PHYSICAL WATER TREATMENT FOR COOLING TOWERS

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Abstract

This paper reviews the fundamental operational principals found in some of the primary Physical Water Treatment (PWT) systems used today to control scale formation in cooling towers. These PWT systems utilize pressure/temperature, magnetic flux, electric current, induced (pulsed), static electric fields and catalysis. Both scientific and empirical data are presented. Field data is presented for small to large cooling towers. Information on COC, pH, conductivity, as well as scale, corrosion, and biological control is reviewed briefly.

Introduction

The formation of scale (calcium carbonate or lime deposits) has been observed by mankind since hot water was first used for cooking. Nature has many examples of these deposits in the form of stalactites and stalagmites, and such natural deposits can be observed around faucets or in plumbing and heat exchanging devices. Water heaters, heat exchangers, cooling towers and chillers become fouled and lose efficiency, all because of scale deposits (primarily $CaCO_3$).

The technologies used in many of today's Physical Water Treatment systems (PWT) have been known for many years. These systems use a variety of techniques for controlling scale deposits (other minerals are involved but the focus is on $CaCO_{3,}$) without the need for chemical additives. In some cases, direct electric fields are used, others use induced fields and some rely on physical properties of sheer force to accomplish their functions.

There are many well-known examples of technologies and natural processes that create physiochemical reactions, for instance, the microwave oven utilizes electromagnetic radiation (~2.5GHz) to cook food (a chemical process), and plants use electromagnetic energy (sunlight) through photosynthesis to process chemical reactions. People even use mechanical energy (stirring) to enhance the rate of chemical reactions or to dissolve a substance in a liquid.

The purpose of this paper is to review some of the basic types of Physical Water Treatment systems available today for cooling towers. The mechanism for these PWT's is based on physicochemical principles we will briefly discuss, and supported by conclusions from sited scientific studies. These mechanisms are corroborated by the field data. We will start with a brief review of some of the fundamental principles behind the PWT phenomenon. These basic principles are some of the foundations of chemistry and will be *italicized* here so they can be reviewed in more detail if one chooses.

A Little Chemistry

Only the *valence electrons* (outer electrons) of an element are involved in chemical reactions (*chemical bonding*). When atoms bond, they often lose, gain, or share electrons to attain a filled outer shell of eight electrons (*octet rule*). Electrons can be added (creating a negative ion) or removed (creating a positive ion) resulting in an electrostatic attraction between the two ions forming an ionic bond (one type of chemical bond). Ionic bonding is the primary chemical bond of interest in this paper. Ionic bonding takes place between atoms with large tendencies to lose or gain their *valence* electrons, (normally between metals and nonmetals—i.e., Na, Ca and Mg [lose electrons] with Cl, O [gain electrons]). This bonding is the result of the attraction between negative and positive charged ions a concept that will be used in the explanation of PWT's. Note that these outer (*valence*) electrons can be added or removed with a relatively small amount of energy to form ions (charged particles/ions). Removing or adding core electrons (below the valance electrons) requires significantly greater energy resulting in unstable, short lived entities and are not involved in chemical reactions. Hence, a technology that claims to add or subtract electrons over and above these criteria should be questioned.

Water is sometimes called the 'universal solvent' due to the fact that the water molecule is *bipolar* in nature with a positive and negative end. This atomic arrangement gives water a strong tendency to orient itself (or to be oriented) in an electrical field with its negative end pointing toward the positive direction of the field and its positive end of the water molecule pointing in the negative direction. By orienting themselves in this way, water molecules tend to neutralize an electrical field—a fact expressed in technical language by saying that water's large *dipole* moment gives it an abnormally large *dielectric constant* of 80. In other word, two electrically charged particles will attract or repel one another with only 1/80 as much strength in water as they would in a vacuum. This bipolar nature of water gives it the remarkable ability to dissolve substances, particularly those held together by ionic bonding.

As ions, both positive and negative, move into solution they are surrounded by the water molecules, a process called *hydration*, and thus an ionized solution is formed. In water the attraction between oppositely charged ions is a fraction of what it would be in air, a direct result of the surrounding *hydration* shell, and the high *dielectric strength* of water. It should be stressed that PWT's can have a lasting impact on aqueous solutions but not on pure water.

The primary focus of this paper will be the control of scale found in heat exchange systems. Normally, scale found in these systems is calcium carbonate and to a lesser extent magnesium carbonate. Unpolluted rainwater is weakly acidic (pH = 5.6) because it contains dissolved CO_2:

$$CO_2 + 2H_2O \leftrightarrow H_3O^+ + HCO_3^- \qquad \text{(Eq. 1)}$$

When the water also contains Ca^{+2} ions, this reaction is especially important as calcium bicarbonate, $CaHCO_3^+$, is soluble in water, but calcium carbonate, $CaCO_3$ is poorly soluble in <u>pure</u> water at only a concentration of 7.1 ppm. When the water is heated the carbon dioxide is driven off or the CO_2 can escape through evaporation the following happens:

$$Ca^{++} + 2HCO_3^- \rightarrow CaCO_3 + CO_2\text{ (gas)} + H_2O \qquad \text{(Eq. 2)}$$

Precipitation (CaCO3) and dissociation reactions are more complicated as shown by Cho [1]. The dissociation of bicarbonate ions into the hydroxide ions and carbon dioxide (in aqueous solution) is shown in:

$$HCO^-_3 \leftrightarrow OH^- + CO_2\ \{\text{may be surface activated, [1]}\} \qquad \text{(Eq. 3)}$$

The CO_2 escapes increasing the hydroxide ions, OH-, concentration resulting in an increase in pH (basic). In cooling towers the pH normally increases since the water is heated plus spread out [fill, spray, etc] passing through the air to enhance evaporation i.e., releasing CO_2. The next chemical step [1] is:

$$OH^- + HCO^-_3 \leftrightarrow CO_3^{2-} + H_2O \qquad \text{(Eq. 4)}$$

The final step is for the carbonate ions, CO_3^{2-}, to react with the calcium ions resulting in the precipitation and crystallization of calcium carbonate.

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad \text{(Eq. 5)}$$

To summarize, calcium carbonate (scale) dissolves in an acid solution and precipitates in a basic solution (the *pH* connection).

$$\text{(basic) } CaCO_3 + H_2CO_3 \leftrightarrow Ca^{+2} + 2HCO^-_3 \text{ (acidic)} \qquad \text{(Eq. 6)}$$

When carbon dioxide, CO_2, is in solution (water), carbonic acid is formed aiding the dissolution due to the reaction, 1 & 6 above.

Because of these reactions, some natural (with low pH-due to acid rain) waters contain more than 300-ppm calcium carbonates or its equivalents. There are other ions present in the system and other conditions in addition to those mentioned here. Problems are much more complex in the real world as opposed to the laboratory. However, the laboratory allows us to control variables and formulate mechanisms to explain observations.

The reaction showed in equation 4 increases the concentration of carbonate ions, causing solid calcium carbonate to form, as shown in equation 5. Since the surface of a heat exchanger has the highest temperature in a flow system of a cooling tower, the above reactions can occur primarily on the heat exchange surface. These solids form on the walls of the heat exchanger, acting as a thermal insulator and thus reducing the efficiency of heat transfer and can lead to blockage of piping.

This information aids in understanding the mechanisms attributed to PWT, i.e., chemical reactions, bonding, pH, and ions, all controlled by the outer shell electrons, all are electrical in nature. With this information one can also see that the solubility of minerals in water is primarily a function of pH, concentration and kinetic energy (temperature, etc.). The scaling / fouling environment is derived from the fact that calcium and magnesium carbonates have an inverse solubility with temperature, therefore they tend to deposit scale with rising temperature, i.e., in the heat exchanger (surface).

A Little Physics

Physical chemistry is the application of physics to chemical systems in an attempt to resolve the effects of intermolecular forces, surface tension in liquids, kinetic energy, and rate of reaction plus many other issues controlling physical/chemical properties. For instance, if a compound is to be formed from the reaction of two molecules, ions, etc. they must come into contact with each other (collide) and then they may react.

Why ‘may react’? The two ions or charged molecules (*polyatomic* ions such as HCO^-_3) that collide must have the right orientation with respect to each other and they have to collide with enough energy for bonds to break and/or form. So all collisions of reactants (ions or molecules) do not form compounds and they bounce off each other and wait to try again. The probability that a reaction will take place is a function of concentration, (# of ions or *polyatomic ions* per volume, i.e., controlling the rate of collision), the migration rate, (toward each other) and the energy of the collision (kinetic energy), etc. Remember that the pH of a solution will affect the saturation level (concentration).

Even if the ions or molecules are orientated properly, you still won't get a reaction unless the two collide with a certain minimum energy called the *activation energy* of the reaction. Again, electrical repulsion and attraction of the charged ions coupled with the hydration shell come into play in orientation and activation energy.

The available kinetic energy to supply the necessary activation energy (collision) can be obtained from a combination of heat (vibrational energy), turbulence, pressure changes, and/or electrical fields. Many of these energy sources can be associated with surface phenomena. Usually, the normal turbulence in a cooling tower provides the mixing for orientation and long range movement of the two ionic species (reactants shown in Eq. 2). The heat provides the kinetic energy for the reaction, while a high pressure change and/or electrical field interaction can provide additional activation energy, but only if focused correctly and sufficient time is allowed, (due to the probability factor explained above).

Because the heat energy of a substance is not uniformly distributed among its atoms, ions, or molecules, (particles or species) some may have enough energy to react while others do not as shown in Fig. 1. As the temperature increases the available energy for reaction increases as shown in Fig. 2.

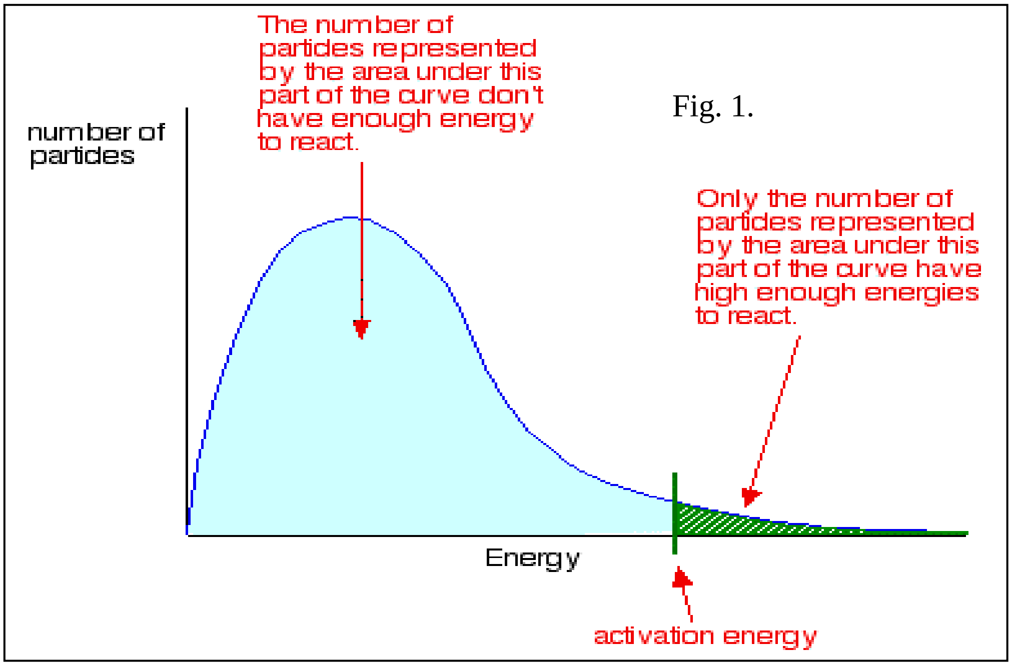


Fig. 1.

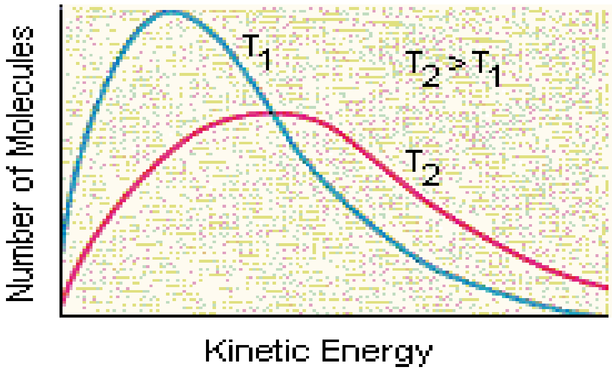


Fig. 2

Hence, before the reactants (ions or molecules) can be converted into products, the available kinetic energy (in a collision) of the reactants must overcome the activation energy (due in part to the hydration shell discussed earlier) for the reaction, as shown in the Figure 3.

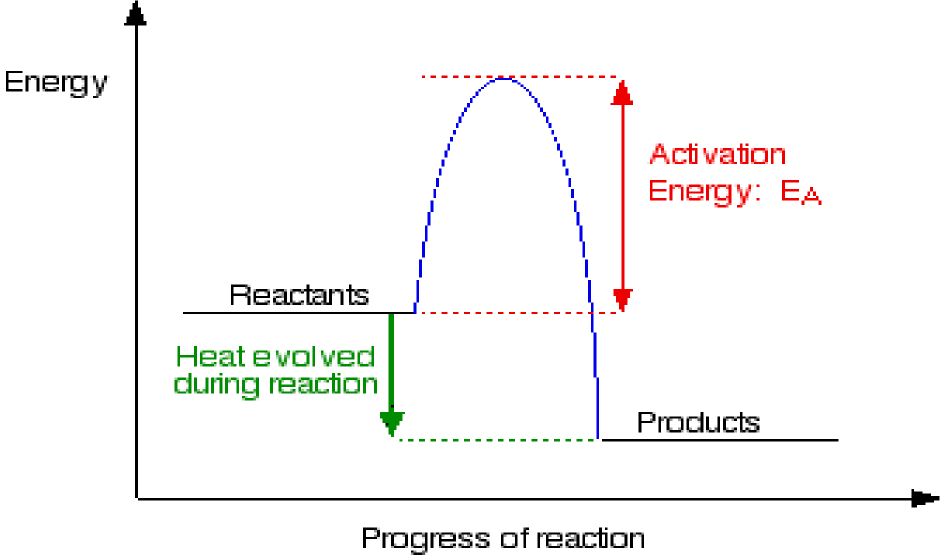


Fig. 3

Raising the temperature (heat) causes the atoms (particles) to move at a higher rate of speed; hence more kinetic energy increases the reaction rate by increasing the number and especially the energy of the collisions resulting in precipitation. Kinetic energy can be enhanced by pressure changes or electric fields (pulsating and/or static) and/or catalyzed by a surface.

In an operating cooling tower the water removes the heat from the heat exchanger via evaporation, which in turn allows a portion of the CO_2 to dissipate into the atmosphere. This evaporation concentrates the minerals in solution leading to a saturation condition resulting in calcium carbonate scaling on the heat exchanger surfaces. The most consistent applications of PWT have been found in cooling towers, where the repetitive treatment of the water by the PWT system can be readily obtained.

To develop an effective PWT system one should formulate a mechanism that describes how the system works and is based on observable facts (both scientific and industrial). The design parameters around which a PWT system operates can be adjusted and reviewed based on this understanding. A successful hypothesis is not necessarily a permanent hypothesis but it is one that stimulates additional research and development, opens up new designs, or helps to explain and coordinates previously unrelated facts. One of the purposes of this paper is to put forth the latest hypothesis taken from scientific literature coupled with some industrial designs and resulting field data to enhance the understanding and continuing development of PWT technology for cooling towers.

In an effort to explain the mechanism of PWT two types of fouling should be reviewed: crystallization and particulate fouling. Crystallization fouling (hard scale) is a form of *heterogeneous nucleation* and growth of calcium carbonate on pre-existing surfaces. Textbooks on precipitation and solidification maintain that the crystal growth process is primarily the result of single atoms / ions arriving at or departing the solid surface. This process allows for crystal growth that is defect free, hard and tightly adherent to the surface.

Particulate fouling is a deposition process of particles (corrosion products, bacteria, etc.), including small carbonate crystals (colloidal particles) carried by a flowing fluid. The probability that a small crystal (floating) would be ‘in register’, i.e., all atomic bonds aligned, with the surface of a pipe or a growing crystal is extremely small. These particles accumulate by particle transport and gravitational settling. Bott [2] explained particulate deposition (fouling) by a transport mechanism and agglomeration. This agglomeration or particulate fouling is usually soft and not tightly adherent. Note that a shear force from a high velocity fluid will keep these particulate from adhering and preventing a stronger bond with the surface via sintering, drying out or cooking process (known as ripping).

In this paper the most plausible hypothesis, (delineated by Cho [3, 4]) utilized in scientific papers and supported by field operations, will be used (data presented in Table I). The PWT’s discussed here appear to cause the precipitation of mineral ions, producing particulates (small seed crystal or colloidal particles) in bulk water. These particulates (fouling) form soft sludge coatings that can be kept in suspension by high flow and turbulence and removed by filtration or blowdown. These hypotheses delineate the functional similarities of the main PWT technologies, utilizing the physiochemical fundamentals stated above.

Permanent Magnets Method

Permanent magnets used in the treatment of water has been cited in literature and investigated since the turn of the 19th century, when lodestones and natural occurring magnetic mineral formations were used to decrease the formation of scale in cooking and laundry applications. History shows that Egyptians used naturally occurring magnets (lodestones) two to three thousand years ago in an attempt to reduce scale deposits in lead pipes / vessels carrying hard water. The use of magnets may be one of the oldest methods for the prevention of scaling in heat transfer components and the transportation of hard water.

Commercialization of this technology began after World War II, with the largest advances coming in the last 20 years with the development of high-power, rare-earth permanent magnets advancing the technology to the point where it can achieve more consistent performance.

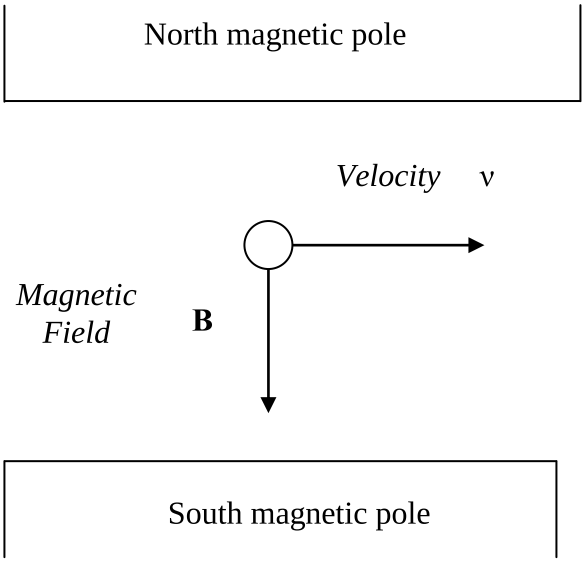
The force exerted by a magnetic field (and resulting electric field) on a charged particle (ionic) is the result of *Lorentz force.*

$$\mathbf{F} = \mathbf{qE} + \mathbf{qv} \times \mathbf{B} \qquad \text{(Eq. 7)}$$

- $\mathbf{F}$ is the force
- $\mathbf{E}$ is the electric field
- $\mathbf{B}$ is the magnetic field
- q is the electric charge of the particle (ions, etc.)
- $\mathbf{v}$ is the instantaneous velocity of the particle and
- **x** is the cross product (used to multiply vectors)

We are interested in the force due to $q\mathbf{v} \times \mathbf{B}$ portion of this equation, which calculates the force exerted on a charged particle (ionic, with charge of q) moving with velocity $\mathbf{v}$ in a magnetic field $\mathbf{B}$, where **x** denotes the vector cross-product and is illustrated in fig. 4.

Therefore, an ionized fluid moving perpendicular across a magnetic field produces an electric current proportional to the *Lorentz force*. This force is perpendicular to both the magnetic field and to the direction of motions and is proportional to the velocity, (See Fig. 4). Since the force is at a right angle to the velocity, it will not affect the magnitude of the velocity but will merely alter its direction. The forces on ions of opposite charges are in opposite directions increasing the frequency of opposite charge ions colliding with sufficient kinetic energy to form mineral colloidal particles in the fluid. This is called bulk precipitation. These particles are suspended in the water but particulate fouling can take place on surfaces (including the heat exchanger), which causes a soft sludge coating. However, when there is a sufficient shearing force due to the water motion, the soft sludge or silt coating can be removed and the mineral fouling prevented. It should be noted that magnetic fields parallel to the direction of motion would not impart a force on the charged particles. Review Fig. 4.



Force due to the magnetic field of magnitude, **qv** x **B**, is perpendicular to both **v** and **B** and away from viewer

Fig. 4

Most magnetic PWT systems are directed at small flow systems, pipes < 3 inches in diameter. This may be due to the design that places the magnets on the outside of the pipe that in most cases limits the perpendicular magnetic field strength and size (therefore reaction time) inside the pipe. Two designs using small magnets outside of the pipe are shown in Fig. 5 and Fig 6 (Trentatron).

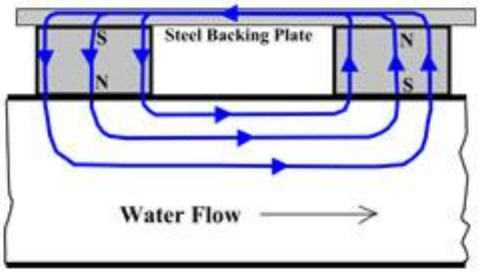


Fig. 5, Small volume of uneven flux density perpendicular to flow (active volume)

Note that in these configurations the magnetic flux density **B** is always less inside the pipe than the magnet ratings placed outside the pipe. Therefore the design and the material (of the pipe and magnet support) will have a strong influence on performance. Generally designs of this type (Fig. 4 & 5) are for smaller flow applications (Mag-Sol Enterprises, LLC, Trentatron, etc.), and have a magnetic flux strength ranging from 1,200 to 9,000 Gauss.

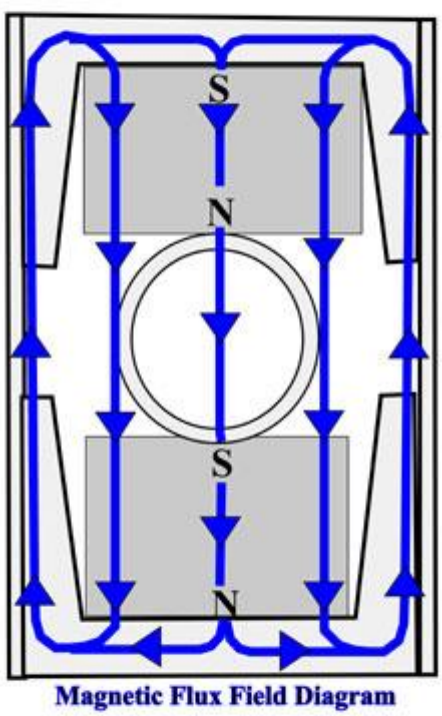


Fig. 6, Trentatrons design produces magnetic flux that results in a large field (active volume) perpendicular to the flow.

A Polish paper by Szkatula on magnetic PWT found non-crystalline silica-rich material to form, as a silicate hydro gel, which will in-turn absorb calcium, magnesium and other metal ions and then precipitate from the solution as agglomerate [5]. The result on scale prevention is similar, but utilizes a different mechanism.

One innovative design places multi-pole magnets inside a pipe giving a large active treatment volume capable of treating large flows. Superior Water Conditioners (patented) from Magnatech Corporation developed a multi-pole magnet for internal placement allowing a sizable number of these units to be placed inside a chamber (pipe) to give a high flux, large active volume (increased reaction or dwell time). These systems were demonstrated to treat sizeable volume of water in large diameter pipes. A single unit is shown in Fig. 7.

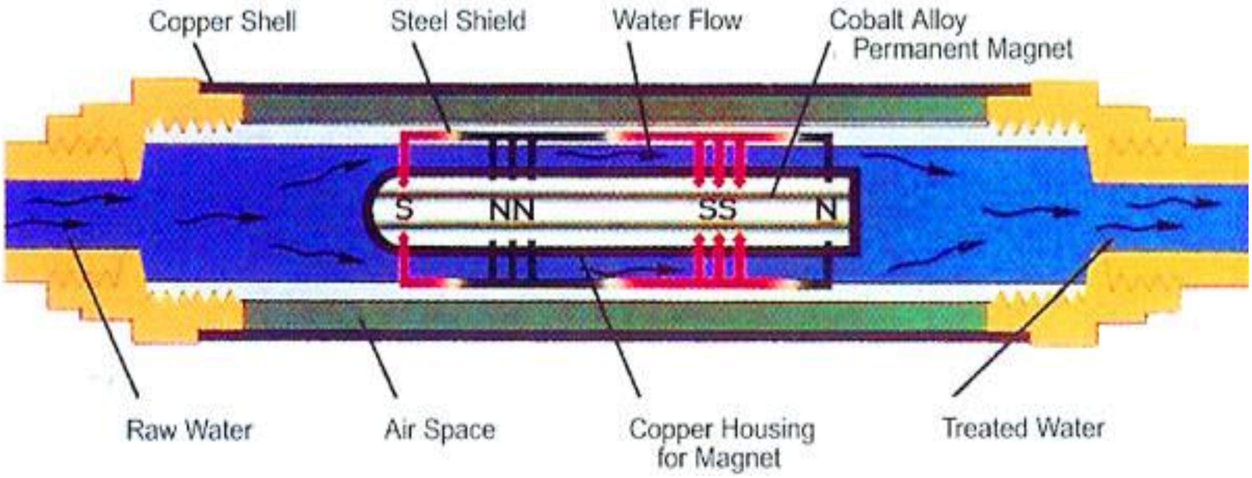


Fig. 7, (Superior Water Conditioner, Magnatech Corporation)

Recalling that the Lorentz force, due to ***qv*** x **B** portion (magnetic), not only includes the magnetic flux vector **B**, but also the velocity vector **v**. As noted by Cho [1, 4] the effect of magnetic PWT on scale prevention has not been consistent due in part to the value of the flow velocity (perpendicular) through the magnetic field. Cho demonstrated that an optimum flow velocity through the magnetic PWT device was necessary to maximize scale prevention in laboratory equipment. At lower velocities the induced force is smaller and at higher velocities the dwell time in an active volume may be too small to allow migration of the ions leading to bulk precipitation. When treated at optimum flow velocity the mineral ions that are dissolved in the cooling water precipitated in the bulk water, grew in size and eventually were deposited on the heat exchanger surface in the form of particulate fouling [1]. Particles deposited on the heat transfer surface as a soft sludge coating, were easily removed by shear force unlike the hardened scale deposit produced by the diffusion of ions forming hard crystalline scale. SEM photographs of scale layers for the two cases (no-treatment vs. PWT-magnetic) have different morphology. For the no-treatment case numerous tiny crystals (0.5 μm) vs. large particles for the PWT case composed of multi-layers of scale supporting the bulk precipitation hypothesis. The variation in the performance is not well understood and further investigation is required. However, for a piping system with a known flow velocity a magnetic PWT could be configured to effectively control scale.

Electric Fields Devices

An electrostatic PWT device has an applied constant (DC) voltage. Since it is known that ‘like’ charged particles repel each other and ‘unlike’ charged particles attract each other, this concept is applied to the relationship between an electric field (positive to negative) and ions as shown in Fig. 8 Both electric fields and magnetic fields can be defined from *Lorentz force law:*

$$\mathbf{F} = \underline{\mathbf{qE}} + \mathbf{qv} \times \mathbf{B} \qquad \text{(Eq. 8, see Eq. 7 above)}$$

In this section, directed at <u>constant electric fields,</u> we will use only the ***q*E** part of this equation. The electric force is straightforward, being in the direction of the electric field if the charge ***q*** is positive as shown in Figure 8.

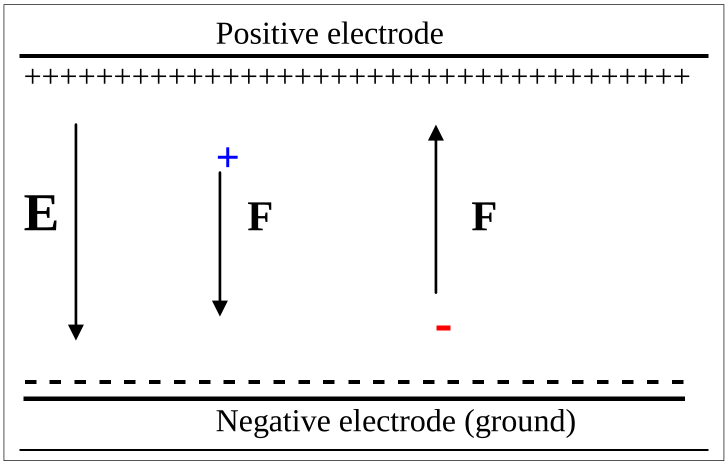


Fig. 8
Electric force ***q*E,** due to electric field **E**

The hypothesis explaining the operating principles of any PWT system must follow the same physical and chemical fundamental concepts used for all water treatment systems. By allowing water with dissolved minerals like Ca^{2+} and HCO_3^- to pass through an electric field the Ca^{2+} and HCO_3^- charged ion/molecules will have a force applied to them as indicated by Equation 7 and shown in fig. 4 & 8.

When an electric field is created between two electrodes the positive ions will be attracted toward the negative electrode and repelled by the positive. Conversely, the negative ions will be attracted to the positive surfaces and repelled by the negative (as shown in fig. 4). The primary function of the applied field and the resulting force on the ions is to impart opposing velocities via the electric force to the oppositely charged ionic particles, thus increasing their respective kinetic energy and hence increasing the probability of a collision overcoming the activation energy and forming a crystalline calcium carbonate compound (bulk precipitation). This phenomenon results in nucleation of small crystals of calcium carbonate and removes the mineral ions from solution and places them in suspension (*colloidal* particles) as seen in Figure 9.

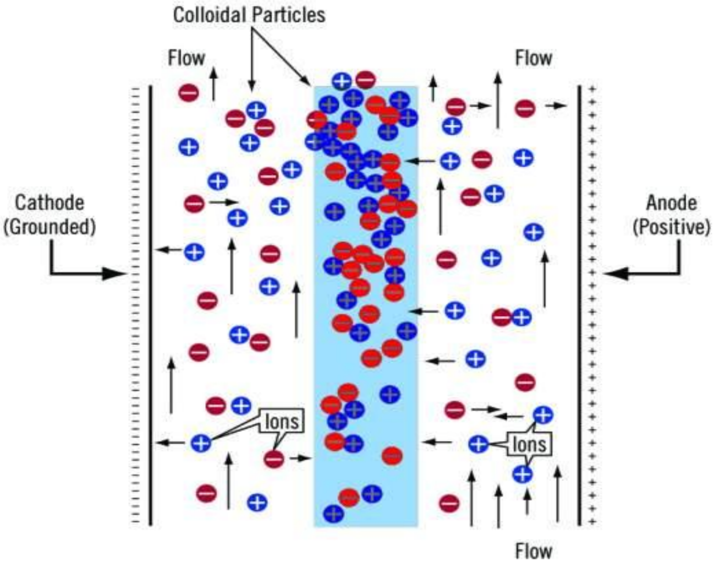


Fig. 9

In an ASHRAE Research Project conducted by Cho [4], tests were run with an electric field PWT. Running at COC (cycles of concentration) of 5 with a conductivity of 3,000 µS/cm, the fouling resistance to heat flow decreased 53% from the values of the no-treatment case. In this study the effect of flow velocity, higher conductivity levels, longer run time, as well as field strength was not evaluated. The results of this science study [4] and the field data in Table I support the bulk precipitation hypotheses.

A brief review on the evolution and market / performance driven developments in electric field PWT water treatment technology may shed some light on these variables. Electric field PWT got its start in North America in 1957 when Roy C. McMahon received a patent and started the company, Electrostatic Equipment Company. The major North American suppliers of electrostatic water treatment technology can trace their roots to McMahon's basic technology. ElectroStatic Technologies, Inc. is a direct descendent of the Electrostatic Equipment Company while Zeta Corporation and York Energy Conservation were formed some years later.

Improvements have been made over time, e.g., increasing the applied voltage from 3 kV to 10 kV and now to 35+kV, (higher **E** results in larger **F**) using different materials for the dielectric (insulator), and increasing the size and changing the shape (tubes vs. plates) of the electrodes. These later developments were directed at improving the uniformity of the electric field and increasing the dwell time of the water in the PWT's active regions. Initially a tubular electrode was primarily used for cooling towers, (Zeta Corporation, Ion Stick, ElectroStatic Technology Inc., etc.) and placed in a grounded (negative) chamber or pipe and in some cases just suspended in the water (electric field shown in Fig 10). Note that the electric field decreases with distance from the electrode. In 2001, Fluid Treatment Solutions, Inc., introduced a flat plate electrode with a grounded metal cage, (patent pending), which gives improved electric field uniformity (see Fig 11). These grounded metal cages can be dropped into a cooling tower basin to treat the fluid stream using multiple cages/electrodes creating very large treatment volumes (uniform electric field). This allows for installation in large, operating cooling tower systems, normally with no backpressure and very little down time. These developments directed at electrical field strength and dwell time are in accordance with the stated basic mechanism and supported by data in Table I.

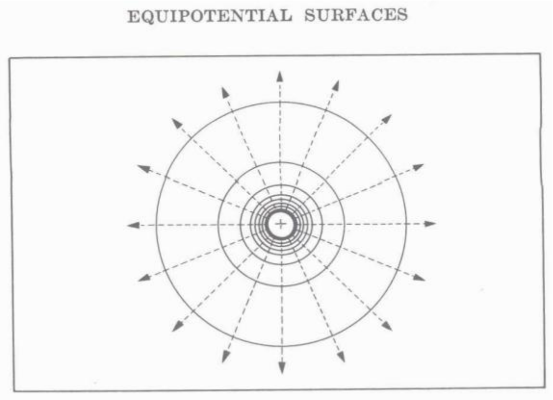


Fig. 10

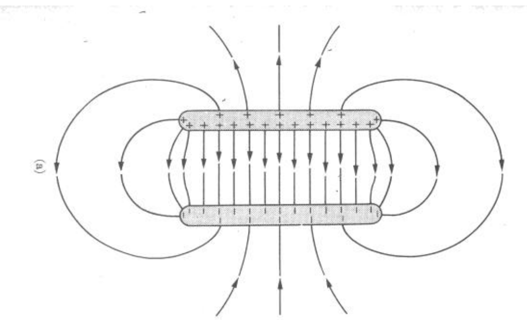


Fig. 11

Solenoid Induction Coils Devices

Physicists consider electrical and magnetic forces to be derived from the same single fundamental force i.e., electromagnetic forces. In the magnetic section, it was put forth that the charged particle must be moving perpendicular to a magnetic field in order for a force to be exerted on it (Lorentz law). In this section, we will consider an electrical field generated by a moving or changing magnetic field **B**. As the discussion of *Faraday's law of induction* coupled with *Lenz's law* is somewhat complex, a detailed discussion is not presented. However, these two laws simply state that an electric field is induced in the volume of a solenoid coil if the magnetic field inside the coil volume is changing with time. Note that the magnetic field is proportional to the current in the coil windings. So as the current in the coil winding changes with time the magnetic field changes with time too and induces a counter electrical field that resists the change, i.e. an induced electric field. It also makes a difference how fast the change is made with time: a quick change induces a stronger electric field than a gradual change, because the magnitude of the induced electric field is proportional to the rate of the change of the magnetic field. Therefore, this time varying magnetic field induces a rapidly changing electric field in the water system of the same frequency as the magnetic field but in a direction around the circumference of the pipe.

This induced voltage is at a maximum at the peripheral of the tube/coil interface and decreases to zero at the center of the coil/pipe. Note that due to the magnetic and conductive characteristics of metal pipes a polymer section of pipe is normally inserted with the solenoid coil.

A study conducted by Cho [4] reviewed the fouling results of a solenoid coil PWT by varying the strength and frequency of the applied current to the system. Flow velocities were fixed at 1.0 m/s with the electric conductivity set at 3,000 μS/cm. As the strength and frequency of the current signal increased from 0.7A, 0.5 kHz to 7.0A, 3.5 kHz, the efficiency of the PWT (as measured by the reduction in the fouling resistance relative to the no-treatment case) increased from 20 to 53%. To support the fouling experimental results, water drop evaporation tests were conducted. For the no-treatment case, crystals did not start forming during the first 30 minutes, and at 45 minutes tiny particles were found at the boundary of the water. With the solenoid coil PWT, crystals appeared after only 30 minutes in the treated water, an indication that bulk precipitation (particulate fouling) was occurring at the suspended seed crystals (colloidal particles).

Various methods are employed to increase the rate of change of the current and therefore the induced voltage. These range from an offset coil with a square wave current at up to 5 kHz, to a 60 Hz sine wave with a spike in the current at each cycle and results in a ringing effect in the megahertz range. These time-varying magnetic fields induce a rapidly changing, alternating electric field in the water system around the circumference of the pipe, as seen in Fig. 12.

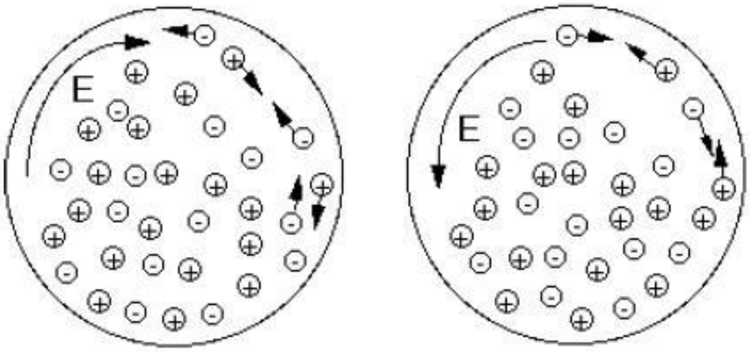


Fig. 12. Applied alternating current, outside the pipe in a coil, results in a longitudinal magnetic field that is constantly reversing direction. In the water a circumferential electric field (E) alternates in opposite direction and at the same frequency as the applied current. (Cho)

In these solenoid coil systems the alternating induced electric field enhances the formation of small crystal nuclei (colloidal) in the bulk solution as suspended particles. This precipitate does not adhere well to metal surfaces but remains with the bulk solution and are removed via blow down and/or filtration. Note these suspended particles can cause particulate (sludge or silt) fouling on the surface of a heat exchanger, which can be cleaned by the shearing force of water (high flow) if water has a sufficient velocity.

The solenoid coil technology (PWT) has been around for a number of years. The smaller units (< 3 inch) normally wrap a wire around the pipe through which the alternating current was applied. Use of solenoid coils in recirculating water systems (cooling towers) started around 1990 in Italy. The induction principle is the bases for the larger Freije system, the Clearwater-Dolphin system, and a new comer, the Evapco – Pulse~Pure system.

Electrolytic Method

A system marketed by Chardon Labs (and others in the US), developed and manufactured by Elgressy Engineering Services Ltd. employs electrolysis to control scale on chiller tubes and heat exchange surfaces. The cooling tower water is treated inside a separate side stream device where electrolysis takes place. The electrolysis causes hydroxide ions (OH^-) to form at the cathode, increasing the pH at the cathode.

$$2H_2O + 2e^- \rightarrow H_2(g) + 2OH^- \qquad \text{Eq. 9}$$

This high pH at the cathode causes $CaCO_3$ to precipitate and adhere to the chamber walls, increasing the electrical resistance. An automatic piston is actuated, when the electrical resistance reaches a trip point, removing the scale from the reaction chamber wall which is discharges down the open drain. These systems precipitate and remove enough of the calcium from the water entering the system to maintain the concentration of calcium and alkalinity below the threshold solubility. Units designed for flows up to 350 gpm are available. Note, as electrolysis is a well-known technology, an independent scientific study for this application (cooling towers) was not found, however, field data (Table I) support the capability of these PWT's.

Hydrodynamic Cavitation Method (sudden pressure / temperature changes)

Cavitation (the formation, growth, and implosive collapse of gas or vapor-filled bubbles in liquids) can have substantial chemical and physical effects [8]. A well-known technique for the generation of cavitation is the use of ultrasonic to produce physical or chemical effects. Ultrasonic technology results in regions of pressure change causing cavitation to occur, and gas bubbles are formed in the liquid. The bubbles collapse, creating shock waves resulting in localized (small) regions of very high temperature and pressure [9]. A literature search revealed few scientific papers on precipitation of calcium carbonate by ultrasonic irradiation [10], with none found for scale control in cooling towers. However, an ultrasonic water treatment system, SONOXIDE®, is a low power, high frequency ultrasonic unit for microbial control for cooling towers, (discussed later).

In a unique approach to hydrodynamic cavitation, VRTX Technologies create cavitation by rotating specially slotted disks at high speed. The VRTX unit that is used in scale control for cooling towers consists of a pressure equalizing and a cavitation chamber. In the cavitation chamber the water is forced to rotate at high velocity through truncated nozzles creating a strong vacuum, (releasing CO_2) which forms micro bubbles. The pressure-equalizing chamber brings several streams together to collide at the mid-point of the chamber forcing the bubbles to collapse. This cavitation results in a high pressure and high temperature micro-zone (solubility of $CaCO_3$ decreases) causing the dissolved calcium and carbonate ions to react and form colloidal calcium carbonate crystals. This in turn increases the pH and allows the colloidal particles to act as incubation sites (also similar to other systems that create colloidal seed crystals) for dissolved calcium and carbonate ions to grow on, in lieu of, metal surfaces. This method is supported by resulting field data (example shown in Table I). The VRTX system includes a filter system that operates independently to remove suspended solids from the recirculating water, thereby decreasing blowdown.

Catalytic Devices

In 1836, J. Berzelius defined a catalyst as a compound that increases the rate of a chemical reaction, but which is not consumed by the reaction. A catalyst provides an alternate path with a lower activation energy by which the reactants can proceed to form the products. Hence, the rate of the reaction can be greatly increased by the presence of the catalyst (generally a surface reaction). Honeywell's Kaltecpro™ is such a technology that is directed at calcium carbonate and is based on a natural process using enzymes (catalyst).

Crystallization takes place as a result of a surface process, utilizing this catalytic principle, generating a large number of seed crystals (colloid particles) or nuclei. This is accomplished by using a container filled with the activated Kaltecpro™ material (balls), as a catalyst to overcome the hydrate envelopes, which usually prevents the forming of crystals in water. However, the Honeywell's technology is primarily focused at the residential market for potable hot water systems, not cooling towers, but it may open the door.

Tijing et al, [6] and Lee et al [7] have tested two other catalytic PWT's. Lee reported that the catalytic materials could reduce the fouling resistance by 17 – 38% producing scales that were soft and easily removable. Tijing tested a Cu-Ni alloy and heat-treated titanium balls also that produce precipitation of mineral ions in water. During the evaluation tests water was passed repeatedly through the PWT(s) and a mini-cooling tower with samples taken periodically. The study found that the number of particles formed of a diameter less than 8μm was significantly greater than that of larger particles and showed a large increase in the total number of particles for both catalytic PWT's compared to the no-treatment case. The increase in the total number of particles (<8μm) was 465% for Cu-Ni and 282% for Ti, with respect to the no-treatment case. This research supports the fact that small seed crystals are formed and that increased exposure to PWT can result in higher precipitation of particles, supporting the bulk precipitation hypnosis of the PWT. Field data for these catalytic PWT's have yet to be made available for large cooling tower.

Corrosion and Biological Control (from a PWT perspective)

In the PWT systems discussed all increase the pH of the cooling tower water, (compared to the no-treated cases). Elevated pH levels aid in controlling or minimizing corrosion rates. Typical pH levels below 5.5 are considered very corrosive and above 7.5 to be non-corrosive (NACE). Alkaline environments are not considered to be corrosive to steel. The field data that is included, Table I, support the low corrosion rates in PWT treated cooling towers; however, corrosion rates will vary based on water chemistry and other environmental operating conditions, therefore, good corrosion monitoring should be a part of the maintenance program.

An independent study on biological effect of PWT's, supported by ASHRAE should commence in 2008. Initial field data indicates that PWT's are likely to be biostatic and not biocidal, (legionella, in the lab, does not grow well in pH level above 8.5). Another factor discussed by Lane [11] is the agglomeration of bacteria onto and into colloidal crystals that does not directly kill but does limit their growth. The ASHRAE study will shed some light on the capability and metrologies of bio-control of PWT. Since, chemical biocides are hazardous and can be corrosive to component of a cooling tower an alternative (PWT) would be advantageous. Ultra violet light (UV) is used for biocidial control in cooling towers. In addition, ultrasonic [8, 9] is a scientific proven technique and supported in the cooling tower industry by SONOXIDE® [15n]. More will be written on PWT bio-control as additional information becomes available. Review biological field date in Table I.

In passing, it should be noted that organic and inorganic matter (dirt) could be a major contributor to both biological growth and damaging corrosion rates in cooling towers. And even with UV it is necessary to filter the water for good performance. Periodic cleaning or continual sweep with filtration is strongly recommended. Note that in three of the above PWT systems; the Elgressy, VRTX and Magnatech have filtration included in their packages and are available from the other manufacture of PWT's.

Typical Field Data

TABLE I FIELD DATA

PWT Type	Hydrodynamic Cavitation (1)	Solenoid Induction Coil (2)	Solenoid Induction Coil (3)	Electric Field	Electric Field	Electric Field	Magnetic (6)	Electrolysis (8)
Location	MI	CA	SC	KS	MO	AZ	IN	OH
Size of Tower	400 T	330 T	200 T	4,000 T	10,000 T	100 T	6000T	800 T
Incoming Water Conductive	220 µmhos	169 µS	~250µmhos	410 µmhos	610 µmhos	1100 µmhos	650 µmhos	520 µmhos
Incoming Water pH	7.4	7.5	na.	7.8	8.7	8.4	7.7	7.2
Operating Conductive	1100 µmhos	462 µS	~2750µmhos	3400 µmhos (4)	3400 µmhos (4)	4500 µmhos (5)	2100µmhos	3500 µmhos
Operating Water pH	8.8	8.5	na.	9.1	9.2	9.5	8.6	9.0
Cycles of Concentration	~ 5.0	~2.7	>11	~8	~5.6	~4.1	>3.2	8.0
Corrosion Data - Mild Steel	0.3 mpy	0.44 mpy	1.50 mpy	na.	na.	3.1 mpy	na.	na.
Corrosion Data - Copper	<0.1 mpy	0.47 mpy	na.	na.	na.	0.08 mpy	na.	na.
Biological Data	$<10^4$ CFU	$<10^4$ CFU	na.	$<10^2$ CFU	$<10^3$ CFU	$<10^2$ CFU	$\sim10^4$ CFU (7)	$<10^3$ CFU

(1) Data for a Marley CT, PWT was by VRTX Technology - [na.] --- not available
(2) Data taken from study by BWI Solutions McClellan, CA at Sacramento OPS Facility
(3) Case study, Alcoa, SC
(8) 880,000 gal. saving from 2006 meter data
(4) Recommended conductivity setting for site
(5) Running at higher conductivity in independent field test - 1 yr.+
(6) Magnetic treatment used 70% less blowdown than chem. treated
(7) Bromine was used in late summer for bio control

Considerations

In the first three PWT systems discussed, electric fields, magnetics and induced electric fields, two main parameters are involved. The force on the ions by an electric field and the time the ions are influenced by that force. The latter is the result of the probability of a chemical reaction occurring, making time a controlling factor if the force is at a minimum level. These electrical systems plus the cavitation system all have similar scale control mechanisms i.e., bulk precipitation. The colloidal particles formed in this bulk precipitation process are the seed crystals for additional precipitation in the recirculating water. These small seed crystals result in very large surface area allowing the ions to move from a saturated solution to the suspended particles. Lane's [11] comprehensive review for operating parameters of non-chemical devices, listed numerous supporting reference as well as sited several third party reviews [3, 12, 13], and additional peer-reviewed papers [14, 15], supporting this basic mechanism. The electrolytic method sited does not form seed crystals but deposit the scale on a surface for removal from the system.

Given the strong supporting evidence it should be noted that the force on the ions is difficult to determine, measure, or calculate precisely and is normally viewed empirically. The factors involved are numerous: velocity vs. magnetic field, the strength and variation of the magnetic field, rate of change of the induced electric field, the dielectric constant of the water, lack of uniformity, etc. However, as presented here, the scientific literature and available field data indicates overwhelmingly that all these systems have the ability to control scale. The question that arises is; why some systems are not consistent? The answer to this may be the remaining parameter; that is 'dwell time', (the total time in the force field or active area). The dwell time is a result of several factors:

1. Total fluid volume of the cooling tower system
2. The rate at which the water is pumped through the system (PWT), i.e., repeated treatment
3. The size, duration and shape of the force field (active treatment volume) in the fluid stream

The first two factors can be used to calculate the number of times the water sees the active area of a PWT in a given time period. The total size and shape of the force field (including the time that it is active and/or its uniformity) can be used in estimating the dwell time in the force field. Simply put, the total time a volume of water spends in the active treatment area (volume of the force field) can determine the efficiency of the system in preventing scale.

Dwell time for chemical reaction is also a controlling factor in the electrolysis, catalytic and cavitation based systems because if sized wrong, (or number of units employed) sufficient chemical reaction will not take place. So the last word is that size and time does matter.

Summation

In this paper the fundamental principles, the scientific supporting hypotheses, and field results have been presented for many of the PWT systems. There are many factors that are driving enhanced interest in PWT systems for standard water treatment applications. Some of these factors are: environmental concerns, the need for water conservation, rising operating costs and concern for employees. The benefit of all PWT's is the reduction or elimination of chemical additives for the purpose of treating cooling towers. These benefits vary by the particular PWT, local water quality and the operating conditions of the cooling tower.

Utilizing the information in this article one can start a selection process that meets their needs. Look at the history of successful installations, the performance criteria, and the likelihood (guarantee) that the supplier and user can reach these goals if both parties live up to good cooling tower practices.
As has been pointed out, the underlying technology behind PWT systems is generally well understood, but perhaps not well accepted, particularly for some applications. It would appear, based on empirical evidence, that the use of these technologies has merit. It will be interesting to note if they continue to expand their influence within the ranks of water treatment options.

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