Heat Balance Analysis to Validate the Heat Dissipation Rate of a Man-Made Lake as a Heat Rejection Device in a Power Plant

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Abstract- Power plants were originally designed to use convenient bodies of water such as lakes and rivers and cooling towers where the natural sources of water bodies are not available to dissipate heat. Though the Environment Protection Agency (EPA) has been pushing regulation that requires all new generation created to incorporate cooling towers, existing plants can still use the bodies of water they are built on at this point. Lakes are typically less efficient than cooling towers in that they cannot usually get the temperatures as cooling towers could get, so the condensers on lakes and rivers are usually designed with a high design inlet temperature. However, there typically would be energy saving by using a lake for no need for cooling tower fans operation. In this paper, through a case study, a thermal balance analysis was conducted to investigate heat dissipation rate of the lake and thus to determine the outlet temperature of the water from the lake to feed into the generator's condenser, which is a critical factor to influence the generator's efficiency. In addition, the analysis is to identify the most dominant variables for enhancing the lake dissipation rate and hence provide cost-effective measures to enhance the power plant efficiency. The case study power plant has 900 MW of power capacity with five power generator and a man-made lake with an approximately 330 acres. Two of generators depend on the lake as a method of heat rejection from the condensers.

Keywords- Power plant, condenser, heat balance, lake water.

1. Introduction

Using lakes as heat sinks for power plants is a common practice where convenient bodies of water are available [ASHRAE handbook, 2007]. Even though Environment Protection Agency (EPA) has taken the stance that cooling towers are the gold standard for heat rejection because of the wildlife impacts in the lake, existing plants can still use the bodies of water they are built on at this point.

In a world where energy consumption is being watched more and more closely, it becomes paramount to be as energy efficient as possible. The primary source of cooling in the lake is natural evaporation. Depending on the environmental conditions, this can be a very effective means of heat transfer. The primary source of heat gains is solar radiation in addition to the machine heat rejection into the lake. Due to the ambient temperature and wind velocity, however, there is a variance in natural convection effectiveness.

There is a large body of research dedicated to modeling the performance of passive cooling systems in both residential and commercial settings. Pezant and Kavanaugh [1990] developed a model for the natural lake temperature behavior of shallow ponds and the more complex behavior of deeper ponds that results from their stratification. The simulations performed were reasonably accurate, despite not being a numerical model.

Ali [2007] investigated the use of open, uninsulated tanks of water as a means of passive cooling buildings in the arid climate of Egypt. The theoretical predictions, calculated numerically strongly agreed with the experimental data. Thus, it was possible to adjust the height of a hypothetical tank in the model to determine the effects on temperature and cooling. When the depth was increased from 0.2 to 0.6 m, the heat transfer ability of the tank jumped from 10.53 to 19.7 MJ/m^2.

Chiasson et al. [2004] proposed an algorithm for predicting the performance of ground-source heat pumps when supplemented by running slinky coils through a shallow pond. The model, implemented in the TRNSYS modeling environment, was used to predict the bulk pond temperature, which was then compared to the observed top and bottom temperatures of the pond in question. In addition, the model predicted the temperature of the cooling fluid. Both experiments demonstrated favorable accuracy.

In this paper, we adopt the previous heat balance method to simulate and analyze the heat dissipation rate for a lake as the heat rejection device through a case study power plant. The power plant provides 900 MW of power with 5 power producing units. Two of the units use the lake as a heat sink. It is designed to transfer the heat from the plant to the surroundings as the water travels around the horseshoe shape. Changing the condenser inlet temperatures a small amount can have a large effect on the efficiency of the condenser. Through the case study, we intend to explore the factors that affect the effectiveness of lake heat transfer in power production situations and demonstrate a procedure for determining the feasibility of using a lake as a heat transfer device.

2. Power plant information

The power plant is located in Oklahoma. The plant provides 900 MW of power with 5 power producing units. They have gone from having coal units, to retiring those units and adding gas units. An ox-bow of the North Canadian River was adapted into a 330 acres and 5 feet deep man-made lake beside the power plant that is used as a heat rejection device for two of the units, as shown in Figure 1. In summer time, make up water is also from Canadian River.

Fig. 1. The case study power plant

The lake is in a horseshoe like shape as shown in Figure 2, with the intent that the hot water from the condensers is discharged on one end and by the time it reaches the other end, the water is cool and ready to absorb the heat in the condensers once more in the process. It is an open loop system, so the condenser water actually is mixed with the lake water.

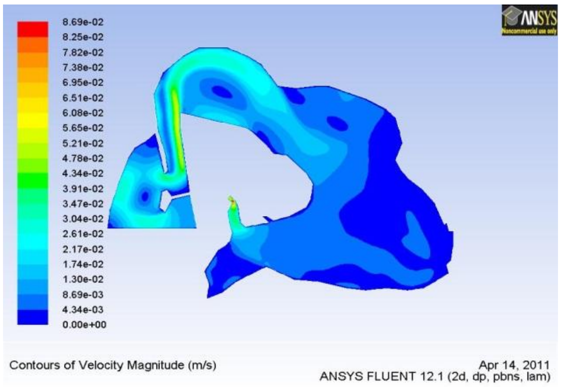


Fig. 2. Lake configuration and water circulation speed in the lake

The two units which use the lake as the heat sink have the condenser water flow of 124,500GPM and 153,000GPM respectively and the heat output from the two condensers are 789,580 MBtu/hr and 970,000 MBtu/hr respectively.

3. Heat balance modeling

Because the lake is shallow (5 feet deep) and is constantly perturbed by input from the condensers, it can be assumed that no stratification in the lake water occurs. This assumption makes a lumped system analysis the appropriate approach. This assumption implies that the entirety of the lake is of uniform temperature at a given time, and that changes to the temperature of the system act uniformly. Further, because the only change in energy of the system, dE, is due to heat sources, the governing equation for the analysis then becomes Equation (1).

$$dE = Q_{in} - Q_{out} \tag{1}$$

where Q is heat transfer rate, with the direction relative the system indicated.

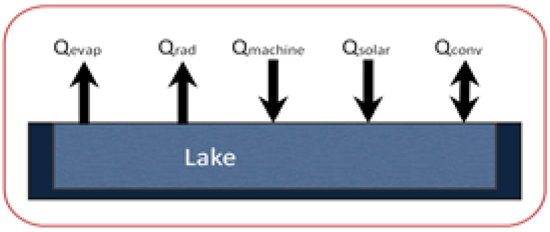


Fig. 3. Heat transfer mode through the lake

As shown in Figure 3, these terms can be more specifically defined as the change in energy of the mass of the lake water and the particular modes of heat transfer into the lake, or it can be expressed by Equation (2).

$$\rho V c_p dT = Q_{convection} + Q_{conduction} + Q_{evaporation} + Q_{solar} + Q_{emitted} + Q_{condenser} \tag{2}$$

where ρ is the density of the water, V is the lake volume, c_p is the specific heat capacity of the water, and the heat transfer sources are as follows:

$Q_{convection}$: natural convection heat transfer

$Q_{conduction}$: conduction through the lake bed (Lake is 5 ft depth)

$Q_{evaporation}$: heat loss due to evaporation

Q_{solar} : heat from solar radiation

$Q_{emitted}$: radiation heat transfer from water to sky

$Q_{condenser}$: heat from condenser outlet water

Convection

Heat transfer associated with convection is given by Equation (3).

$$Q_{convection} = hA(T_a - T_w) \tag{3}$$

where h is the convection heat transfer coefficient, A is the surface area of the lake, T_a is the temperature of the surrounding air, and T_w is the temperature of the lake water.

The heat transfer coefficient itself was estimated from tabulated values corresponding to various wind speeds, with linear interpolation done for intermediate values.

Conduction through the lake bed

For the purposes of this analysis, $Q_{conduction}$ is ignored, as it is difficult to estimate, and is not a large contributor to the overall heat transfer from the lake, given its depth is less than 5.0 ft [Pezant and Kavanaugh, 1990].

Evaporation

The Carrier equation [ASHRAE Handbook 2009] describes evaporation, the largest remover of heat from the lake, as dependent on velocity of the air (v), the surface area the lake, and the difference between the saturated vapor pressure at the lake temperature and partial vapor pressures of the ambient air, P_w and P_a , respectively, or symbolically shown in Equation (4).

$$Q_{evaporative} = A(95 + .425v)(P_w - P_a) \tag{4}$$

where both saturated and partial vapor pressure of the ambient air is calculated through measured hourly dry bulb and relative humidity and the elevation of the location.

Solar radiation

The amount of solar radiation absorbed by the lake water is given by the equation

$$I_{abs} = I_t - I_r \tag{5}$$

where I_{abs} is the solar radiation absorbed by the lake, I_t is the total solar radiation experienced at the surface of the lake, and I_r is the reflected portion of radiation experienced at the lake surface.

Additionally, the reflectance of the lake surface, ρ^*, is defined as Equation (6).

$$\rho^* = \frac{I_r}{I_t} \tag{6}$$

Rearrangement of Equations (5) and (6), and yields

$$I_{abs} = I_t(1-\rho^*) \; I_{abs} = I_t(1-\rho^*) \tag{7}$$

Thus, to determine the total solar heat transfer, which is simply the product of total solar radiation and the lake surface area, the reflectance must be calculated. Duffie and Beckam [1974] include a curve of the absorptance $(1-\rho^*)$ of a blackened surface to solar incident angle, which can be applied to the murky water of Horseshoe Lake.

The incident angle θ was calculated from the method described in the ASHRAE Handbook [2007] and Hsieh text [1986] for every hour of June, July, and August.

The absorptance, and subsequently the percentage of solar radiation absorbed during a given hour are determined from aforementioned curve.

Water to air radiation

The lake water also emits radiation from its surface back to the sky, by the following relationship,

$$Q_{emitted} = A\varepsilon_w \sigma (T_w^4 - T_{sky}^4) \tag{8}$$

where ε_w is the emittance of the water, σ is Boltzmann's constant, T_w is the temperature of the lake, and T_{sky} is the sky temperature.

Condenser heat

The water in the lake is used as the cooling fluid for two condensers. Data provided the power plant include the temperature of the water at points entering and exiting both of the condensers, as well as the flow rate of the two pumps responsible for moving the cooling fluid through the system. Thus the heat transfer rate introduced into the lake from cooling the condensers can be calculated by Equation (9).

$$\dot{Q}_{condenser} = \rho \dot{V}_t c_p \Delta T_{avg} \tag{9}$$

where $\dot{V}_t$ is the total volumetric flow rate of the two inlets, and ΔT_{avg} is average temperature change of the water as it travels through Horseshoe Lake,

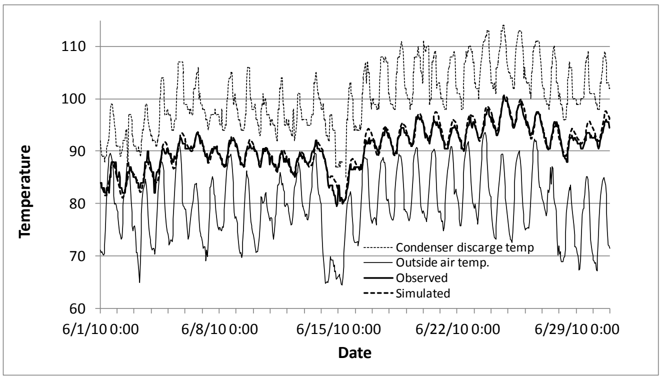
$$\Delta T_{avg} = \frac{(T_{in} - T_{out})\dot{V}_1 + (T_{in} - T_{out})\dot{V}_2}{\dot{V}_t} \tag{10}$$

where "in" and "out" refer to refer to the direction of flow with respect to the lake, not the condensers.

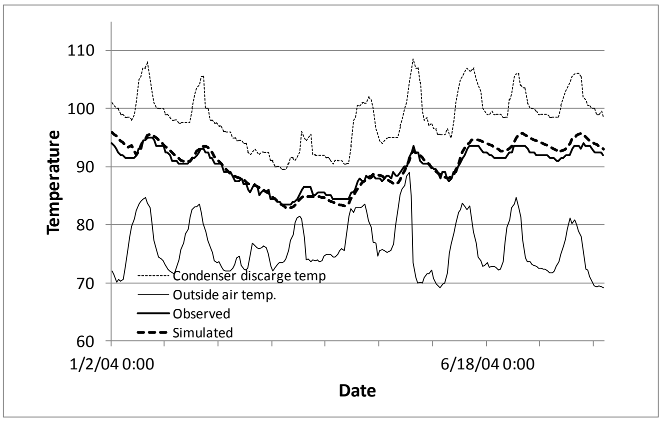
4. Simulation results

To validate the accuracy of the simulation, the simulated temperature was compared to the measured water temperature, which was measured at the two condenser inlets by the utility plant operators for the plant's operation from June 1, 2010, to August 18, 2010. The average temperature of water leaving the lake was assumed to be the average of the recorded temperature at the two condenser inlet points. The first instance of this measurement is also assumed to be the initial lake temperature. The surface area of the lake for this simulation was assumed to be 220 acres, the estimated usable portion of the lake, as reported by the utility plant operators. This assumption is based the water's apparent short circuit around the island, leaving the outer parts of the lake not fully mixed. The average lake depth was taken to be 5 feet.

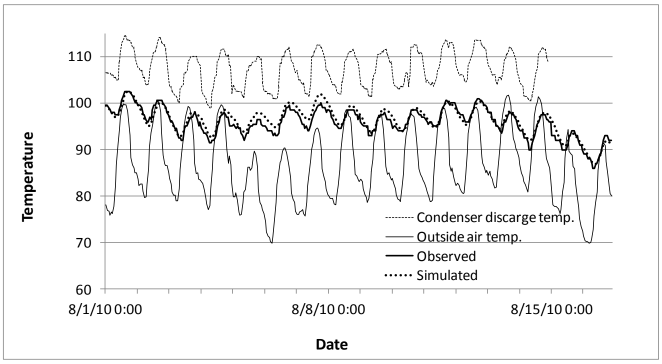
The simulation was conducted based on a one-hour time step because the lake is a low-frequency dynamic system, that is, the large heat capacity of the water prevents rapid temperature fluctuations. Another set of inputs required to execute the algorithm is the weather data, which were taken from weather data provided by the Oklahoma Mesonet weather station. Hourly atmospheric data, which include ambient air temperature, pressure, and relative humidity, wind speed, and amount of downwelling insolation, were entered into the equations above to determine the total heat flux. Figure 3 displays the results of the simulation.



(a)



(b)



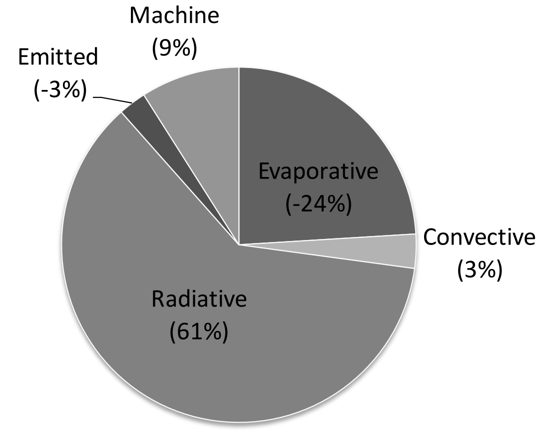
(c)

Fig. 3. Charts display the simulated and measured temperatures (°F) for the months of June (a), July (b), and August (c). Minor gridlines on the abscissa mark 24-hour periods. Gaps in the dates are omitted and are resultant of missing records or erroneous Mesonet data.

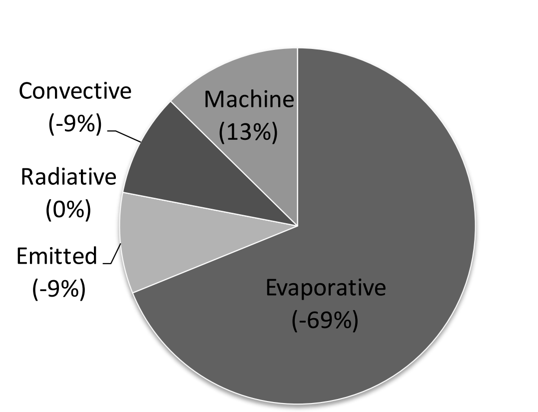
From the figures, it is evident that the simulation follows very nearly with the trended data. In fact, over the entire period, the simulation underestimates the temperature by an average of 0.94%, with a standard deviation of 1.23%. However, this number disguises some necessary compromises in the simulation whose effects on the accuracy are unknown. Chiefly, where atmospheric or trended water temperature data is missing, such as between July 7 and August 1, the simulation reinitializes itself, using the average outgoing temperature as the lake temperature. The effect of this procedure can be seen in Figure 3b, at the sudden peak where both curves meet at approximately July 7.

Also, the simulation does not consider the heat contribution of water from sources other than the condensers. This includes makeup water from the nearby North Canadian River, which is brought in to replace the water lost to evaporation. The simulation also does not consider cooling via precipitation. The contribution from this source is observed most strikingly at June 14, were it rained for several hours.

In Figure 4, the heat transfer contributions from different heat transfer modes are also presented by a typical day in June. The heat transfer contribution at noon time is shown in Figure 4(a) and that at nighttime is shown in Figure 4(b). At noon time, the total heat transfer into the lake is positive, i.e., the lake absorbs heat instead of dissipates heat due to significant amount of solar radiation (61%) into the lake other than the machine load (9%) by the generator's condensers and convective heat transfer (3%) which is driven by temperature differences between lake water and the air temperature. The convective heat transfer to the lake (3%) is positive, because the air temperature is higher than the lake water temperature at the noon time. The biggest heat transfer out of the lake (negative heat transfer) is the evaporative heat transfer, i.e., evaporative cooling which is latent heat being absorbed from the lake when the top layer of the water evaporates, which is -24% of total heat transfer between the lake and the surroundings. Other than the evaporative cooling, there is a small amount of the heat emitted (-3%) to the sky by the lake, which is also a heat loss to the lake. As shown in Figure 4(b), at nighttime, the overall heat transfer to the lake is negative when the lake water can be actually cooled down. The solar radiation becomes zero because it is after sunset and the convective heat transfer direction is from the lake to the surrounding air because the air temperature is lower than the lake temperature at night. The emitted heat loss and the evaporative heat loss from the lake both increase to 9% and 69% respectively at nighttime. The only heat gain to the lake is the generators' condenser heat discharge, which is 13%. From Figure 4, it is clear that the most heat gain to the lake is from the solar radiation and the most heat loss is from evaporative cooling, which can be significantly improved by the air velocity increase as shown in Equation (4). The air velocity increase is mechanically achievable by installing nozzles and water fountains in the lake.



(a)



(b)

Fig. 4. Heat transfer rate contributions from different modes for noon in June (a) and nighttime in June (b)

Alternatives for heat dissipation enhancement

The same simulation model is used to predict the behavior of lakes of different depth, area and evaporative cooling, as pictured below in Figure 4 due to the overall accuracy of the simulation demonstrated in Figure 3.

To make decisions for improving existing infrastructure, it is necessary to determine the most effective approaches of the lake temperature to changes in configurations of the lake. Figure 4 compares the original simulation to those of three additional lake configurations, with a 50% increase of depth, surface area, and evaporative cooling, which simulates supplemental active evaporation by fountains. This corresponds to a depth of 7.5 feet, so that assumptions for shallow bodies still hold, and a surface area of 330 acres, the estimated total area available at Horseshoe Lake. 50% of evaporative cooling can be done by building in water fountains or nozzles to mechanically enhance the water evaporation rate.

From the figure, it is clear that a 50% increase in surface area has a larger effect on the estimated temperature than does a 50% change in depth. The average temperature decrease for the deeper lake configuration is only 0.09°F for the entire operating period, whereas the broader lake is estimated to be 1.40°F lower than the original configuration over the same time period. This is logical, as the overwhelming majority of heat transfer in from the lake takes place at the air-water interface, whereas an increase in depth merely increases the overall heat capacity of the lake, decreasing its rate of temperature change. Best of all is the 50% increase in evaporative cooling, which provides a 4.34°F improvement. This is achieved based on the original lake area and depth.

Table 1. Comparison of average simulated temperature of four lake configurations

Period	**Original Lake**	**Increased Depth***	**Increased Area***	**Increased Evaporation ***
June	91.25	91.06	89.32	87.11
July	91.07	90.85	88.99	87.58
August	96.91	97.12	96.91	91.71
Summer	92.86	92.77	91.46	88.52

(*Increased depth, area and evaporation by 50% based on original lake)

The increase of depth does reduce the amplitude of temperature oscillation, which may be desirable under different circumstances. However, for applications requiring a lower operating temperature, increasing surface area, either by expanding the size of the lake or by mechanical means to enhance the evaporative cooling, will provide better results.

5. Conclusion

The simulation developed is able to replicate the trended lake temperature accurately. Because of this, knowledge of the climate for the region can be used to project the thermal behavior of the lake in subsequent months or years. The simulation is also robust enough to alter the rudimentary geometry of the lake to obtain a desired thermal behavior. As analysis results, it is evident that evaporative cooling is most effective heat loss mode for the lake and thus mechanically enhanced evaporative cooling is the recommended to improve the heat transfer rate and to reduce the returning water temperature from the lake.

In continuing the refinement of the model, some of the more liberal assumptions and approximations will be updated to perform a more rigorous calculation of the convection coefficient. Effects of loss of mass will be more considered.

To make the model applicable to a wider set of heat sink design problems, its reliance on Mesonet data will be scaled back partially, instead using data readily attainable where large-scale meteorological observations are not present.

Acknowledgements

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