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The Effect of High Temperature Feedwater on the Performance of an Evaporative Cooler Installed in a Gas Turbine Combustion Air Inlet System

R.S. Johnson, Sr., P.E.
Solar Turbines Incorporated
San Diego, California

ABSTRACT

Feedwater temperatures above the ambient air wet-bulb and dry-bulb temperatures can significantly reduce the effectiveness of an evaporative cooler. Using the standard evaporative cooler equation significantly underestimates the temperature of the air leaving the evaporative cooler. This, in turn, causes an over estimate of the available power of the gas turbine. This paper describes a procedure for use in estimating the impact of bigh temperature feedwater on evaporative cooler effectiveness.

NOMENCLATURE

c_{pa} = Specific heat of air, kJ/kg-°C
c_{pw} = Specific heat of water, kJ/kg-°C
ρ_w = Density of water, kg/l
G = Water flow rate to the header of the evaporative cooler, l/hr
m_a = Air mass flow rate, kg/hr
m_w = Water mass flow rate, kg/hr
η = Evaporative cooler efficiency, %
ρ_a = Density of air at dry-bulb temperature, kg/m³
Q_a = Thermal energy flow in the inlet air, kJ/hr
Q_w = Thermal energy flow in the feedwater, kJ/hr
T_{DB1} = Dry-bulb temperature of air entering the evaporative cooler, °C
T_{DB2} = Dry-bulb temperature of air leaving the evaporative cooler, °C
T_{FW} = Feedwater temperature, °C
T_{WB} = Ambient air wet-bulb temperature, °C
V = Gas turbine air volume flow rate, m³/hr
$T_{DB1'}$ = Dry-bulb temperature of air in evaporative cooler, intermediate process, °C
$T_{FW'}$ = Feedwater temperature in evaporative cooler, intermediate process, °C
$T_{WB'}$ = Ambient air wet-bulb temperature, intermediate process, °C
$\Delta T_{a'}$ = Change in air temperature, intermediate process, °C
$\Delta T_{w'}$ = Change in water temperature, intermediate process, °C
$Q_{a'}$ = Thermal energy flow in ambient air, intermediate process, kJ/hr
$Q_{w'}$ = Thermal energy flow in the feedwater, intermediate process, kJ/hr
$Q_{a''}$ = Thermal energy flow in ambient air, final process, kJ/hr
$\Delta T_{a''}$ = Change in air temperature, final process, °C
$Q_{w''}$ = Thermal energy flow in the feedwater, final process, kJ/hr
$\Delta T_{w''}$ = Change in water temperature, final process, °C

INTRODUCTION

Water is usually delivered to an evaporative cooler (Figure 1) from wells, the municipal water supply, or from an onsite water storage. The temperature of water from these sources is typically close enough to the ambient air wet-bulb temperature to be ignored in the evaporative cooler performance calculations. However, water left over from manufacturing processes is often considered for use in evaporative coolers, even though the temperatures of this process water can be quite high, sometimes as high as 80°C. Because high temperature process water is widely available, questions about the suitability of its use in evaporative coolers are frequently asked by operators of gas turbines with evaporative coolers.

The theory of evaporative coolers, including the use of feedwater (feedwater is the term for water delivered to the header of an evaporative cooler) at temperatures above the ambient air wet-hulb temperature, but, below the ambient air dry-bulb temperature, is discussed in Johnson (1989). This paper extends the treatment of the earlier paper to feedwater having a temperature above both the ambient air wet-bulb and dry-bulb temperatures.

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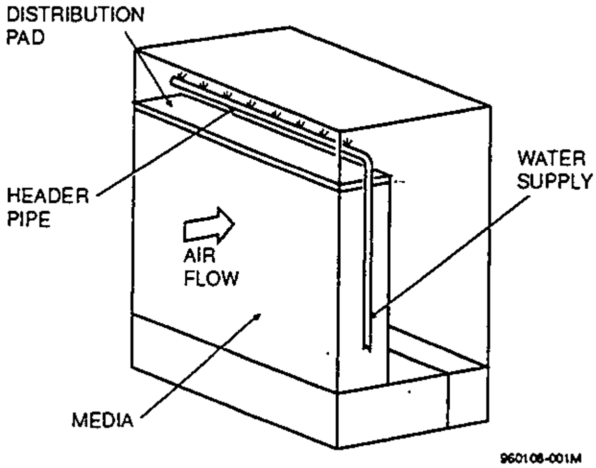

Figure 1. Evaporative Cooler

THEORY

Evaporative cooling involves heat and mass transfer, which occur when water and the unsaturated air-water mixture of the incoming air are in contact. These transfer processes are a function of the differences in temperatures and vapor pressures between the air and water. Heat and mass transfer are both operative in the evaporative cooler because heat transfer from the air to the water evaporates water and the water evaporating into the air constitutes mass transfer.

Heat flow can be described as either latent or sensible heat; whichever term is used depends on the effect produced by the flow of heat. If the effect raises or lowers the temperature, it is sensible heat flow. Latent heat flow produces a change of state, e.g., freezing, melting, condensing, or vaporizing.

In evaporative cooling, sensible heat from the air is transferred to the water, becoming latent heat as the water evaporates. The water vapor becomes a component in the air/water mixture, carrying the latent heat with it. The air dry-bulb temperature is decreased as it gives up sensible heat. The air wet-bulb temperature is not affected by the latent heat in the water vapor because the water vapor enters the air at the air wet-bulb temperature. This exchange of sensible heat for latent heat continues until the air is saturated. At this point, the air and water temperatures, and the vapor pressures of air and water, have reached equilibrium. This process is adiabatic saturation.

However, when the feedwater temperature is greater than the ambient air wet-bulb temperature, non-adiabatic saturation occurs and a correction has to be made for heating the water to the saturation temperature (Berghardt, 1982). The calculation of the temperature of the air leaving the evaporative cooler becomes complicated.

NON-ADIABATIC SATURATION

When the temperature (T_{FW}) of the water delivered to the header pipe (Figure 1) is above the entering air dry-bulb temperature (T_{DB1}), as well as above the wet-bulb temperature (T_{WB}), the process is evaluated using Equation 1:

$$T_{DB2}=T_{DB1}+\Delta T_{a'}-\frac{\eta}{100\%}(T_{DB1}+\Delta T_{a'}-T_{WB'})+\Delta T_{a''} \qquad (1)$$

where:

$$\Delta T_{a'}=\frac{\dot{Q}_{a'}}{\dot{m}_a C_{p_a}}$$

$$\Delta T_{a''}=\frac{\dot{Q}_{a''}}{\dot{m}_a C_{p_a}}$$

Equation 1 is derived from the standard evaporative cooler equation, Equation 2:

$$T_{DB2}=T_{DB1}-\frac{\eta}{100\%}(T_{DB1}-T_{WB}) \qquad (2)$$

by modifying the standard equation to include the terms $\Delta T_{a'}$ and $\Delta T_{a''}$, and replacing T_{WB} with $T_{WB'}$. These modifying terms allow the evaluation of the non-adiabatic saturation condition for a feedwater temperature greater than both the ambient air wet-bulb and dry-bulb temperatures.

In a non-adiabatic saturation process, air enters the evaporative cooler at Position A (Figure 2) at an air dry-bulb temperature (T_{DB1}), and moves to Position B as the sensible heat transfer from the water to the air increases the air dry-bulb temperature. The air then moves toward Position D with increasing enthalpy and wet-bulb temperature, as the air absorbs the extra heat from the water. Position C is the air wet-bulb temperature (T_{WB}), and line B-C is the path of adiabatic saturation, which cannot occur because the feedwater temperature (T_{FW}) is higher than the air wet-bulb temperature (T_{WB}). T_{DB2} is above the saturation temperature of Position D because the evaporative cooler is less than 100% efficient.

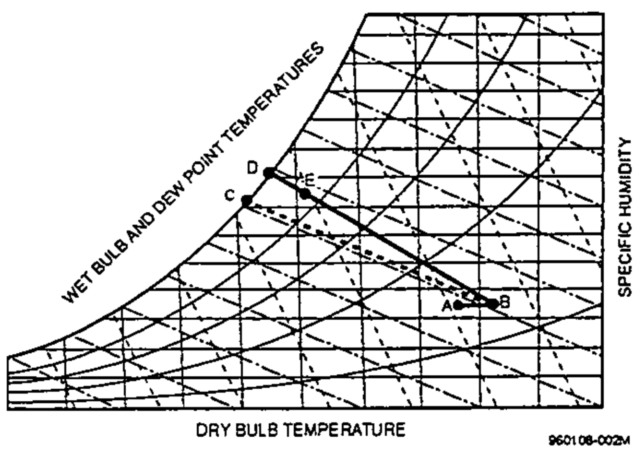

Figure 2. Non-Adiabatic Saturation Psychrometric Chart (Watt, 1986)

Initially, then, the feedwater is supplied at a temperature (T_{FW}) which is above the ambient air dry-bulb temperature (T_{DB1}). The feedwater is cooled as it gives up thermal energy to the ambient air, which, in turn, is increased in temperature as it absorbs the thermal energy given up by the feedwater. This process continues until the feedwater temperature and the air temperature reach equilibrium with each other, at the new temperatures $T_{FW'}$ and $T_{DB1'}$, respectively, at Position B. This is represented by the line followed by the air in moving from Position A to Position B in Figure 2, as the air cools the feedwater and absorbs thermal energy from it. As the process moves from Position A to Position B, the air wet-bulb temperature also rises because some of the thermal energy in the water is passed as latent heat to the air as some water is evaporated. Therefore, at Position B, a new wet-bulb temperature ($T_{WB'}$) is also shown.

As the air and feedwater temperatures converge to the equilibrium temperature ($T_{FW'} = T_{DB1'}$), the thermal energy gained by the ambient air ($\dot{Q}_{a'}$) is equal to the thermal energy given up by the feedwater ($\dot{Q}_{w'}$):

$$\dot{Q}_{w'}=\dot{Q}_{a'} \tag{3}$$

The thermal energy given up by the feedwater is:

$$\dot{Q}_{w'}=\dot{m}_w c_{p_w} \Delta T_{w'}\ , \qquad kJ/hr \tag{4}$$

where:

$$\Delta T_{w'}=T_{FW}-T_{FW'}\ , \qquad ^{\circ}C \tag{5}$$

And, the thermal energy absorbed by the air is:

$$\dot{Q}_{a'}=\dot{m}_a c_{p_a} \Delta T_{a'}\ , \qquad kJ/hr \tag{6}$$

where:

$$\Delta T_{a'}=T_{DB1'}-T_{DB})\ , \qquad ^{\circ}C \tag{7}$$

The increase in the ambient air dry-bulb temperature from T_{DB1} to the new dry-bulb temperature $T_{DB1'}$ is calculated from Equation 8, which is derived by substituting $T_{DB1'}$ for $T_{FW'}$ in Equation 5, then substituting Equations 4 and 6 in Equation 3 and solving for $T_{DB1'}$:

$$T_{DB1'}=\frac{\dot{m}_w c_{p_w} T_{FW}+\dot{m}_a c_{p_a} T_{DB1}}{\dot{m}_w c_{p_w}+\dot{m}_a c_{p_a}}\ , \qquad ^{\circ}C \tag{8}$$

The process now moves from Position B toward Position D at increasing enthalpy and wet-bulb temperature, as the air absorbs the extra heat from the water.

As the process moves away from Position B and toward Position D, the temperature of the water is dropping below the new air dry-bulb temperature ($T_{DB1'}$), but it is still above the new value of the ambient air wet-bulb temperature ($T_{WB'}$). The process continues as the water is cooled from its new temperature ($T_{FW'}$) to the new air wet-bulb temperature ($T_{WB'}$). As the water is cooled, some water will be evaporated and will pass latent heat into the air, which slightly raises the air wet-bulb temperature. As the feedwater at $T_{FW'}$ cools to the new wet-bulb temperature $T_{WB'}$, the thermal energy given up by the water to the air is calculated from Equation 9:

$$\dot{Q}_{w''}=\dot{m}_w c_{p_w} \Delta T_{w''}\ , \qquad kJ/hr \tag{9}$$

where $Q_{w''}$ is the thermal energy given up by the water, and $\Delta T_{w''}=T_{FW'}-T_{WB'}$:

Because the heat given up by the water as it cools from $T_{FW'}$ to $T_{WB'}$ is absorbed by the air, $Q_{a''}=Q_{w''}$, and $Q_{a''}$ is substituted for $Q_{w''}$ in Equation 9:

$$\dot{Q}_{a''}=\dot{m}_w c_{p_w} \Delta T_{w''}\ , \qquad kJ/hr \tag{10}$$

Using $Q_{a''}$ calculated from Equation 10, the air temperature increase occurring as the process moves from Position B to Position E is estimated from Equation 11:

$$\Delta T_{a''}=\frac{\dot{Q}_{a''}}{\dot{m}_a c_{p_a}}\ , \qquad ^{\circ}C \tag{11}$$

Now, having calculated $\Delta T_{a'}$, $\Delta T_{a''}$, $\Delta T_{WB'}$, and knowing T_{DB1} and η, these variables can be substituted in Equation 1 to calculate T_{DB2}, the dry-bulb temperature of the air leaving the evaporative cooler.

EXAMPLE

An example using a non-recirculating evaporative cooler shows how to evaluate the process. (In a non-recirculating evaporative cooler, feedwater is connected directly to the header from the water supply: it is not delivered to the reservoir. Water not evaporated in the evaporative cooler is drained away immediately.) Assume the following parameters:

- Ambient air dry-bulb temperature, T_{DB1}, 38°C
- Ambient air wet-bulb temperature, T_{WB}, 18°C
- Gas Turbine Combustion air flow rate, V, 61200 M^3/hr
- Evaporative cooler efficiency, η, 90%.
- Water flow rate to evaporative cooler header, G, 3420 l/hr
- Feedwater temperature, T_{FW}, 65°C
- Specific heat of air, c_{pa}, 1.014 kJ/kg-°C
- Specific heat of water, c_{pw}, 4.18 kJ/kg-°C

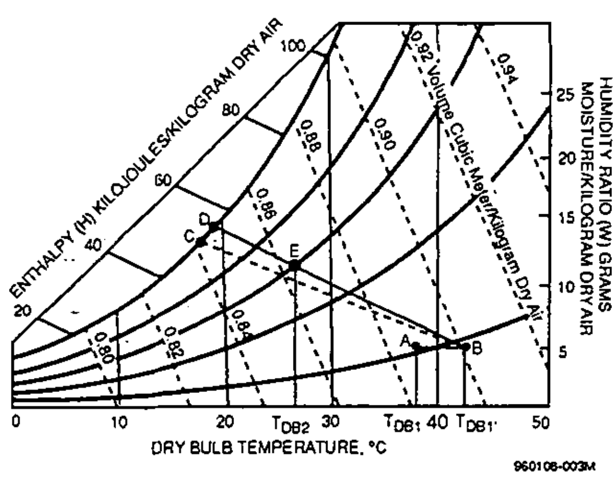

Figure 3. Psychrometric Chart

From the psychrometric chart, Figure 3, enter the chart at 38°C (T_{DB1}) and proceed upward to the 18°C (T_{WB}) line. Interpolate between the specific volume lines of 0.88 and 0.90 kg/m^3 to determine the specific volume of air at 38°C dry bulb and 18°C wet bulb. This value is found to be 0.8888 M^3/kg. Air density (ρ_a) is the reciprocal of specific volume, and ρ_a=1.125 kg/M^3.

From V=61200 M^3/hr and ρ_a=1.125 kg/M^3, calculate $\dot{m}_a$:

$$\dot{m}_a = 68,850\,kg/hr$$

From the water flow rate to the evaporative cooler header (G = 3420 l/hr) and water density (ρ_w=0.998 kg/l), calculate $\dot{m}_w$:

$$\dot{m}_w = 3379\ kg/hr$$

Because the feedwater temperature (T_{FW}) is greater than the ambient air temperature (T_{DB1}), the water will be cooled by the air as sensible heat is transferred from the water to the air. This sensible heat transfer will continue until the water temperature and the air temperature have reached an equilibrium level ($T_{FW'} = T_{DB1'}$). Using Equation 8, Calculate $T_{DB1'}$:

$$T_{DB1'} = 42.5°C$$

Enter the psychrometric chart, Figure 3. From the intersection of the 38°C dry-bulb and 18°C wet-bulb lines, move horizontally to the right to intersect with the 42.5°C line brought up vertically from the bottom of the chart. The intersection of these two lines is the new wet-bulb temperature ($T_{WB'}$), 19.5°C.

From Equation 10, calculate $\dot{Q}_{a''}$:

$$\dot{Q}_{a''} = 324,857\ kJ/hr$$

Now, use Equation 11 to calculate $\Delta T_{a''}$:

$$\Delta T_{a''} = 4.7°C$$

From Equation 7, calculate $\Delta T_{a'}$:

$$\Delta T_{a'} = 4.5°C$$

Finally, having calculated the correction factors $\Delta T_{a'}$, $\Delta T_{a''}$, and $T_{WB'}$, use Equation 1 to calculate $T_{DB2'}$:

$$T_{DB2'} = 38°C + 4.5°C - \frac{90\%}{100\%}(38°C + 4.5°C - 19.5°C) + 4.7°$$

For comparison, calculate the temperature of the air leaving the evaporative cooler for the adiabatic saturation condition; i.e., when the feedwater temperature is equal to the ambient air wet-bulb temperature. This is done using Equation 2, the standard evaporative cooler equation which applies to the adiabatic saturation condition. This calculation predicts that the dry-bulb temperature (T_{DB2}) leaving the evaporative cooler will be 20.0°C. Therefore, if the feedwater temperature had been ignored and the standard evaporative cooler equation for adiabatic saturation had been used to calculate the temperature of the air leaving the evaporative cooler, the effect of the evaporative cooler would have been over estimated by 6.5°C. Because a gas turbine's available power depends upon the air temperature, this result would have led, in turn, to a significant over estimate of the gas turbine's available power. For the conditions given in the example, the available power from an 5140 kW (15°C match) gas turbine driven compressor set is 4020 kW without evaporative cooling. If the high temperature feedwater is neglected, power obtained from the standard evaporative cooler equation is 4975 kW. By evaluating the impact of the high temperature feedwater, the calculated available power is 4670 kW. Therefore, using the standard evaporative cooler equation and neglecting the effect of the high temperature feedwater, over estimates the available power by 305 kW.

CONCLUSION

The standard evaporative cooler equation does not accurately predict the combustion inlet air temperature of a gas turbine when high temperature feedwater is used. Therefore, a procedure for evaluating the impact of high temperature feedwater on the cooling effect of an evaporative cooler has been described and demonstrated. When a non-recirculating evaporative cooler is used to cool the combustion inlet air of a gas turbine, failure to consider the effect of high temperature feedwater will cause a significant over estimate of the available power.

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