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An Investigation of Electrostatic Water Treatment for Industrial Systems

JOHN P. COULTER, CESAR A. SILEBI, AND C. ALEXIS BENNETT
Lehigh University, Bethlehem, Pennsylvania

PAUL Q. McLAINE
Chemfree Water Systems Inc., Nazareth, Pennsylvania

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ABSTRACT

The study focused on Electrostatic Water Treatment. This technology utilizes electrostatic fields to replace chemicals. We evaluated the extended temporal performance metrics of the system in an industrial pharmaceutical facility near Philadelphia. It was found that the system was quite effective. Several issues were explored in controlled laboratory settings at Lehigh University. The study focused on an analysis of the cylindrical geometry prevalent in existing electrostatic water treatment systems. The electric field strengths were compared for various applied voltage levels. Overall, the study shed some useful light into the promising and yet complex area of electrostatic water treatment.

INTRODUCTION

Systems that provide heating and cooling in industrial facilities utilize enormous amounts of both energy and water. With this in mind, maintaining such systems at peak operational efficiency levels is of great importance. The traditional means for controlling problematic scale and bacteria levels in industrial water systems is through periodic chemical water treatments. While such treatments are indeed effective, they are not idealized solutions. Chemical water treatments involve the ongoing purchase and addition of the selected chemicals, necessitate increased water usage associated with more frequent system drainage and replenishment, and require the consideration of the environmental effects of the added chemicals that become integral components of the drained water. In response to this, the search for an ideal means to manage industrial water system problems has led to the development of numerous concepts that can be generically classified as non-traditional.

NON-TRADITIONAL WATER TREATMENTS

The use of "non-traditional" water treatments can range from industrial systems to domestic environments. For all practical purposes, we are interested in the types of water treatment that apply to industrial settings. Some of these particular types of treatment include, vortex water treatment technology, magnetic water treatment, electromagnetic water treatment and electrostatic water treatment. In general the effectiveness of and mechanisms underlying these non-traditional water treatment systems are not fully understood. For this reason such systems are not yet widely used.

Vortex water treatment manufactured by Chesterton® is based on a relatively new concept. Vortex technology operates by colliding two water jet streams at high velocities. The kinetic energy of the collision creates cavitations, which in turn creates a local rise in temperature and in theory should precipitate calcium carbonate. The precipitated calcium carbonate can then be filtered and kept out of the bulk water. Vortex technology has been studied in a laboratory environment by Suslick at the University of Illinois [1].

Magnetic water treatment consists of passing water through a strong (1,000 to 10,000 Gauss) magnetic field. The magnetic field can be generated by permanent magnets or electromagnets that will emit a constant magnetic field. The magnets are usually installed in or on a feed water pipe in industrial systems. A number of theories on the mechanism to explain how magnetic treatment works have been theorized but research studies to date have in general not been able to sustain the theories [2,3,4,5,6,7]. In some cases, however, researchers have claimed that magnetic treatment does have an effect on calcium carbonate particles and deposition [8,9,10,11].

Electromagnetic water treatment also known as electronic anti-fouling treatment (EAF) or pulsed power treatment (PPT), is another form of non-chemical non-traditional water treatment. Typically, a 14 gauge single stranded wire is wrapped around a feed pipe to a heat exchanger. The two ends of the wire are connected to a wave generator, which produces a pulsing square wave current to create a time-varying magnetic field inside the pipe. Subsequently, the time varying magnetic field creates an induced electric field inside the pipe, which also oscillates with time. There are many companies that manufacture electromagnetic water treatment devices. Some of these companies include Sonical, Scale*watcher*®, PLR Parrot® and Clearwater Systems LLC. All of these companies have reported positive results on their product and some have even backed their claims with field data. Researchers at Drexel University [12] and at the University of Connecticut [13] have also positive results when they conducted studies on the effectiveness of electromagnetic water treatment systems.

Electrostatic water treatment involves the passing of system water through an imposed d.c. or static electric field. Electrostatic water treatment has been proposed to operate as a dispersant to foulants, particularly calcium carbonate particles. It has been theorized that the electric field passing through the water will in effect induce a like surface charge on foulants and calcium carbonate particles. The similar charge on particles will prevent agglomeration and as a result deposition will be decreased. It has also been theorized that electrostatic water treatment can inhibit the growth of bacteria.

For the most part very little fundamental research has been completed on electrostatic water treatment systems. One study focused on the effects of such systems on foulant deposition was done by Limpert and Raber [14]. To date the effects of electrostatic treatments on bacteria remains virtually unexplored. Thus much remains to be learned about this potentially promising technology.

The current paper explores two general issues. The first is the overall effectiveness of electrostatic technology based water treatment systems in industrial installations. Along this line, an actual one year case study of an electrostatic water treatment system installed at a pharmaceutical plant is presented and discussed. The second general issue that is explored is the means and mechanisms through which effects such as those observed during the case study arise. In this area, investigations into fundamental areas such as the electrostatic conditions involved and the effect that such conditions have on scale and flowing planktonic bacteria are discussed.

ELECTROSTATIC WATER TREATMENTS

Typically, electrostatic water treatment devices are installed in industrial cooling water systems either in a pipe bend configuration or a side stream configuration. Figure 1 shows the operation of an electrostatic water treatment device in a side stream configuration

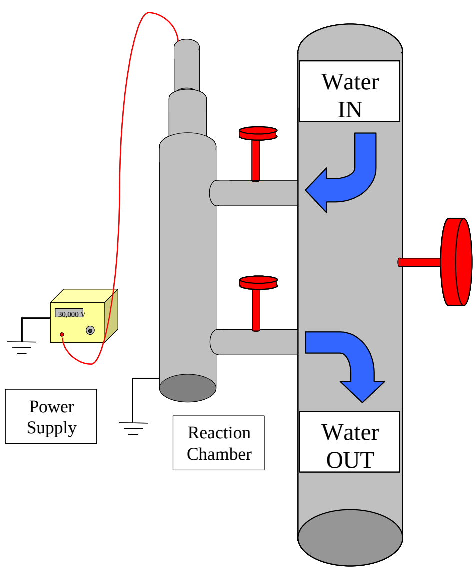

Figure 1: Typical configuration of an side stream chamber based electrostatic water treatment system.

An electrostatic water treatment device consists of a voltage supply, an electrostatic rod and a reaction chamber. The electrostatic rod is placed inside of the reaction chamber and water is allowed to flow in the reaction chamber and around the electrostatic rod. The voltage supply delivers a DC voltage at a specified level and current limit to the electrostatic rod. For current systems provided by Chemfree Water Systems typical voltage and maximum current levels are 25,000 V and .02 mA. Throughout the present paper such systems will be focused on.

A typical electrostatic rod contains an inner cylindrical electrode made of a conducting material coated with a specified thickness of a dielectric insulating material. A treatment chamber is formed when an electrostatic rod is placed within an electrically grounded larger conduit through which water flows. Currently available electrostatic rods contain conductive electrodes with a 0.0175 m outer radius coated with a 0.004 m dielectric layer. Available side stream type treatment chambers are cylindrical with an inner chamber radius of 0.0556 m.

ELECTRIC FIELD MODELING

A starting point for the development of a full understanding of the performance of electrostatic water treatment systems is a consideration of the electrical conditions imposed. As previously stated, an electrostatic water treatment device generates an electric field in flowing water using a cylindrically shaped electrode that is coated with a dielectric polymer. To generate the electric field, the inner electrode is supplied with 15,000 to 30,000 volts. In order to understand the mechanism by which electrostatic water treatment has been proposed to work, one must first understand the principles of Gauss's law and the characteristics of electric fields in cylindrical coordinates. The use of Gauss's law will aid in the solution of the electric field present at time $t = 0^+$ and time $t = \infty$. As will be seen, the values of the electric field will differ for the two time cases.

For the sole purpose of determining the electric field, the electrostatic water treatment device can be described as a lossy media. Lossy media possess both capacitive and conductive properties. The media is described as lossy due to its tendency to leak or loose charge over time once it is fully charged. The energy storage loss in the lossy media is accounted for in the small amount of conductivity the material may possess.

For the case of electrostatic treatment we are confronted with a pair of lossy media in cylindrical geometries. The first lossy media will be the dielectric material surrounding the inner electrode and the second lossy media will be the water that flows around the dielectric material. A circuit representation of the system involved can be seen in Figure 2, where R_1 and C_1 are the material properties of the dielectric material surrounding the electrode and R_2 and C_2 are the material properties of the water. A cross section of the device to be studied can be seen in Figure 3, where the electrode coating is material (1) and the water is material (2).

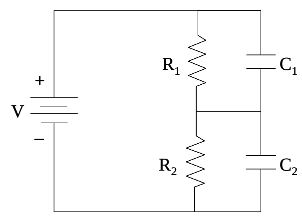

Figure 2: Circuit Diagram of Series Lossy Media.

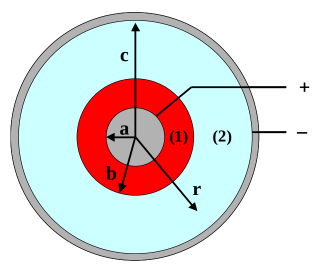

Figure 3: Cross Section of Electrostatic Rod in a Pipe Filled with Water.

Since the system contains lossy media the characteristics of the electric field will vary with time. For this reason, we will study the systems at both time t = 0 and time t = ∞. We will notice that at time t = 0 the surface charge at the interface where the two capacitive materials meet will be zero. We should also note that at time zero the system acts as a pure capacitor and current will flow freely. The circuit will act purely as a series of capacitors and the resistive portion of the circuit will be ignored. Thus, permittivity will be the controlling factor. With no surface charge density, the field is continuous across the interface so that:

$$\varepsilon_1 E_1 = \varepsilon_2 E_2 \tag{1}$$

This condition will help us to solve the electric field equation at time zero.

For time t = ∞ after the material is exposed to a potential for an extended period of time, the fields will reach their steady-state values. We should also note that, at time infinity, the system is fully charged and the capacitors will no longer pass current. Current will only be flowing through the resistors due to the lossy characteristic of the system, thus conductivity will be the controlling factor. Since there are no more time variations, the current density must be continuous across the interface and the interface will be such that:

$$\sigma_1 E_1 = \sigma_2 E_2 \tag{2}$$

In order to solve for the electric field in the cylindrical, series lossy media system we start with Gauss's equation in polar coordinates. Gauss's law requires [15].

$$\nabla \bullet (\varepsilon \mathrm{E}) = 0 \Rightarrow \frac{1}{r}\frac{\partial}{\partial r}(rE_r) = 0 \Rightarrow E_r = \frac{c}{r} \tag{3}$$

Where c is an integration constant found from the voltage condition that in our case with a series lossy capacitor will be:

$$\int_a^b \mathrm{E}_r dr + \int_b^c \mathrm{E}_r dr \Rightarrow c_1 \ln r\Big|_a^b + c_2 \ln r\Big|_b^c = V \tag{4}$$

From equation 3:

$$E_1 = \frac{c_1}{r}, R_a < r < R_b \tag{5}$$

$$E_2 = \frac{c_2}{r}, R_b < r < R_c \tag{6}$$

Using equations 5 and 6 in conjunction with 4 we are left with:

$$E_1 r \ln\left(\frac{b}{a}\right) + E_2 r \ln\left(\frac{c}{b}\right) = V \tag{7}$$

To solve for the time $t = 0^+$ case we will use equation 1 with 7 and find that the electric field E_1 in the dielectric material coating the electrode is:

$$E_1 = \frac{1}{r}\frac{\varepsilon_2 V}{\varepsilon_2 \ln\left(\frac{b}{a}\right) + \varepsilon_1 \ln\left(\frac{c}{b}\right)} \tag{8}$$

The electric field E_2 in the water at time $t = 0^+$ is:

$$E_2 = \frac{1}{r}\frac{\varepsilon_1 V}{\varepsilon_2 \ln\left(\frac{b}{a}\right) + \varepsilon_1 \ln\left(\frac{c}{b}\right)} \tag{9}$$

At time t = ∞ we will use equation 2 with equation 7 and find that the electric field in the dielectric material coating the electrode is:

$$E_1 = \frac{1}{r}\frac{\sigma_2 V}{\sigma_2 \ln\left(\frac{b}{a}\right) + \sigma_1 \ln\left(\frac{c}{b}\right)} \tag{10}$$

The electric field E_2 in the water at time $t = \infty$ is:

$$E_2 = \frac{1}{r}\frac{\sigma_1 V}{\sigma_2 \ln\left(\frac{b}{a}\right) + \sigma_1 \ln\left(\frac{c}{b}\right)} \quad \textbf{(11)}$$

For electrostatic water treatment we will mostly be concerned with electric field in the water at time $t = \infty$. Assuming the dimensions of the treatment systems utilized during the industrial case study, the corresponding electric field in water for multiple applied electrode voltage levels at time $t = \infty$ can be seen in Figure 4. The values for a, b and c were respectively, .0175 m, .0215 m, and .0556 m. The value of conductivity for the dielectric material used was $\sigma_1 = 5 \times 10^{-13}$ Ψ/m and the value of conductivity for the water used was $\sigma_2 = .21$ ψ/m.

As can be seen form Figure 4, the values for the electric field through the water are rather small. As mentioned earlier, this is due to the fact that at time infinity the system becomes a pure resistive case and only the conductivities of the materials are used. Since the dielectric material has a very small conductivity also know as a very high resistivity, almost all of the voltage will drop across this material. The remaining voltage will drop across the water. The highest electric field for such configurations occurs near the surface of the dielectric material, and the field level decreases exponentially as the radius increases. Thus it is likely that the effects that such electrostatic treatment systems have on water take place near the surface of the treatment rods.

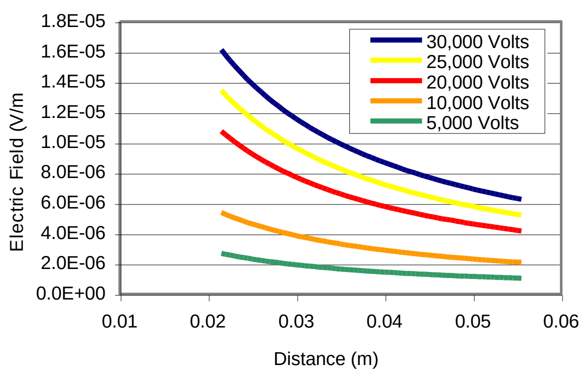

Figure 4: Electric field imposed in the water for multiple supply voltages.

BACTERIOLOGICAL TESTS

Acceptable bacterial plate count results such as those found during the present case study are common to electrostatic water treatment system installations. Electrostatic water treatment systems could potentially effect bacteria levels in both direct and indirect ways. For example, a direct effect would exist if planktonic organisms traveling in the flowing water were weakened or killed by exposure to an electric field. An indirect effect, on the other hand, would exist if a reduction in scaling deposits and thus convenient sessile bacteria growth sites led to a corresponding reduction in overall bacteria level. In order to shed some light in this area, some laboratory tests were conducted on the effects of electrostatic fields on coliform and total bacterial counts.

The experiment, which was conducted at Lehigh University, was designed with the intention of simulating a water processing system. It was also the intention that the experiment should be a controlled environment that would allow for the direct study of the effects of electrostatic water treatment on bacteria growth. The experimental setup consisted of a 60 Liter sump and a 7.5 gallon/min pump. The pipes used were ¾" PVC. The sump was covered but still allowed to breath air. These components were used in conjunction with an electrostatic water treatment device. Water flowed from the base of the sump to the pump and then subsequently through an electrostatic water treatment device as shown in Figure 5. Temperatures for all tests were kept between 68°F and 75°F.

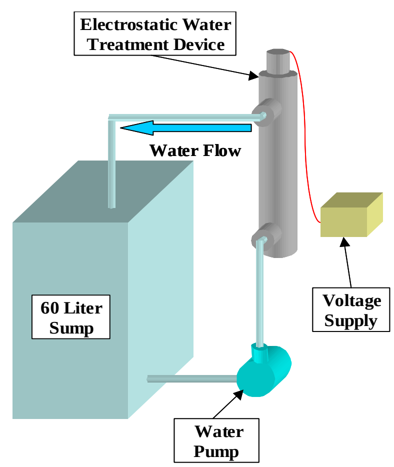

Figure 5: Diagram of bacterial experimental setup.

When testing the effects of electrostatic water treatment on bacteria, the sump was filled with 60 liters of water from a local stream in Bethlehem, Pennsylvania. The pump was turned on and the water was allowed to flow through the pipes at 7.5 gallons/min. The electrostatic rod was immediately turned on and supplied with 25,000 Volts DC.

This system was also used for a control experiment. It was felt that control experiments should be run so that comparisons could be made between water that was treated and untreated. In the control experiment the sump was filled again with 60 liter of water from the local stream. The pump was turned on and the water was allowed to flow through the pipes at 7.5 gallons/min. For the control experiment, the electrostatic rod was not turned on.

Samples of water were taken from the sump on a daily basis. The samples were then delivered to ABE Laboratory in Bath, Pennsylvania within 15 minutes, where coliform, total plate count (TPC) and pH were measured and recorded.

The first test was run with electrostatic water treatment. As mentioned, coliform, TPC and pH were measured on a daily basis. Coliform was measured after the first day of treatment. Total plate count and pH were measured during the first day of treatment. The experiment lasted for a total of 10 days. The coliform count and pH for treated water can be seen in Figure 6.

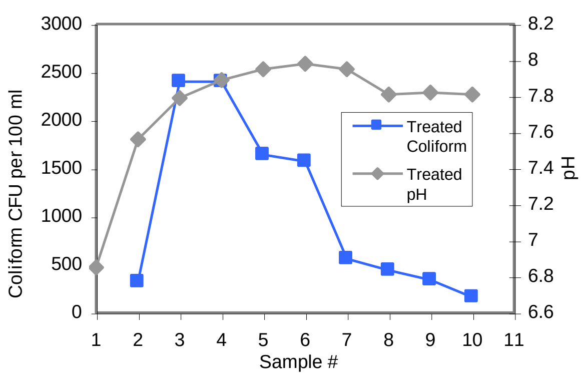

Figure 6: Coliform CFU per 100 ml of water and pH levels for a treated system.

The next test completed was the control. The control or untreated system was run in the same fashion as the treated system. Once again, coliform was measured after the first day of treatment. Total plate count and pH were measured during the first day of treatment. The experiment lasted for 10 days. The coliform count and pH for untreated water can be seen in Figure 7.

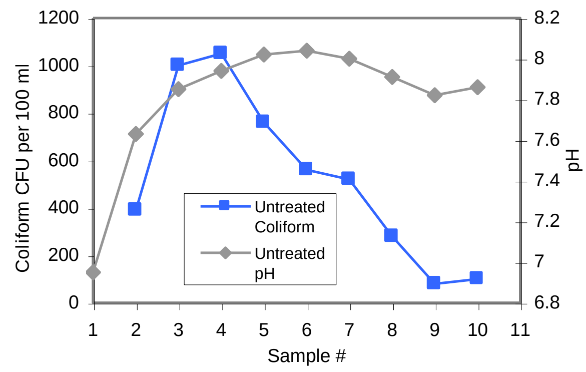

Figure 7: Coliform CFU per 100 ml of water and pH levels for an untreated system.

The comparison between the treated and the control experiments for coliform, TPC and pH for these tests can be seen in Figures 8, 9 and 10 respectively. From these results, no obvious and dramatic direct effect of the current electric field exposure on system planktonic bacteria levels can be seen. Additional testing is planned in this area, but the present results appear to support that concept that any effects that such electrostatic water treatment systems have on bacteria are indirect effects.

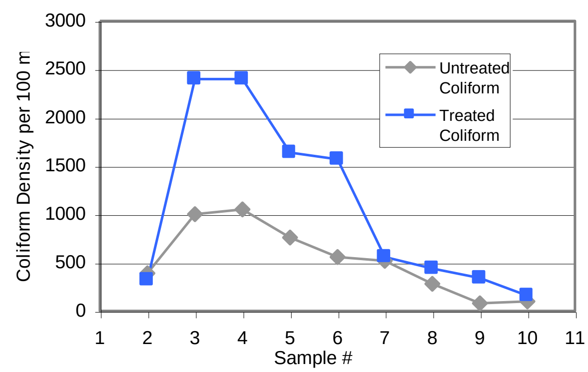

Figure 8: Coliform CFU 100 per ml of water for a treated and untreated system.

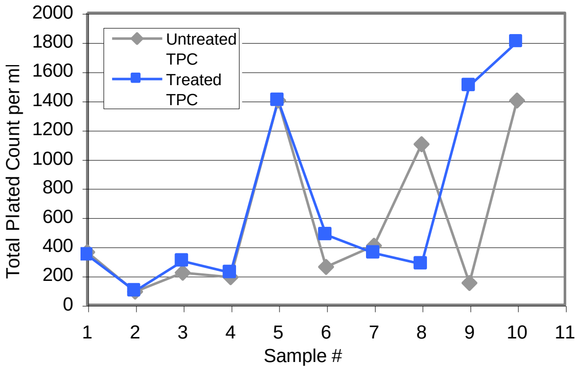

Figure 9: Total plate count (TPC) per ml of water for a treated and untreated system.

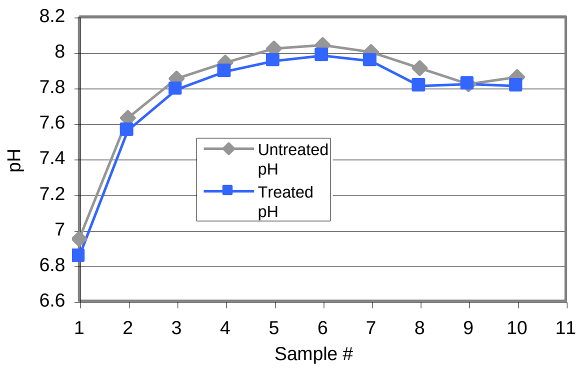

Figure 10: pH for a treated and untreated system.

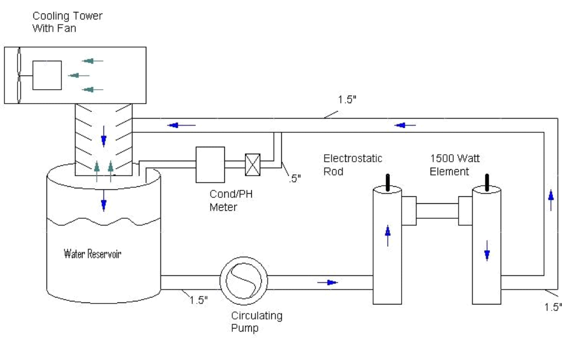

Figure 11: Diagram of the experimental scale removal flow loop studied.

LABORATORY SCALE REMOVAL STUDY

To begin to probe the scale removal capabilities of electrostatic water treatment systems, a laboratory based scale removal study was conducted. This involved the establishment of an experimental water facility that to some degree mimics actual industrial cooling systems. A diagram of the facility that was developed is shown in Figure 11. The system was created with 1.5" diameter copper piping and had a water capacity of 70 gallons. Water in the system flowed from a reservoir through an electrostatic treatment chamber and then past a 1500 watt electrical heating element. It was then returned the reservoir through a small cooling tower.

The system was seeded with calcium and magnesium carbonate in the form of scale taken from an existing industrial facility. Water chemistry measurements were then taken on the system (conductivity, pH, total hardness, alkalinity, temperature, etc.) and it was determined that the Langelier Saturation Index was in the 2.5 to 3.0 range. The LSI remained in this range throughout the testing.

Scale was formed on the heating element by running the system at a relatively slow flow rate (10 gal/min) for 5 days. Pictures of the heating element at the end of this scale growth period are shown in Figures 12 and 13.

Figure 12: Experimental heating element with sufficient scale formed after 5 days without electrostatic treatment.

Figure 13: Base of experimental heating element with sufficient scale formed after 5 days without electrostatic treatment.

Figure 14: Base of experimental heating element with sufficient scale removed after 4 days of electrostatic treatment.

After the scale growth period was completed the flow rate was increased to 33 gal/min. After a few days at this higher flow rate without electrostatic treatment the scale still remained. The electrostatic water treatment system was then turned on and the scale was monitored over a one month period. The heating element remained on during this full period. The results that were observed are shown in Figures 14 and 15. In as little as 4 days noticeable reductions in scale became evident, and at the end of the 30 day period the heating element was once again clean. Thus the scale removal effect of electrostatic water treatment systems was supported by this experiment.

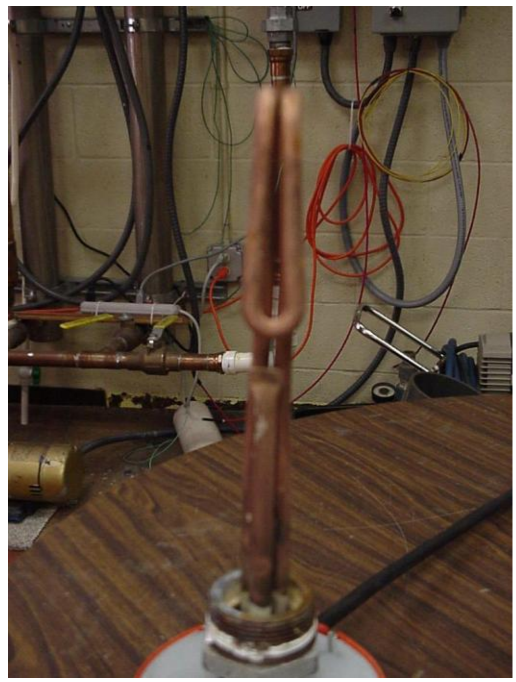

Figure 15: Experimental heating element with scale removed after 30 days of electrostatic treatment.

INDUSTRIAL CASE STUDY

As non-traditional technologies are evaluated, case studies of performance in real-world application settings are invaluable. In the present case, the overall applicability of electrostatic water treatment technology was evaluated through a one year case study of an actual system in industrial use. The location where the case study was performed was a pharmaceutical manufacturing facility in the greater Philadelphia region of the Northeastern United States.

The target facility for the case study had been in operation for a number of years with several water based cooling systems in operation during the warmer months of the year (April through September). Prior to the initiation of the present study, all of the cooling systems had been maintained using traditional chemical-based water treatments. Furthermore for the 2000 calendar year, which was the year prior to the present study, a complete set of energy and water consumption data as well as average outdoor temperature information was available.

The case study performed focused on the performance of two selected chiller loops, which hereafter will be referred to as loops C (chemical water treatment) and E (electrostatic water treatment). The cooling capacities for loops C and E were 1100 and 750 tons respectively. During the baseline usage year (i.e. April-September of 2000), both of the loops were maintained through periodic chemical water treatments. The usage of chemical water treatment continued throughout 2001 for cooling loop C. In the case of cooling loop E, however, in March of 2001 an electrostatic water treatment system was installed and the application of chemical water treatments was discontinued. The electrostatic water treatment device used was similar to what was previously described. Thus throughout the 2001 usage year (i.e. April-September of 2001) a comparison between simultaneously operating chemical and electrostatic water treatment systems was made possible.

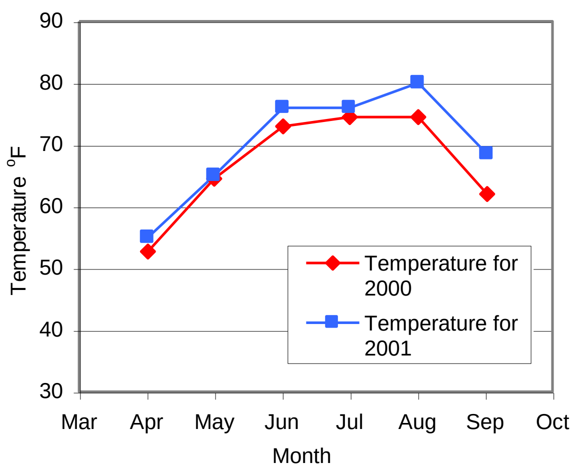

Figure 16: Average monthly outdoor temperatures during the 2000 and 2001 cooling seasons.

Prior to discussing the system performance results arising from the industrial case study, it is useful to first clarify the relative cooling needs during the two year period in the form of average monthly outdoor temperatures. Figure 16 presents graphs of the relevant local average April through September monthly outdoor temperatures for the 2000 and 2001 years. From the Figure it is clear that the average outdoor temperatures during the summer of 2001 were significantly higher than those during the summer of 2000. This is exceptionally true for the month of August where the average outdoor temperature for 2001 was 80°F as compared to 74°F for 2000. Thus it can be assumed that the cooling demands placed on the systems during the summer of 2001 were greater than those for the summer of 2000.

With the relative cooling demands between the two years understood, a useful analysis of the energy and water usage levels can be performed. For cooling loop C, which again remained on chemical water treatments throughout the two year period, average monthly energy usage information is presented in Figure 17. The information presented is the average horsepower required over the duration of each one month period. As expected, for the system that remained on chemical treatments the energy required to meet the cooling demands of 2001 were for the most part greater than those required during 2000.

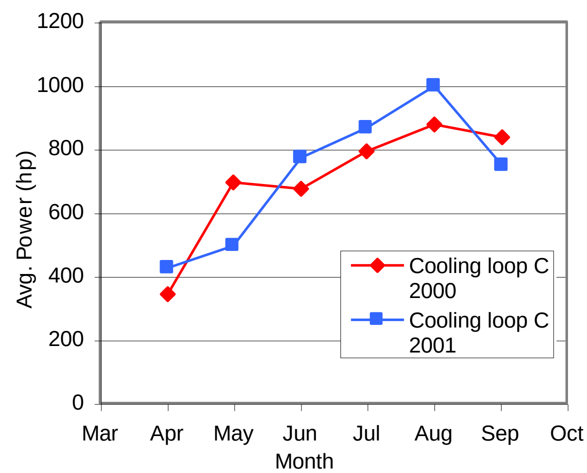

Figure 17: Average monthly energy usage for cooling loop C during the 2000 and 2001 cooling seasons.

Now considering cooling system E, the average monthly energy usage information for this system during the two years studied is presented in Figure 18. In this case it can clearly be seen that the energy required to meet the cooling demands of 2001 was significantly less than that required during 2000. Thus system E required significantly less operational energy when maintained through electrostatic water treatment than it did when maintained through traditional chemical water treatment. This was true even though the system when treated electrostatically had to meet higher cooling demands than the year before when it was treated chemically. Thus the results of the case study supported the concept that cooling system energy usage is decreased by the implementation of electrostatic water systems of the present type. A detailed analysis of the energy savings for this case revealed a 6-10% cooling system efficiency increase with the electrostatic water treatment system installed.

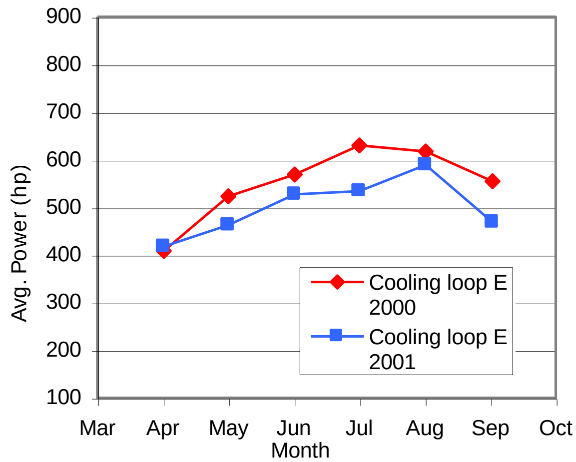

Figure 18: Average monthly energy usage for cooling loop E during the 2000 and 2001 cooling seasons.

Turning now to water consumption, Figure 19 contains the average daily water usage for the chemically treated system (cooling loop C) over the two year period. It should be noted that these water usage results encompass both the make-up water associated with cooling tower evaporation and the system replenishment water associated with periodic blowdowns. As expected, the water usage requirements for cooling loop C were higher during the 2001 cooling season when the outdoor temperatures and associated cooling demands were higher.

The water usage information for cooling loop E during the two years of the case study is presented in Figure 20. In this case the trend as to whether or not more total water was used in one year versus the other is not clear. It is clear, however, that the higher August temperatures during 2001 as compared to 2000 did lead to significant additional water usage. A comprehensive evaluation of the effect that the introduction of the electrostatic water treatment system had on the water usage of cooling loop E is difficult to perform, as it would require consideration of issues such as the differential evaporation rates related to varying outdoor temperatures. A partial evaluation of water savings, however, can be performed by simply determining the water saved by the avoidance of additional system blowdowns that would have been induced by the added chemicals in a chemical water treatment system. By eliminating chemicals, total dissolved solids are reduced. This, in turn, reduces conductivity levels and bleed water expended. When such an evaluation was performed for cooling loop E during the 2001 usage year, it was estimated that a total of 300,000 gallons of water had been saved by the introduction of the electrostatic water treatment system.

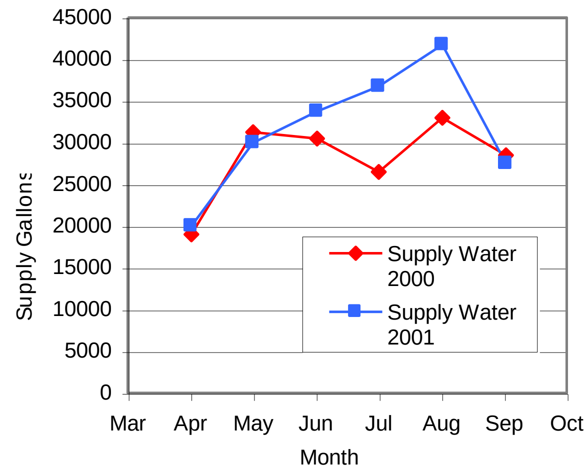

Figure 19: Average daily water usage for cooling loop C during the 2000 and 2001 cooling seasons.

Lastly, turning to bacteria issues, it was desired that the present cooling systems operate with total organism plate count levels of less than 1000 cfu/mL. As is shown in Figure 21, during the 2001 operational year the total plate count levels for the system maintained entirely by the electrostatic water treatment system stayed well below this threshold.

CONCLUSIONS

Electrostatic water treatment systems are evolving non-traditional alternatives to chemical water treatment. The results of a year long case study of such a system at an industrial pharmaceutical plant have supported the realization of both energy and water savings through electrostatic treatment system implementation. Some preliminary insight into the performance of such systems has been gained through the modeling of the electrical conditions imposed. In addition, experimental tests focused on bacteria issues have supported the concept that any effects that electrostatic system treatments have on bacteria levels are likely to be indirect. Elimination of traditional chemical treatment will reduce added nutrients in the basin which, in turn, will decrease biological growth. In addition, scale removal will take away potential biological surfaces and reduce colonization, as well as under-deposit corrosion. While much remains to be learned in the area of electrostatic water treatment, the performance of presently available systems made possible as a result of recent electronics and materials improvements supports the current applicability and expanded future promise of this technology.

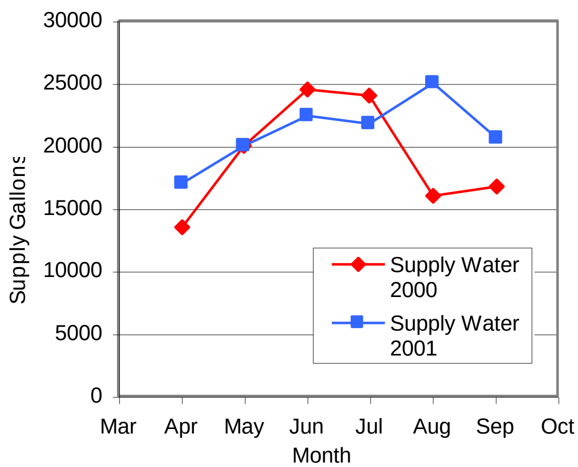

Figure 20: Average daily water usage for cooling loop E during the 2000 and 2001 cooling seasons.

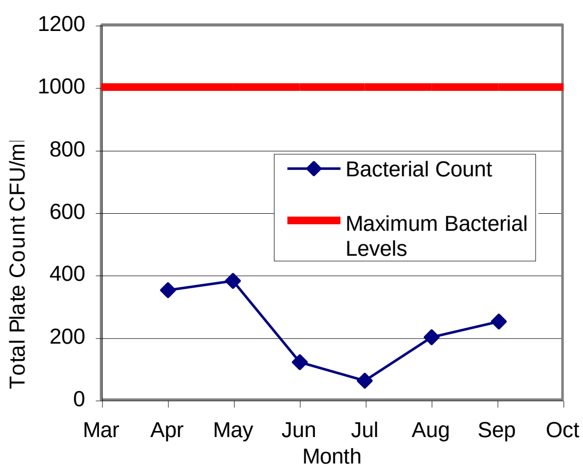

Figure 21: Monthly total plate count levels for cooling loop E during the 2001 cooling season.

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