Scientific Background of Hydrodyne Magnetic Treatment for Scaling Control in Evaporative Cooling Systems

Introduction

Evaporative cooling systems are ubiquitous in power generation and industrial, chemical and manufacturing processes, computer data centers and building HVAC systems throughout the world. Process water in evaporative cooling systems builds up a large mineral concentration during repeated cycles of water evaporation and replenishment ("makeup"). These minerals, especially calcium and magnesium, can precipitate onto surfaces within the cooling system forming a hard scale that can inhibit heat transfer, restrict flow area and serve as sites for formation of biofilms and bacterial growth. In practice, the dissolved concentration of scale-forming salts is kept below an acceptable limit with frequent dumping ("blowdown") of the high mineral content process water and/or by using scale and corrosion control chemicals that add to the toxicity of the wastewater during blowdowns. Other methods to control scale include pre-precipitation of scale-forming minerals with lime or soda ash or the replacement of these dissolved minerals with more soluble ions by ion exchange [1].

This high dissolved mineral content, however, also gives the process water a significant electrical conductivity, which makes the water susceptible to magnetohydrodynamic effects when exposed to a strong magnetic field. Hydrodyne has developed a strong magnetic field treatment using a Halbach magnet array attached to the exterior of the water flow pipe (see Fig. 1, we call it the "bracelet"). Precipitation of a soft calcium form of scale that doesn't adhere strongly to surfaces is triggered by the magnetic treatment and this calcium precipitate is largely swept along with the flow and is either discharged with the blowdown water, capture by side-stream filtration, or accumulates in low-flow areas (e.g. the cooling tower basin). This magnetic interaction mechanism can potentially be exploited to allow operation of the evaporative cooling systems at higher cycles of concentration with a reduced need for chemical scale suppressants, and thus reduced volume, toxicity, disposal and replenishment costs of the blowdown water.
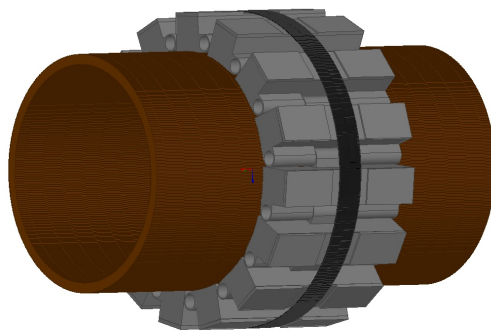

Figure 1: Hydrodyne magnetic cells attached to the exterior of a cooling system process flow pipe, the "bracelet."

The effectiveness of the Hydrodyne magnet bracelets was tested by replicating the conditions of a typical cooling tower process in a scaled down simulator at the Hydrodyne lab. A series of experiments was performed, with and without magnetic treatment, which show a measurable effect on the quantity and characteristics of the precipitate. With magnetic treatment, the process water forms large quantities of soft, powdery, easily removable precipitate. Without magnetic treatment, the process water forms smaller quantities of tenacious scale that requires both chemical treatment and vigorous scrubbing for removal. Solids removal by filtration, by blowdown and by physical removal are all enhanced. Tests also showed a reduction in biological colony growth in the treated water compared to control tests.

Lorentz Force and Magnetohydrodynamics

Dissolved minerals such as calcium, magnesium and sodium compounds that segregate into ions can give water a significant electrical conductivity, which can vary from several 100's to several 1,000's µS/cm in river and ground water sources and up to 50,000 µS/cm in seawater [2]. These ions, when moving with the flowing water through a magnetic field, will experience the Lorentz force:

(1) $\mathbf{F}_{Lorentz} = q^*(\mathbf{u} \times \mathbf{B})$ (in N)

$\mathbf{F}_{Lorentz}$ is proportional in magnitude to ion velocity being carried with the flow (u), the ion charge (q) and the strength of the magnetic field (B) and is directed perpendicular to both the velocity and the field direction and in the opposite direction depending on the charge sign. In a simple geometry with a uniform magnetic field and flow velocity like that shown in Fig. 2 below the Lorentz force will lead to charge separation, which in turn will create a resulting electric field E (i.e. voltage gradient $-\nabla\phi$).
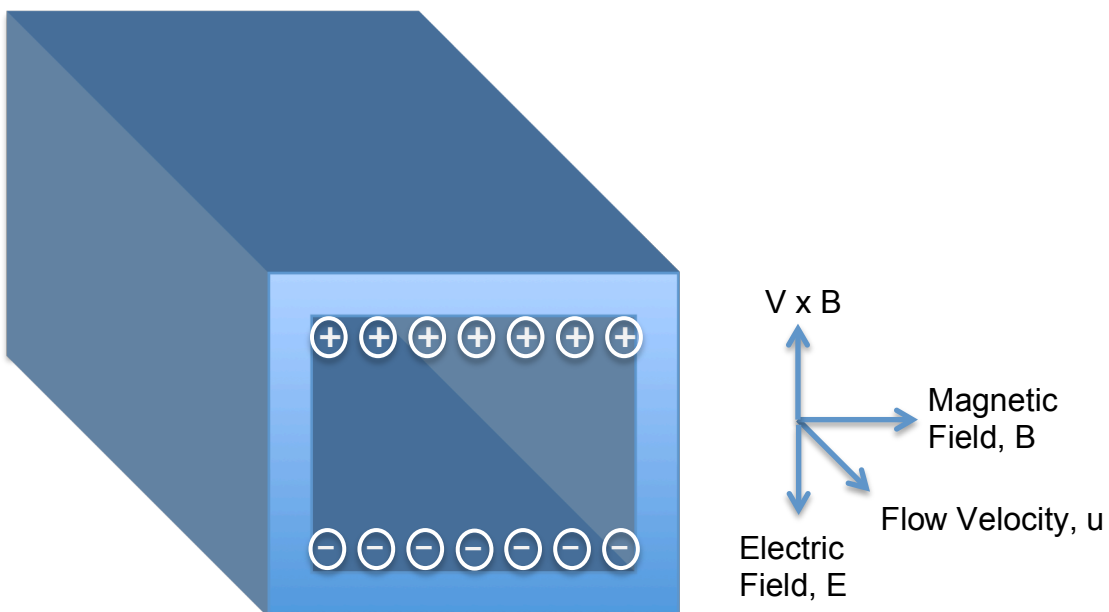

Figure 2: Simple process water flow channel in a uniform magnetic field. MHD forces lead to charge separation and a resultant magnetic field

The electric field will also exhibit a force on ions in the flow:

(2) $\mathbf{F}_E = q\mathbf{E} = -q\nabla\phi$ (in N)

and also on electrons in the pipe wall if that material is metallic and thus also electrically conductive. These combined forces on charges lead to electric current flow in the fluid according to the modified Ohm's law:

(3) $\mathbf{j} = \sigma(-\nabla\phi + \mathbf{u} \times \mathbf{B})$ (in A/m^2)

where $\mathbf{j}$ is the current density and σ is the electrical conductivity. This electric current, a stream of ions moving through the water, creates a drag force on the surrounding water volume:

(4) $\mathbf{f}_{Laplace} = \mathbf{j} \times \mathbf{B}$ (in N/m^3)

such that the water velocity itself can be altered by the flowing electric current j. The electric current flow also creates heat due to the medium's resistance to electric current, known as Joule dissipation:

(5) $h = \mathbf{j}^2/\sigma$ (in W/m^3)

All these effects acting together in a self consistent, nonlinear fashion on a conducting fluid flowing through a magnetic field is known as magnetohydrodynamics, or MHD for short.

Past experiments and theoretical studies (summarized in [1]) indicate that MHD effects play a role in the modification of calcium scaling behavior. While past experiments are not completely consistent in the literature, the evidence suggests that the enhanced precipitation of soft calcium carbonate tends to increase with the following variables:
   • strength of the orthogonal magnet field, B
   • velocity of the water flow through the magnetic field region, u
   • time of exposure to the treatment, t (i.e. multiple recirculation through the treatment region increases this treatment time)
   • electrical conductivity of the electrolyte, σ, which increases both with temperature and ion concentration of the process water

All of these factors are variables in the equations for Lorentz force and MHD current flow given in the above expressions and indicate that MHD effects are critical. This conclusion suggests a figure of merit such as:

(6) $M = \sigma \cdot u \cdot B \cdot t$

which should be maximized to enhance the effect. Some studies also show a benefit from multiple rapid variations of the magnetic field as well [3], rather than just a uniform magnetic field in the treatment region. Perhaps this is due to the formation of more

electric current loops in the flow. In this case, we might consider modifying the figure of merit to include a term like B.∇B as a measure of both field strength and field gradient.

Underlying Mechanisms

While likely related to MHD phenomena, the exact physical mechanism by which calcium behavior and scaling is affected is still uncertain and difficult to assess. Unlike in highly conducting liquid metals or moderately conducting molten salts [4], the comparatively lower conductivity of even high cycle cooling water means that any impact of MHD effects on the flow momentum or local temperature of the fluid flow is unlikely to be significant. In other words, flow mixing or heating effects suggested by some researchers are not likely the critical mechanism.

Instead, the effect on calcium scaling likely stems from the impact of the Lorentz force on charges and polar water molecules, triggering one or more of the following mechanisms:

1. Ca precipitation is enhanced at cathodic surfaces due to net current flow or modification of the electrical double-layer near the pipe interface.

   Given the charge separation and current flow described above, it is possible a reverse electrolytic reaction takes place precipitating loosely adhered $CaCO_3$ at or near cathodic regions of the pipe wall. Evidence supporting this case is bolstered by Hydrodyne experiments that show loose calcium accumulation on the inside of the pipe near the magnetic field poles of the Hydrodyne device (see Fig. 3, the Hydrodyne bracelet is on the exterior of the pipe shown in this image and not viewable here). An alternate or complementary mechanism is that the layer of charges that form in response to the Lorentz force is different than the typical electrical double-layer that forms near any charges or interfaces in an ionic electrolyte. This voltage change in the double-layer somehow accelerates precipitation of loose crystalline $CaCO_3$. Whatever the exact mechanisms of formation at the pipe wall interface, a plausible theory for the continued effectiveness of the treatment, even after magnets are removed, is that this loose precipitate then breaks off and is carried along with the flow. These colloids serve as sites for continued homogeneous nucleation in the flow itself until they are either filtered out, settle in a low velocity area (e.g. the cooling tower basin), or are swept out with the blowdown.

2. Homogeneous Ca precipitation is enhanced in the flow itself due to disruption of charge or polar water molecule layers that form around ions and colloids in the flow.

   This disruption may be due to the motion of the ions themselves, i.e. the electric current driven by the Lorentz force, which increases the frequency of collisions between positively and negatively charged ions within the bulk flow [5]. A larger number of Ca and CO_3 ions collide with sufficient kinetic energy to homogeneously precipitate within the bulk flow as opposed to precipitating onto heat exchange

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surfaces. Additionally, polar water molecules that normally would form hydration layers around charged ions or colloids to shield their charge are now are forced to align with the magnetic field and have a reduced effectiveness in preventing the attraction of oppositely charged ions [6]. Once formed, it has been proposed that these electrically distorted colloidal particles provide large surface areas for the adsorption of Ca and CO_3 ions and subsequent crystal nucleation and growth of a morphologically powdery calcium carbonate precipitate. The precipitate formed in the bulk flow is benign as it travels through the system and will eventually be settled, filtered, or blown down. Perhaps the behavior shown in Fig. 3 can then be attributed to agglomeration of these crystals near the strong magnetic field regions, a sort of magnetic trap, rather than the explanation given above.

Figure 3: Image of inside of 304 stainless steel pipe after magnetic treatment. Accumulations of loosely bound calcium precipitates are clearly seen near the location of the magnetic pole faces of the Hydrodyne magnetic treatment bracelets.

3. Generation of free iron ions from the pipe wall into the flow that are known to have antiscalant properties. It is possible that this is a contributing effect in some cases, but researchers have shown that the positive effect of magnetic treatment is still present even with non-metallic systems. Additionally, corrosion rates in metal pipes in general appear to be reduced as an ancillary benefit.

In addition to calcium scaling, there appear to be secondary benefits of magnetic treatment of process water. Hydrodyne experiments have shown the decrease in biological growth following a week of magnetic treatment. Other researchers have seen

similar effects. There are several possible explanations why magnetic treatment suppresses the growth of biological agents:

(a) reduction of hard scale where biologicals might grow
(b) entrapment of biological agents on precipitating calcium crystals in the flow (which are subsequently blown down)
(c) stressing and deforming cells via the small MHD voltages and currents in the flow that may damage the cell wall or trigger a response to delay replication of the cell.

Other researchers have reported a reduction in metallic corrosion as well in systems with magnetic treatment. One simple explanation for this effect may be that the process water is able to operate to higher cycles in a high pH regime, one that is less susceptible to corrosion concerns.

Critical Technical Milestones

A better understanding of the mechanism governing the magnetic treatment effectiveness on scaling behavior is necessary to make important decisions concerning their feasibility in real-world practice and their optimization for best performance.

Determine if magnetic treatment mechanism is a bulk or an interface effect. As one moves away from the magnet location on a large pipe, the field will fall off rapidly (see Fig. 4). If the effect is largely an interface effect, then extrapolation of results to larger
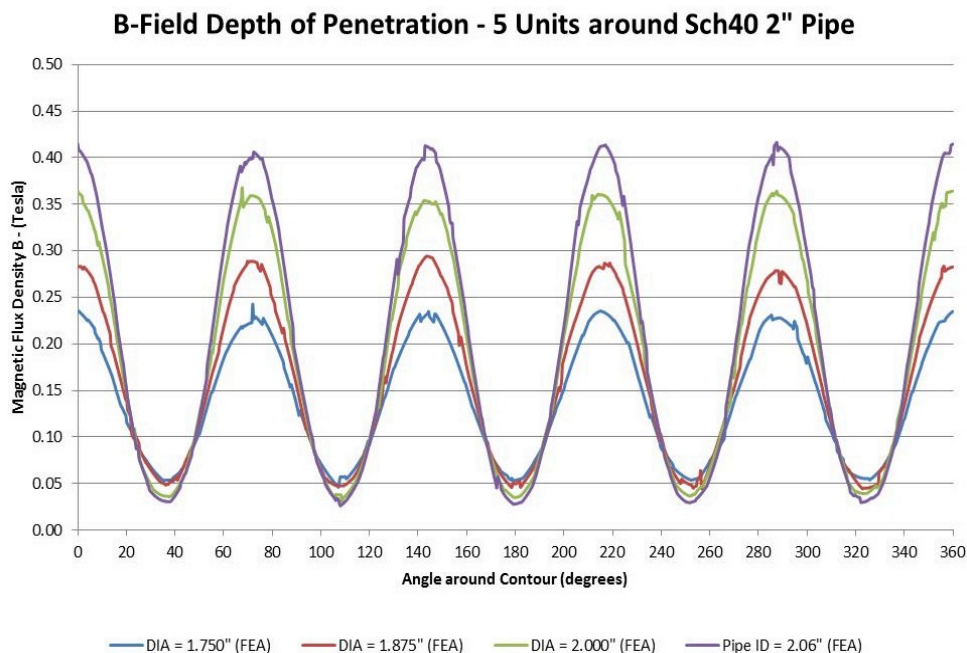

Figure 4: Variation of the magnetic field both around the pipe and as a function of distance into the pipe.

pipe sizes is less of a feasibility issue since the dominant effect will be near the pipe wall where the magnets are located and where the field is highest. In this case it may be reasonable to assume that the same number of bracelets that are used on a small pipe will have the same effect on a larger diameter pipe (note that each bracelet will still have more magnetic cells to accommodate the larger circumference). If magnetic treatment is more of a bulk flow effect, however, we would expect to need significantly more bracelets, spaced downstream along the larger diameter pipe, to generate the same bulk effect. The idea is that each bracelet treats an annular control volume of the bulk flow near the pipe wall, and that this fluid mixes into the turbulent flow downstream such that the next bracelet treats a new control volume of the flow. In this case a larger number of bracelets would be needed, and the total number of magnetic cells would increase proportional to the area of the pipe and not the circumference only.

Determine the influence of process water constituents on the effectiveness of magnetic treatment. There is a significant amount of variability in make-up water chemistry and cooling tower operation around the country and around the world. Makeup water impurities (for example chlorides, silica, etc.), rather than calcium scaling criteria, may set the triggers on when to perform blowdowns. Additionally, magnetic treatment may

be used in conjunction with a more traditional but reduced chemical treatment regimen to control scaling, corrosion and biological growth. Companies will likely wish to start with their current chemical and operational regimen and slowly modify it and assess whether magnetic treatment is picking up the slack. Study is needed as to whether the presence of additional chemicals complicates or influences the mechanisms of magnetic treatment.

Determine real operational scenarios and validation metrics. A series of beta tests in operational evaporative cooling water systems in industry will be required to establish efficacy in commercial use. Figures of merit need to be determined for measuring how the magnetic treatment is affecting the system over time. These should include regular water chemistry and heterotrophic plate count measurements as well as pumping power, pressure drop over filters, heat exchanger efficiency, corrosion coupon mass loss, and visual inspection of tower louvers, fill, spray nozzles, basins, and filters for hard scale or powdery calcium compound, biofilm and algae accumulation. Final metrics will need to be coordinated with the commercial system partners.

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