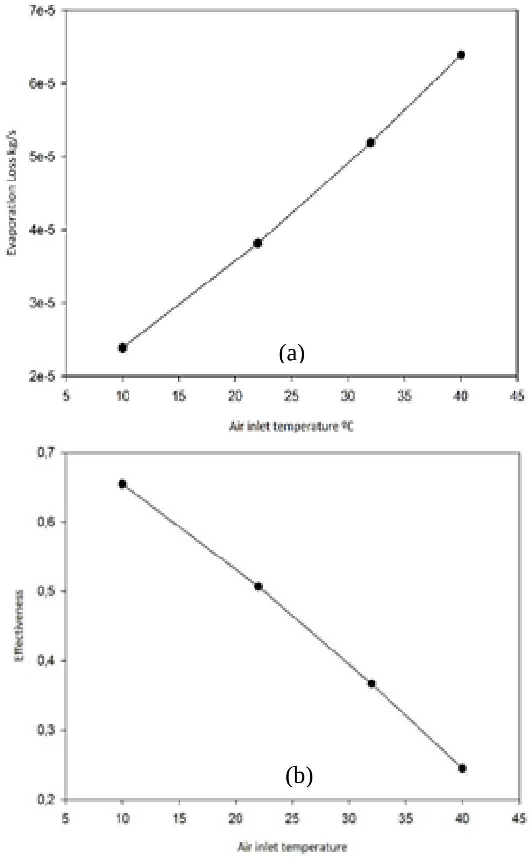

Figure 4. Changing evaporation loss a) and effectiveness b) of cooling system on different air inlet temperature

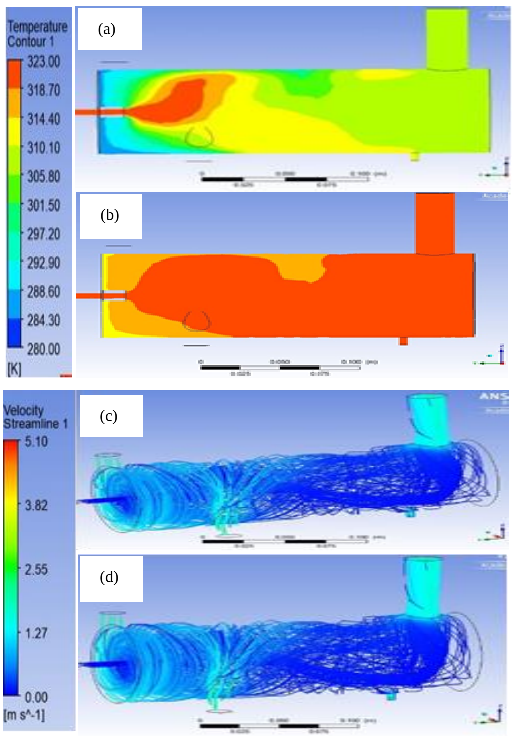

Figure 5. Temperature contour a) 10°C, b) 40°C and streamlines c) 10°C, d) 40°C for Re= 5200

4. Conclusions

This study is mainly focused on the numerical investigation of evaporation loss and effectiveness of a new type cooling tower. The e-NTU method is used for calculation of these. The different parameters were used in numerical study. Our model is validated using reference solution. The evaporation loss is depended on the wet bulb temperature and outlet temperature. The mass flow rates are not affected to effectiveness and NTU number. The ANSYS FLUENT analyzed results specify the numerical calculations are the same for outlet temperatures in different parameters. Increasing the air inlet temperature causes an increase on evaporation loss. When decreasing the air inlet temperature from 40 °C to 10 °C, the evaporation loss is decreased about 62% and when increasing the air inlet temperature from 10 °C to 40 °C, the effectiveness decreases of 62,3%. The increasing Reynolds number causes an increase on evaporation loss and effectiveness of the system. Because the more air velocity can take away more mass flow rate of water vapor and water. When Reynolds number is decreased from 8500 to 3900, the evaporation loss decreased of 30%. But it also causes a decreased of 28.5% on cooling effectiveness of the system. When the results were compared with the experiment results of Smrekar et al. [11], by using this new cooling system, the effectiveness of the system can be increased of 20%. Results of this study and numerical model, which we used, can be used in many areas such as space requirements, electric power plant, aerospace application and industrial application.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

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Nomenclature

c_p : Specific heat at constant pressure (J/kgK)
h : Heat transfer coefficient (W/m^2K)
hd : Mass transfer coefficient (kg/m^2s)
h : Enthalpy (J/kg)
h_{fg} : Latent heat (J/kg)
k : Thermal conductivity (W/mK)
m : Mass flow rate (kg/s)
NTU : Number of transfer units (UA/C_{min})

P : Pressure (N/m^2)
Q : Heat transfer rate (W)
ω : Humidity ratio (kg water vapor / kg dry air)
Re : Reynolds number
λ : Correction factor (j/kg)
Φ : Relative humidity
ε : Effectiveness

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