Numerical Investigation of a Single Phase Air Flow inside Porous Media of a Cross Flow Cooling Tower

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Abstract: ***Cooling tower in the HVAC industry is used to reject heat from a system. The refrigeration cycle requires that the heat absorbed from a refrigerated space be rejected and this is done through the condenser where the water from the cooling tower exchanges heat so that it can be discharged by the cooling tower. It is essential that the performance of the cooling tower be improved so the refrigerant cycle can take place at its optimum.The paper explores the area in the cross-flow cooling tower where the focus on where the porous media or the fill / packing is located and the area in the vicinity for a single phase flow. The behavior of the air intake flow into the cooling tower from the side part through the fill will be observed and how it affects the distribution of the air flow inside the fill will be analyzed. The solution of the related governing equation for the basic flow and for flow involving porous media will be presented. It was revealed that the porosity introduced a high pressure drop inside the cooling tower. The pressure inside the cooling tower generally is lower that before the porous media was introduced. The results also revealed that if the heat transfer inside the porous media is to be improved, higher dynamic pressure inside the cooling tower is required which would result in higher fan power output.***

Keywords: cooling tower, porous media, cross flow cooling tower, CFD.

1. Introduction

A cooling tower in HVAC application is widely used. There are many types of cooling tower available. The forced draft cross flow and counter flow cooling tower are the most common ones used in HVAC application.

[1] A study by the North American Electric Reliability Council also estimated that cooling tower inefficiencies alone contributed to 5% waste of heat rate.Taking into account of other inefficiencies that might occur in the system apart from the cooling tower, it is important to address these weaknesses and allow more information to be generated about the cooling tower processes so this waste can be reduced.

The main function of a cooling tower is to reject heat from the chiller or compressor by transferring heat from the water as the medium. The increase of temperature of water as a result of heat transfer from the chiller operation will flow through the cooling tower. In the cooling tower, the warm water will be broken down into smaller droplets to allow better heat transfer process between the air and water by increasing the water surface area. The process of breaking down water into smaller droplets takes place inside the packing or fills which is a form of a porous media.

As the smaller droplets of water flow down the porous media, the air coming from the air inlet will interact with the warm water droplets where heat transfer will occur. The slightly cooled down water droplets will then flow down to be collected at the bottom of the cooling tower to be re circulated back into the system and the cycle continues [2].

In a cross flow cooling tower, the water inlet is located on the upper side of each porous media while the air inlet is at the outer side of the cooling tower. The air inlet will come into contact with the water in perpendicular direction to oneanother.

In normal operating condition, the heat transfer process that occurs inside the cooling tower involves multiphase between water and air. The study in this paper concentrates on the single phase of operating condition where only air is considered where the behavior of the fluid will be monitored and analyzed.

The governing equations that are used in the solutions of the porous media will be based on the general momentum equations where there will be a momentum source term added to represent a momentum sink which signifies pressure drop[3]. This solution will enable the air behavior inside the cooling tower to be determined and their properties examined.

In the interest of investigating the energy conservation and management of the cooling tower, several cooling tower model had been developed in the past 80 years. These models describe the relationships that exist between the parameters that are included and part and parcel of the principles of the heat and mass transfer.

Porous media is a simple heat transfer tools in which its ability to provide an environment for heat transfer process to take place can be difficult to analyze. The complexity of the processes and reactions inside the porous media depends on the working fluid and type of application.

There are many different types of porous media material available that are normally used in cooling tower application. All the various types differ in surface area per unit, pitch, spacing type of surface and type of corrugation. These specifications will affect the airflow in the fill as well as the state of the water that is flowing down from the top.

The heat transfer between the air and water will be affected by this. It has also been experimented and a value of factor to determine the performance of the packing (fill) has been developed as a result. From this factor, it was identified that the pressure drop and air flow rate will be inversely proportionate to the factor while the pack/fill volume and density will be directly proportionate[1].

2. Literature Review

A method to ascertain the thermal performance of a counter flow cooling tower was developed through experimental work. In this specific investigation, the thermal performance capacity of a wet cooling tower is studied focusing on the weather condition specifically the ambient wet bulb temperature.

The general governing equation of the analysis take into account the control volumes where the mass flow rate and dry air flow rate flow in a plane are. The mass balance for dry air and mass balance for water are incorporated into the energy balance to determine the heat transfer rate which is removed by the air from the warm water by sensible heat transfer which is due to a difference in temperature gradient.

The experiment was done using an induced draft counter flow cooling tower with one side of its wall is translucent which makes it possible to observe the condition and process inside. The inlet hot water temperature used remains constant throughout the procedure while the variation of flow for water and air were done.

Through the analysis of the experimental results the water evaporation and unsaturated air leaving the tower were able to be incorporated into the method to predict the characteristics of the induced draft wet cooling tower. [4]

In other research, clay bricks as the packing or fill material inside the cooling tower were studied for an induced draft cooling tower. In an experimental setup of the cooling tower, the burned clay bricks that were used as the fill material made up to 12 layers consisting each of 18 bricks of dimensions 235x120x64 mm with void fraction of 0.4.

The general heat and mass transfer relationships were used and applied in this investigation and the experimental result were presented graphically. The Reynolds number was influencing the heat and mass transfer coefficient which also affect the heat transfer coefficient.

The data revealed that as the water to air flow ratio was increased, the mass transfer coefficient increased. The mass transfer coefficient was found to be within an error of 10% from the developed relationship and new variables that were introduce to define the parameter settings. [5]

Another experimental study was done to the cooling tower to investigate the performance of a mechanical induced cooling tower with two different types of film packing. The vertical corrugated packing VCP and horizontal corrugated packing HCP were used to collect data and compared with previous work.

The determination of the characteristics of the cooling tower was the main objective of the study. The Merkel method was used to obtain the NTU value. From the NTU value, the overall mass transfer coefficient can be obtained as a function of the type of packing used, arrangement of the packing, water and air flow inside the cooling tower as well as the height of the tower.

The results of the experiment revealed that the use of HCP as the packing type resulted in lower water loss during the heat transfer process compared to VCP packing type. The higher performance was also recorded for the vertical corrugated type of packing compare do the horizontal corrugated type. [6]

According to another work done on a porous medium, the region of the porous media and the free fluid region are considered as being homogenous while the region that separates the two is considered a heterogenous region. It is also known as the inter-region between the porous medium and the free flow fluid region. The local thermal equilibrium LTE at the heterogenous region was investigated to determine the degree of assumptions made by performing the one domain approach.

In a one domain approach or the ODA, the homogenous and heterogeneous regions are considered to be a single continuum. The modeling is done in such a way that the generalized transfer equation GTE is valid on any point and contains position dependent effective coefficient.

The volume averaging technique was used to derive the macroscopic governing equations heat transfer in the porous media and the fluid region. Under the investigation two different modeling were done which are the local and non-local thermal equilibrium models. The aim is to obtain the coefficients related to both of the models by solving the associated closure problems. [7]

A horizontal porous layer saturated with liquid was subjected with a convective instability in another study. The Darcy Benard problem is specifically referring to the porous layer which has two horizontal boundary walls that are impermeable and conducting.

This allows heat transfer from the external boundary walls and creates a temperature difference. Such temperature difference creates an unstable thermal flow in the porous layer or medium. Such disturbances are of interest in research especially when it involves contaminant transport specifically in the exploit of geothermal reservoir.

According to another research, the effect of viscous dissipation and the mass diffusion which is caused by the applied thermal gradient will affect the convective instability.The numerically solved disturbances equations by using RungeKutta of the 6th order were done and the first order perturbation method was done analytically to further identify the mass transfer and viscous dissipation contribution to the convective instability. [8]

In another porous media study, a partially porous medium was investigated in depth-averaged turbulent heat and fluid flow in a channel. In this particular study the porosity is referred to as vegetation porosity. The density and vegetation porosity were set at the domain inner channel which was then extended to the boundary porosity near the surface. Three different vegetation porosityarrangements were used. From numerical analysis the heat and fluid flow in a non-flexible vegetated porous media was simulated.

In one of the result observed, there is a region downstream of the vegetated porous media where the turbulence of the kinematic energy was found to below when the channel is partially vegetated. This means that when the magnitude of the turbulence kinematic energy is small enough it cannot be applied to a high Reynolds number model. It was concluded that the choice for suitable turbulence model will depend on the turbulence strength in the main channel, the vegetated porous region and the zone downstream from the vegetated porous medium.

The study also managed to develop a model to take into account the vegetation porous media material effect on the heat flux through the walls where numerical simulations were done to study the effect of porosity-induced heat flux and thermal dispersion near the vegetated porous media was done. [9]

3. Methodology

The solutions of the single phase flow inside the cooling tower will be obtained from the numerical derivation through CFD solver. The following section outlines the principle governing equations that will be used in this paper.

3.1 Governing Equations

The more familiar Navier-Stokes Equations are combinations of the following basic governing equations [10] which were manipulated in accordance to the specific properties or spatial requirements of case.

Continuity:

$$\frac{\partial \rho}{\partial t} + div(\rho u) = 0 \qquad (1)$$

X-momentum:

$$\frac{\partial(\rho u)}{\partial t} + div(\rho u \boldsymbol{U}) = \frac{\partial p}{\partial x} + div(\mu grad u) + S_{Mx}(2)$$

Y-momentum:

$$\frac{\partial(\rho v)}{\partial t} + div(\rho v \boldsymbol{U}) = \frac{\partial p}{\partial y} + div(\mu \, grad \, v) + S_{My}(3)$$

Z-momentum:

$$\frac{\partial(\rho w)}{\partial t} + div(\rho w \boldsymbol{U}) = \frac{\partial p}{\partial z} + div(\mu \, grad \, w) + S_{Mz}(4)$$

Energy:

$$\frac{\partial(\rho i)}{\partial t} + div(\rho i \boldsymbol{U}) = -p \, div \, u + div(k \, grad \, T) + \phi + \boldsymbol{S_i}(5)$$

The focus of the paper lies on the porous media in the cooling tower where the governing equation is different from the ones applied in the basic flow. The porous media model used in the simulation [3] is simply a momentum sink of the general momentum equations.

$$S_i = -(\sum_{j=1}^{3} D \, \mu \, \rho|v|v_j) + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho|v|v_j)(6)$$

The equation above is the momentum source term that is added to the standard fluid flow equations which is consisting of the viscous loss term (Darcy, the first term on the right hand-side) and the inertial loss term.

The pressure drop is proportional to the velocity and the constant C2 can be assumed to be zero when a laminar flow is considered in a porous media. The porous media model would then be simplified to Darcy's Law.

$$\nabla p = -\frac{\mu}{\alpha} \vec{V} \qquad (7)$$

However, at high flow velocities, the constant C2 is an inertial losses correction factor which can be viewed as a loss coefficient per unit length along the flow direction through the porous media where the simulated of the pressure drop will be signified as a function of dynamic head.

$$\nabla p = -\sum_{j=1}^{3} C_{2ij} \, (\frac{1}{2} \rho|v|v_j)(8)$$

4. Results and Discussion

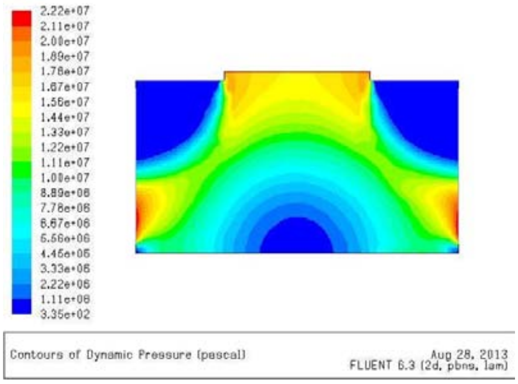

Figure 1: Dynamic pressure no porous media

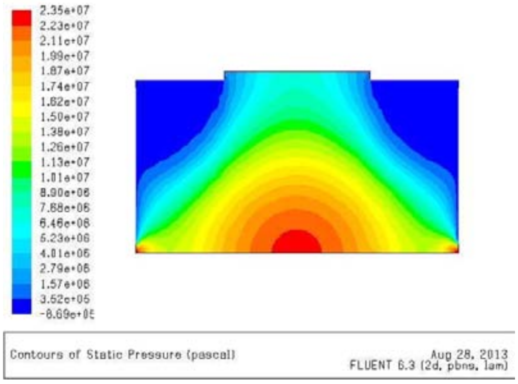

Figure 2: Static pressure no porous media

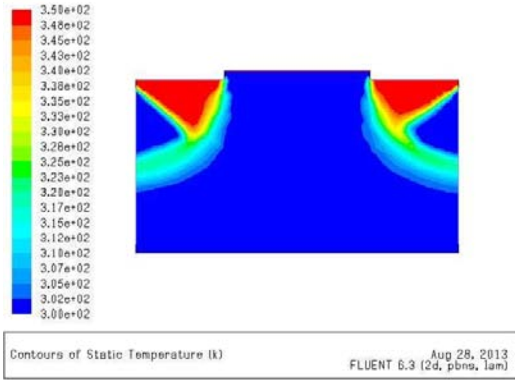

Figure 3: Static Temperature no porous media

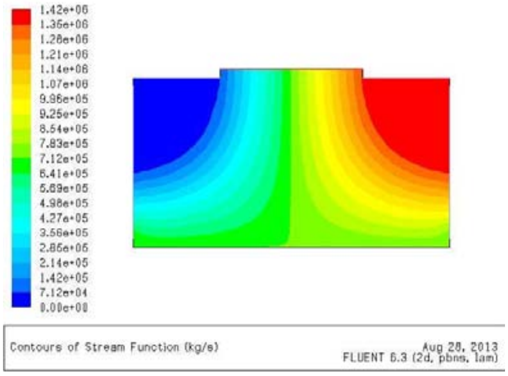

Figure 4: Stream Function No porous media

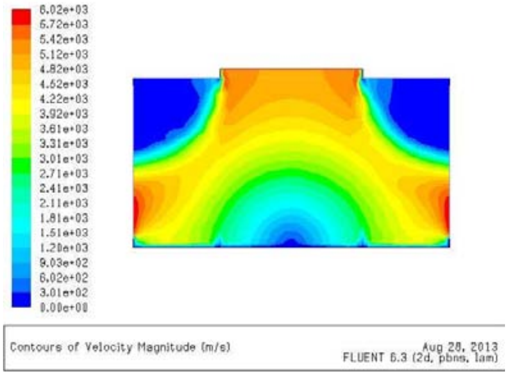

Figure 5: Velocity Magnitude No Porous Media

The static temperature (Figure 3) indicates that the temperature is relatively higher in the region in both the upper corner. The static temperature in that region appeared obstructed by the low temperature flows. The rest of the region inside the cooling tower exhibits relatively lower and homogenous static temperature.

The stream function (Figure 4) reveals that the flow of air is very streamlined from the air inlet towards the exhaust fan. The mass flow rate is however skewed heavily towards one side of the cooling tower only where the opposite side recorded no mass flow rate at all.

There are three distinct zones exist in this case where the no mass flow rate zone is concentrated on the left most of the upper side of the air inlet, the highest mass flow rate zone is located on the opposite side and the third zone is the average mass flow rate which is located in the middle vertical section of the cooling tower.

The velocity magnitude (Figure 5) of the case however reflects symmetrical behavior where the air inlet seems to be concentrated on the bottom half of the air inlet. The upper half of the air inlet does not record any velocity magnitude on both sides. A small portion of the region in the middle bottom vertical zone also recorded no velocity. There are three distinct zones where the zero velocity zones, the average velocity zone which seems to envelope the high velocity region concentrated near the exhaust fan and immediately after the air inlet.

The static pressure (Figure 2) reveals to be symmetrical with the values to be increasing from the middle bottom of the cooling tower outwardly. The dynamic pressure (Figure 1) is also symmetrical with three distinct zones can be identified where the highest is located in the bottom half part of the air inlet and continue upstream towards the exhaust fan.

5. Single Phase with Porous Media

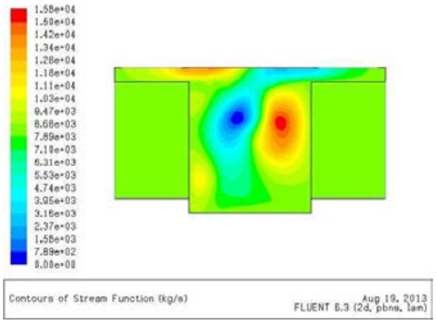

Figure 6: Stream Function with Porous Media

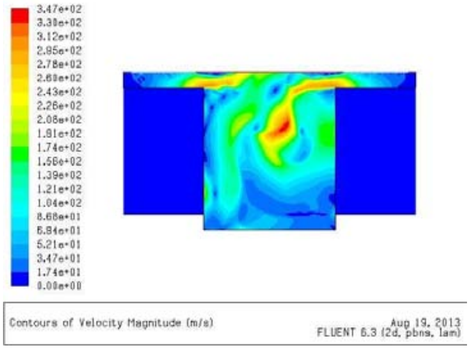

Figure 7: Velocity Magnitude with Porous Media

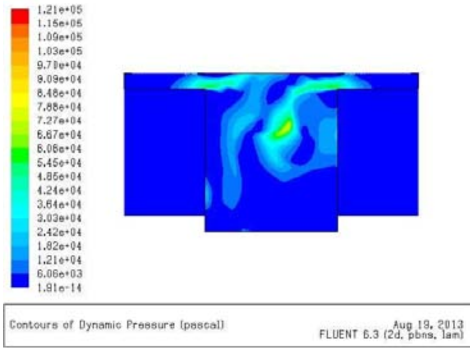

Figure 8: Dynamic Pressure with Porous Media

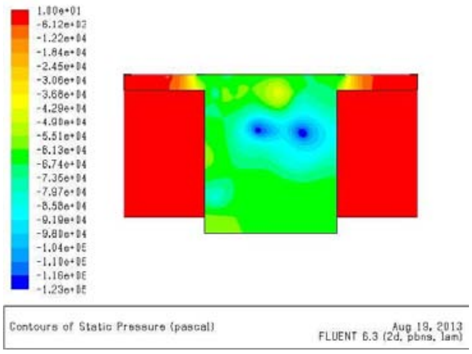

Figure 9: Static Pressure with Porous Media

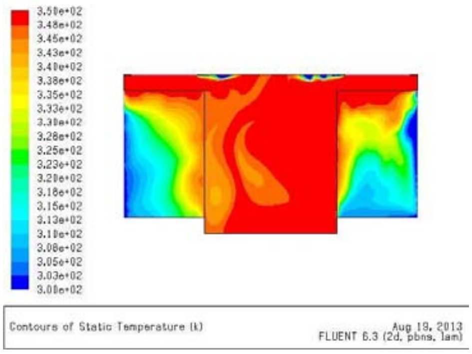

Figure 10: Static Temperature with Porous Media

The stream function (Figure 6) reveals that there is a heavy flow concentrated on the right part of the middle of the cooling tower. The low to zero flow seems to be originated from the right water inlet. The rest of the flow in the middle of the cooling tower shows that the flow is in circular motion mixing with the separate flow of high and low flow rate. The flow inside the porous media indicated flows that are average in magnitude but homogenous in nature. There is no pattern inside the porous media to observe.

The velocity magnitude (Figure 7) of the cooling tower with the porous media in place shows that there are 3 distinct major velocities that are dominant inside the cooling tower while the velocity inside the porous media recorded homogenous zero velocity.

The dynamic pressure (Figure 8) indicates that the lowest value dominates the cooling tower especially in the porous media. There are only two distinct dynamic pressures exist and the highest dynamic pressure is located in the middle of the cooling tower concentrated near the infiltration from the left water inlet and near the bottom of the cooling tower. There exists a small patch of the highest dynamic pressure inside the flow from the infiltration

The static pressure (Figure 9) shows that the highest static pressure exists in the porous media. The negative values of static pressure seem to dominate the middle part of the cooling tower where a circular form of static pressure with the lowest values occur just slightly in the middle of the cooling tower.

The static temperature (Figure 10) of the cooling tower showed that the region in the middle of the cooling tower where the empty space is located is dominant with higher temperature. The air from the water inlet was set to be higher 50K than the air from the air inlet located at each side of the porous media. The higher air temperature in the middle region of the cooling tower seems to have originated from the water inlet where the infiltration from the space near the water inlet and the top of the porous media contributed to this thermal distribution.

The static temperature inside the porous media however exhibits a more variant temperature where four distinct temperatures exist. The lower temperature inside the porous media is near the air inlet and it increases across the length of the porous media into the middle of the cooling tower.

The shape of distribution of the temperature in the left and right of the porous media are not the same where the left porous media showed a more stable temperature increase with the upper left corner of the porous media being the axis point. The right porous media was observed to be more turbulent in nature where the pattern of the thermal distribution is more disruptive compared to the left porous media

6. Conclusion

According to the results, the porosity does have an effect on the air behavior inside the cooling tower. The free stream function of the air flow from the simulation without the porous media indicated no obstruction to the flow of air inside the cooling tower. The thermal and pressure were observed to be influenced directly by this air inlet.

The porous media however provided an obstruction to the air inlet and the porosity of the porous media had reduced the velocity, pressure and stream function of the air inlet going into the cooling tower. From this porosity, the flow inside the cooling tower especially in the middle, had exhibited air flow that is relatively low in dynamic pressure compared to dynamic pressure without the porous media. The velocity in this region was also found to be reduced significantly. The thermal properties in the middle of the cooling tower when the porous media is present also showed that the temperature is just slightly reduced. The porous media exhibited a mixture of temperature variation which indicated heat transfer interaction between the air inlets.

Based on the overall result of the air distribution inside the porous media, there is generally a uniform drop of dynamic pressure and velocity compared to the rest of the cooling tower but a rise in static pressure especially inside the porous media.

From this observation, it can be concluded if the heat transfer inside the porous media is to be improved, higher dynamic pressure is required near the fan outlet which would result in higher fan power output.

7. Future Scope

The porous media codes based on the cooling tower need to be developed. By identifying the suitable governing equations that could analytically model the dynamic of the porous media which takes into account the surface condition, type of material and type of corrugation, the codes for the porous media used in the cooling tower can be developed.

This will enable the result to accurately depict the real process.

The multiphase governing equation solutions also need to be focused on to obtain a more detail and accurate depiction of the heat transfer and air flow inside the cooling tower.

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