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Investigations on the Effect of Fouling Factor in the Air Side of Air Cooled Condenser

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Abstract- *As the electrical power demand increases and water resources become more limited, fouling on the air side of Air Cooled Condensers (ACC) is a growing concern. ACC's are widely used as a method to exhaust waste heat from power plants to the environment while using very little water. Generally fouling on the air side is neglected but with wider implementation of ACC, demands need to be considered to maximize efficiency. Air fouling is partially due to the following: pollen, dust, insects, leaves, and large debris. Fouling limits the convection heat transfer coefficient of the condenser and can cause an increase in backpressure to the turbine or incomplete condensing. Either case will result in a decrease in the plant efficiency and power output. The objective of this study was to experimentally and computationally calculate the convection heat transfer coefficient for both a clean and fouled condenser. Bee pollen was selected as the experimental fouling particle, and engineering data for similar particles were used for the computational model in ANSYS Fluent. Both the experimental and computational results have similar trends showing pollen has a negative impact on the heat transfer. The experimental results show between a 15% and 20% reduction in the coefficient of heat transfer while the computational results show between a 6% and 9% reduction.*

Keywords – *Power Plant, ACC, Fouling, Heat Transfer.*

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I. INTRODUCTION

Electricity in the United States is currently produced mainly by releasing energy contained in coal, natural gas, or nuclear isotopes. The demand for electrical energy will only increase over the next decades at approximately .5% per year (EIA). To handle the increase in demand more power plants will need to be built, the efficiency of existing plants needs to be improved upon, or a combination of these two. Demand for electricity is dramatically increasing in the southwest United States where water scarcity is on the rise. This demand for electrical power and the reduced abundance of water is due to the increase in population. The burning of coal, natural gas, and nuclear fission generally follows a steam cycle, where the heat released by these fuels boils water resulting in steam. A simple steam cycle known as the Rankine Cycle is shown in Fig 1.

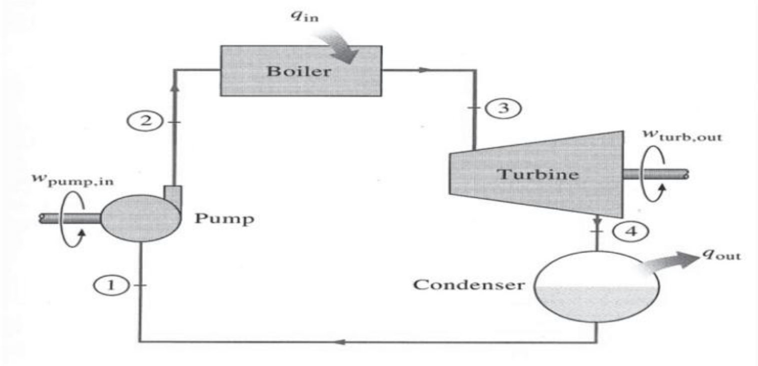

Fig 1. Simple Rankine Cycle

The Rankine cycle contains four components: Pump, Boiler, Turbine, and Condenser. Each of these components has a complex thermodynamic process associated with them; however for a simple Rankine cycle the processes will be simplified. Each of these components and their processes are explain in the sections following. It is common practice in the power industry to have more than one of each component to help boost efficiencies; however one of each component is a good simplified model. As a further simplification of the power plant model only water is used as the fluid which is not the case for actual power plants. The simple Rankine cycle also neglects effects pressure drops and heat losses in the pipes between the components. It is important to keep in mind that a perfect model of a power plant does not exist, and that the Rankine cycle is the best approximation for maximizing component efficiency. This research focuses on the condenser and how its efficiency degrades overtime.

The condenser rejects heat to the atmosphere, allowing the steam to condense back to a saturated liquid. In the ideal case this should be done at constant pressure. In reality this is not possible as most condensers consist of large lengths of pipes. Due to friction in pipes a pressure drop, ΔP, exists and is defined by:

$$\Delta p = \frac{f\rho l v^2}{2D}$$

If the pressure drop in the condenser is greater than the difference between these devices, the steam will not be expanded completely, decreasing the efficiency of the turbine and consequently limiting the electrical power output. In order to increase efficiency of the overall plant, it is important to design the condenser to have the smallest possible pressure drop. This can be achieved by material selection as well as by building the condenser as small as possible, decreasing length.

Shell and tube heat exchangers are one of the oldest forms of condensers in power plants. Steam from the turbine enters one side of the tube and exits at the other side of the tube as a saturated liquid. Advantages of the shell and tube heat exchanger include its compact size, due to high heat transfer rate between the shell and the tube sides.

Cooling towers are used in conjunction with shell and tube heat exchangers, solving the problem of returning the hot fluid back to the atmosphere. This is accomplished by placing the cooling tower at the exit of the shell side of the heat exchanger.

A third option for condensing steam for the power industry and the scope of this research is the air cooled condenser. The air cooled condenser or dry cooling works simply by passing steam through pipes as atmospheric air is forced across them.

Dry cooling is becoming a popular method of condensing steam because the units completely closed and there is no water required to cool it. Only the water enclosed within the Rankine cycle is needed for the entire plant. This allows power plants to be built away from bodies of water compared to those with the shell and tube heat condensers and the cooling tower.

Fouling is the deposition of unwanted particles or species on a solid surface restricting the fluid flow or the performance of a heat transfer surface. Fouling types include but are not limited to precipitation, particulate, corrosion, chemical reaction, solidification, bio fouling, and composite fouling. Fouling increases pressure drops in pipes which consequently limits the fluid flow through pipes. The fouling acts as a thin layer of insulation on the heat transfer surface, which causes the decrease in heat transfer.

Fouling on the air side of air cooled condensers is a known problem to the industry. For this thesis the reduction in performance of heat transfer surfaces will be studied for particulate fouling. Power plants using air cooled condensers have noticed improvements in the efficiencies of their condensers after cleaning.

The primary goal of this research was to experimentally obtain and theoretically predict the convection heat transfer coefficients for clean and fouled air cooled condensers. In order to conduct experiments, a condenser was first constructed made from a 60’ coil of 7/8” copper tubing. Further design specifications are explained in Chapter two. The experimental results were first taken for the clean condenser at varied forced air speeds and then for the fouled condenser at the same forced air speeds. For fouling, bee pollen was chosen to be the only contaminant considered. Once the experimental results were obtained, the impact that pollen has on the heat transfer coefficient was determined. A computational fluid dynamics (CFD) model was constructed using the commercially available software ANSYS Fluent to compare with experimental results. The CFD model was then run at a higher air velocity than the experimental setup could produce. This model allows for a correlation of how pollen deposition and air velocity affect the heat transfer coefficient. The convection heat transfer coefficients of the experiment were compared to those of the CFD model. It was assumed that the experimental results were more accurate than the computer model.

II. LITERATURE REVIEW

Cowell & Cross (1980) investigated the performance of gas side fouling for automotive heat exchangers and found out that the dust is accumulated on the frontal face of the heat exchanger, and fouling is more severe on the front face as compared to the rear face.

Siegel et al. (2002) analyzed the performance of residential evaporator coil by presenting a fin and tube heat exchanger fouling model. They studied the fouling time as a function of filter efficiency and indoor concentrations. They calculated the mass concentration distribution function, which describes the amount of fouling material deposited on the coil surface as a function of particle diameter.

Bilal and Syed (2005) concluded that fouling of evaporative cooler and condenser tubes is one of the most important factors affecting their thermal performance, which reduces effectiveness and heat transfer capability with time. In this paper, the experimental data on fouling reported in the literature are used to develop a fouling model for this class of heat exchangers. The model predicts the decrease in heat transfer rate with the growth of fouling. A detailed model of evaporative coolers and condensers, in conjunction with the fouling model, is used to study the effect of fouling on the thermal performance of these heat exchangers at different air inlet wet bulb temperatures. The results demonstrate that fouling of tubes reduces gains in performance resulting from decreasing values of air inlet wet bulb temperature. It is found that the maximum decrease in effectiveness due to fouling is about 55 and 78% for the evaporative coolers and condensers, respectively, investigated in this study. For the evaporative cooler, the value of process fluid outlet temperature Tp, out varies by 0.66% only at the clean condition for the ambient wet bulb temperatures considered.

Bell at el. (2010) investigated the performance of two different types of heat exchangers: plate and fin as well as micro channel. They experimentally observed that for the same type and amount of dust material, the performance of the micro channel heat exchanger was more severely affected as compared to the plate and fin exchangers.

Rupesh at el. (2011) studied the effects of air flow pattern as well as ambient conditions are studied. Unfortunately ACC becomes less effective under high ambient temperature and windy conditions. Fin cleaning plays a vital role in heat rejection. External surface cleaning improves air side heat transfer coefficient. Ambient conditions affect the steam temperature and heat rejection rate. It is observed that rise in wind velocity decreases thermal effectiveness of ACC up to considerable level. Ambient temperature not only affects performance of ACC at the same time turbine back pressure also increases with rise in ambient temperature. Skirts are effective solution to reduce the effect of wind on volumetric effectiveness. Hot air recirculation increases with wind velocity. Now a days wind walls are usedto reducethis effect. Second option is to increase fan speed. It counter affects on electrical power consumption.

Vijay K (2012) suggested that heat transfer (Q) is directly proportional to heat transfer rate (U) and Area. If the value of fouling factor increases then heat transfer rate decreases. So, more Surface area required to transfer the heat. So, when we select that type of material which has less effect of fouling then we reduce the surface area. Also select the cooling media which has low value of fouling factor at that time also reduced the surface area for heat transfer.

Omer Sarfaraz at el. (2016) Fouling in heat exchangers depends on a number of factors on both the system as well as the air-side. The overall impact of fouling is degradation of the performance of heat exchangers. This includes a degradation of the heat transfer by accumulating on the heat transfer surface as well as an increase in pressure drop. Numerous studies found that for a different type of fouling material, fouling is more severe on the front face as compared to the rear face. The impact of fouling in increasing pressure drop for constant air flow rate is greater than the decrease in heat transfer especially at the initial phase of the fouling process and if fibrous materials are involved.

III. EXPERIMENTAL SETUP

3.1 Experimental Apparatus Design

A schematic of the experimental setup can be seen in Figure 3.1. Input steam would enter at point 1, and then pass through a flow control valve; at point 2 the steam would either be diverted in to the condenser, point 3, or straight in to the collection barrel at point 4. If the steam was diverted to the condenser it would pass through the coils being studied and the left over steam would then be fed to the collection barrel at point 4. Temperatures would be taken at three positions: (a) at point 2 which would be used as the input temperature of the steam, (b) at the exit of the condenser showing if the steam has been sub-cooled or if it has remained in the same phase, and (c) at point 4 the collection barrel.

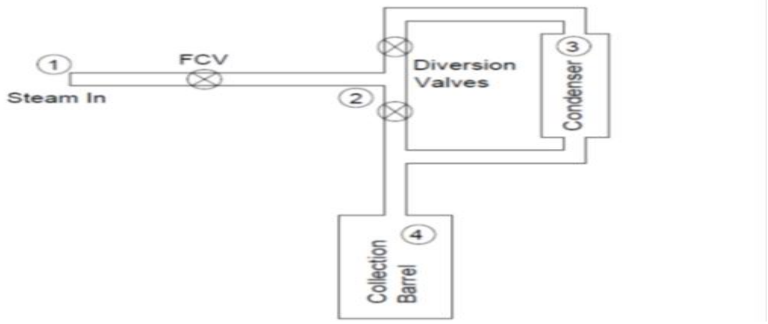

Figure 3.1 Schematic of Apparatus

Air temperature in and out of the condenser was also recorded. The temperature change of the barrel can be used to calculate the enthalpy change of the barrel. Two types of experiments were conducted, one to find how much enthalpy the steam contained initially, and a second found how much enthalpy the steam contained after passing through the condenser. The difference of these two experiments yielded the amount of heat lost through the condenser.

3.2 Experimental Apparatus

An aluminum frame with clear glass walls was constructed with dimensions 50x50x300, split into three section. The first section was to house the condenser and was at the top of the frame. The second section held the fan and filter, and final the section allowed the fan to expel air back to the atmosphere. All pipes leading to and from the condenser were insulated, and thermocouples were attached at necessary points. The collection barrel was insulated and had a plastic lid, as well as a floating foam lid keeping all heat contained to the collection water. This barrel was placed on a scale such that the mass flow rate could be obtained. A mixer was used to insure the liquid in the barrel was at a consistent temperature throughout the experiment.

The copper tubing was shaped into a continuous helix of 12.5 coils of approximately 18” in diameter. This helix was mounted vertically to the first section of the aluminum frame. The helix was confined to the top 72” of the frame. The dimensions of the coil ensured that it would be far enough from the walls; therefore having little effect on the fluid flow near the heat transfer surface.

A three speed box fan was mounted in the second section of aluminum frame. This pulled air downward across the coils, mimicking a full size Air Cooled Condensers. It was found using an anemometer that the high speed of the fan yielded an average speed of 5fps in the apparatus and a 3.5fps velocity for the medium speed. The low speed was not be used as it did not generate a consistent significant velocity. On top of the fan there is a simple furnace filter to catch containments during experiments.

3.3 Experimental Setup & Procedure

The goal of this thesis was to find the coefficient of convection heat transfer for an air cooled condenser experimentally and then compare with a computer simulation for clean and fouled cases. The experiments are conducted in two parts.

In the first part the experiment, one ACC is kept clean and later part of the experiment on the ACC, Bee pollen was considered and applied to the pipes. Two points on the helix were wrapped with a strip of foil. This foil was removed and placed under a microscope after each different level of fouling. This allowed for the effects of various amounts of deposited pollen to be tested and compared. After the pollen was deposited and the concentration was recorded.

Then the steam is passed into the condenser and allowed to cool. Calculating the convection heat transfer coefficient for the clean condenser was done by first diverting the steam directly to the collection barrel with a closed off route to the condenser. Once the system reached stead state results were taken. It was necessary to find the enthalpy of the steam, which was at a liquid vapor mixture thermodynamic state. The both parts of the experiments are conducted in same time to get the same quality of the steam for the both portions of experiment.

Experiments were conducted for each of the cases for the fan speeds and with or without pollen in the manor explained. Convection heat transfer coefficient was calculated for each experiment. The comparison with Reynolds number allows for results to be compared to other fluids as Reynolds number is a non-dimensional value. Both the clean and fouled data show similar trends in the heat transfer coefficient as velocity was varied. A power trend line was fit to each set of data, with the expectation that the heat transfer coefficient would eventually reach an asymptote and flat line out as velocity is increased.

Each experiment had two parts; the first was to find the enthalpy of the steam and the second was to find the convection coefficient. It was known that the enthalpy of the steam varied greatly at the location in the building from previous research and thus it was best to calculate it per experiment to get the most accurate readings possible.

After all the clean data was obtained, bee pollen was applied to the surface of the coil. The entire coil was first sprayed with water; this forced pollen to stick to the surface. This was done to greatly reduce the amount of time it would take for pollen to deposit in a significant amount on the surface of the coil and resulting in pollen deposition on the heat transfer surface. The majority of the pollen was deposited on the top half of the pipe in an even manner along the coil.

IV. Governing Equations

To form a numerical model of the air cooled condenser the following fundamental equations are needed: conservation of mass, momentum, energy, and particle deposition. The commercially available computational fluid dynamics software ANSYS Fluent was used which discretized these equations and solved those numerically using control volumes.

Conservation of mass and momentum are required to describe the fluid’s motion through the air cooled condenser and is given by the following eqn.

$$\frac{\partial \rho}{\vartheta t} + \rho(\nabla . \vec{V}) = 0 \ldots\ldots (1)$$

But in ACC, the velocity of the air is comparatively low, it is considered as the incompressible flow. The heat transfer from the surface of the coil to the surrounding air also needs to be modeled and is done by using the energy equation. It balances the enthalpy of the control volume and accounts for the energy dissipation to the surroundings and is given by

$$\frac{\partial(\rho h_0)}{\partial t} = k\nabla^2 t + \nabla . \left(\pi_{ij} \vec{V}\right) + S_h \ldots (2)$$

V. Computational MODEL

A solid model was drawn with a dimensions the same as one fourth of the experimental model and imported into ANSYS. The surface of the helical coil is the heat transfer surface, simulates the experimental setup. A fluid zone was created around the coil as shown in figure 5.1. The element is meshed full scale which could result in a non-converged solution.

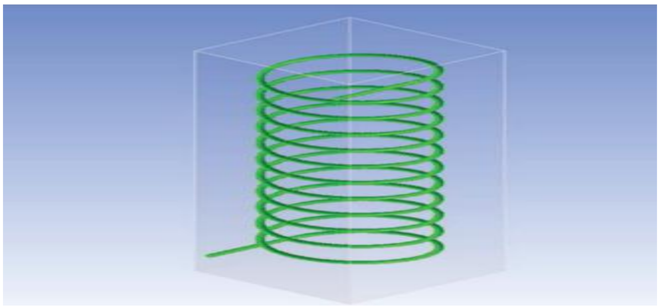

Fig 5.1 Geometry of Full Model

Reynolds number was calculated from the input air velocity to determine the type of flow. The turbulent flow model is used by activating the k and module. The energy equation module was used to solve the heat transfer phenomena. The walls were prescribed a no slip condition and a heat flux of zero. The top and bottom of the condenser were set to be a velocity inlet and outlet with a given velocity and given temperature. The velocity was varied in the fluent models to match the velocities of the experimental installation.

VI. Results And Discussions

The heat transfer coefficients are determined experimentally and computationally for both the clean condenser and the fouled condenser.From the results, the convective heat transfer coefficient increases with increasing air velocity. The results for the clean condenser are, in particular good agreement with the experimental results indicating more sensitivity of the coefficient to the increased air velocity than the computational results. The fouled condenser shows a similar trend between the computational and experimental results, and in fact at first look seem to correlate better.The computational results predict a higher level of particle deposition than the experiment had. Despite this the heat transfer of the computational results are higher than those from the experiment. This is unexpected and will be discussed more in the next section.

The results show that the computational results are well within an acceptable range for engineering predictive simulation. The fouled condenser heat transfer coefficient was not compared in this manner due to the significant difference in pollen concentration between the experimental concentration and the computational concentration.

Table 7.1 Effect of fouling and comparision of heat transfercoeffiecients in both experimnetal and computational investigations

	Experimental Results			Computational Analysis Results		
Velocity m/s	Clean ACC	Fouled Acc	% Reduction	Clean ACC	Fouled ACC	% Reduction
1	60	56.5	5.8%	57.3	54.1	5.6%
1.5	70	60	14.2%	65.01	58.2	10.5%
2	-	-	-	67.5	62.5	7.4%

Instead the percent reduction in heat transfer from clean to fouled for both the experiment and the computational was calculated and is tallied in Table 7.1. Notice that the percent reduction in the heat transfer coefficient was significantly more in the experimental results even though the particle deposition was less. This is opposite of what one would expect. However, both the experimental and computational results indicate that fouling has a great effect on the coefficient reduction at higher air velocities. That is fouling seems to impede the boost that air speed gives to the heat transfer coefficient.

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