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HEAT TRANSFER

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PREFACE

For more than 40 years, the serial publication *Advances in Heat Transfer* has filled the information gap between regularly published journals and university-level textbooks. The series presents review articles on topics of current interest. Each contribution starts from widely understood principles and brings the reader up to the forefront of the topic being addressed. The favorable response by the international scientific and engineering community to the 38 volumes published to date is an indication of the success of our authors in fulfilling this purpose.

In recent years, the editors have published topical volumes dedicated to specific fields of endeavor. Examples of such volumes are volume 22 (Bioengineering Heat Transfer), volume 28 (Transport Phenomena in Materials Processing), and volume 29 (Heat Transfer in Nuclear Reactor Safety). The editors intend to continue publishing topical volumes as well as the traditional general volumes in the future. Volume 32, a cumulative author and subject index for the first 32 volumes, has become a valuable tool to search the series for contributions relevant to their current research interests.

The editorial board expresses its appreciation to the contributing authors of Volume 38 who have maintained the high standards associated with *Advances in Heat Transfer*. We also would like to welcome Professor Avram Bar-Cohen who joins the editorial board of *Advances in Heat Transfer* with the publication of this volume. Lastly, the editors would like to acknowledge the efforts of the staff at Academic Press and Elsevier Inc. who have maintained the attractive presentation of the volumes over the years.

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Physical Water Treatment for Fouling Prevention in Heat Exchangers

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I. Introduction

A. BACKGROUND

Physical water treatment (PWT) is an attempt to treat hard water for the purpose of preventing or mitigating fouling using a physical means, without adding chemicals to water. PWT has a long history of applications. Early patents for PWT devices were issued almost 100 years ago [1]. Numerous field applications of various PWT devices have been made and resulted in both successful and unsuccessful case studies. After 100 years of field applications, scientists are still looking for the operating principle and mechanism of PWT, and there are several proposed mechanisms as summarized in several articles [2–11].

The goal of PWT technology is to prevent or mitigate scale build-up at heat exchangers. Figure 1 shows that scaling (or fouling) problems involve three different academic disciplines: physics, chemistry, and mechanical engineering (heat transfer). The fouling problem starts because of hard water being heated inside heat transfer equipment. The precipitation of dissolved mineral ions and subsequent scale deposit on the heat transfer surface critically depend on water chemistry. In addition to water chemistry, the deposit and removal rates of scale also depend on flow velocity, heat flux, and heat exchanger geometry. The PWT tools we attempt to use to solve the fouling problem are governed by various laws of physics. Hence, we need to include all three disciplines to study the PWT technology. In general, PWT (without a filtration system) is not a bona fide water-softener as it does not remove any mineral ions from water. Neither does PWT add anything to water. Given that PWT does not change anything in the structure of water molecules, one may not expect to detect any changes in

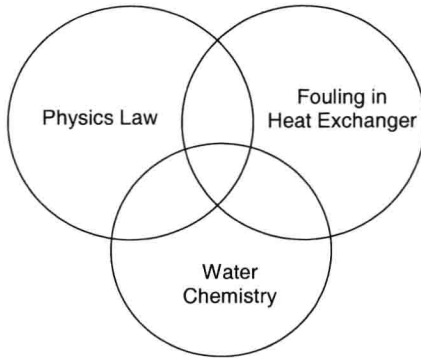


FIG. 1. Scaling problem involves three different disciplines.

water characteristics even with sophisticated analytical tools. If the benefit of PWT takes place at the heat transfer surface, one should carefully examine the fouling mechanism at heat exchangers.

The field of fouling is a unique area of research in mechanical engineering where a large number of papers and books have been published [12–18]. Billions of dollars are spent each year in the maintenance and replacement of heat transfer equipment that has been coated with various forms of scale through the fouling process [5]. A large amount of money and labor would be saved if these effects could be fully understood and controlled.

Let us briefly examine why the fouling problem exists. Due to the large amount of carbon dioxide released from various combustion sources, rain-water becomes acidic and absorbs mineral ions (mostly calcium) by dissolving limestone in subterranean aquifers [19]. These ions, when transported through piping in ordinary plumbing systems can form scaling. Scaling typically occurs when water with a high concentration of these ions is subjected to a change in temperature, which forces these ions out of solution. For every solute and solvent combination, there is a characteristic amount of solute that will dissolve under a given condition such as temperature, pressure, and pH. The solubility of a substance is the amount that will dissolve in a given solvent to produce a saturated solution [20]. Two forms of solubility are possible: normal and inverse. Some salts have greater solubility as the temperature is raised; these salts are called normal solubility salts, and examples include NaCl, NaNO₃, and silica. Other salts show less solubility as the temperature is raised, usually termed inverse solubility salts such as CaCO₃, CaSO₄, and MgSiO₃ [20]. Due to the heating (or cooling) process in thermal equipment, the temperature-dependent solubility leads to a supersaturated state. Calcium carbonate

has an “inverse solubility”, which as a result, drives the ions out of solution at a high temperature. This often accounts for crystallization fouling in and around heat exchangers [13,15,18]. Thus, calcium carbonate scaling is one of the most common scale problems in many heat exchangers where water is used as a cooling medium.

The study on the effect of magnetic or electric fields on the fouling behavior of hard water is relatively new. Despite numerous positive results, however, there has been very little data that define the parameters that control the interactions between water and magnetic or electric fields. There is consequently much skepticism in the scientific community over the effects of these magnetic and/or electric devices, since a majority of the hard science has been replaced with claims based on inaccurate or misleading principles.

In order to understand the mechanism of PWT, we should find the passageway between the PWT and fouling mitigation. The key to the passage appears to be the phenomenon of bulk precipitation, a chemical process which may be affected by a number of parameters including the external applications of magnetic or electric fields.

B. CRYSTALLIZATION AND PARTICULATE FOULING

In order to explain the mechanism of PWT, we briefly review two types of fouling: crystallization and particulate fouling. Although PWT has been used for fouling mitigation in various heat exchangers, the highest consistency in successful applications of PWT have been reported in heat transfer equipment in cooling tower water loops, where the repetitive treatment of PWT in recirculating cooling systems may have contributed to success.

Circulating cooling tower water contains an excess amount of mineral ions such as calcium and magnesium due to the evaporation of water, making the circulating water hard even if the make-up water is relatively soft. When hard water is heated inside heat transfer equipment, the calcium and bicarbonate ions precipitate due to the changes in solubility, forming hard scale on heat-transfer surfaces and clogging heat exchanger pipes and manifolds. When any undesirable material deposits on a heat exchanger surface, it is called fouling [12–18].

When the circulating water is not treated, one often finds hardened scale depositing on the heat transfer surface (Fig. 2a). This is due to crystal formation on the heat-transfer surface, often known as crystallization fouling. Factors affecting nucleation and subsequent crystal formation are the concentration of fouling materials (foulants), temperature, pH, pressure, time, flow velocity, mechanical motions, radiation, and impurities.

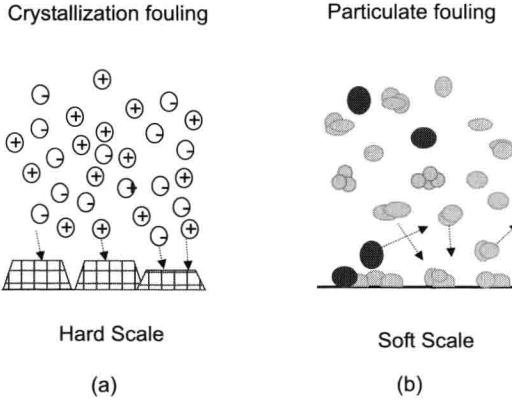


FIG. 2. Sketches of crystallization and particulate foulings.

Mechanical motions include shaking, mixing, and friction, which can be characterized as turbulence.

The initial crystals formed by a precipitation reaction may not be the most stable solids (i.e., thermodynamically stable phase) for reaction conditions. Over a period of time, however, the crystal structure changes to that of a stable phase. This change may be accompanied by additional precipitation from solution. A phenomenon, called ripening, may also take place whereby the crystal size of the precipitate increases [1]. Such hardened scale is common in heat transfer equipment using untreated water as a cooling medium. It is well known that such hardened scale cannot be removed by brush punching. Acid cleaning is often required to remove the hardened scale, which may cause premature equipment failure and replacement as well as producing chemical wastes for disposal.

Particulate fouling is a deposition process of particles carried by a flowing fluid as well as by matters generated in a solution. When compared with the scale produced in crystallization fouling, the scale produced in particulate fouling is much softer, as illustrated by Fig. 2b. The term “particle” is general and may refer to particulate matter, bacteria, corrosion products, and so on. The term “particle” also refers to particles that may be generated at the surface, such as the products of chemical reaction or crystallization [12]. The arrival of particles at a surface can take place by two mechanisms, i.e., gravitational settling or particle transport.

Beal [21] categorized the particulate fouling into three major processes: transport of the particles from the bulk fluid to the surface, the attachment of the particles to the surface, and re-entrainment of previously deposited particles from the surface back into the bulk fluid. Bott [12]

divided particle deposition into transport mechanism and agglomeration. First the particle has to be transported to the surface by one or a combination of mechanisms including Brownian motion, turbulent diffusion, or by virtue of the momentum possessed by the particle. Other factors that must be borne in mind in a consideration of the particle deposition include the agglomeration of particles in the bulk or at or near the surface, and the complex interactions of the forces near the wall.

It is of note that calcium bicarbonate is used to represent a group of mineral salts that deposit as foulants on the surface of a heat exchanger. Calcium carbonate is one of the most common scale types in cooling tower applications. The two structures of calcium carbonate crystal commonly found in nature are calcite and aragonite in morphology. They have the same chemical component, CaCO_3 , but differ in many aspects. Calcite is formed at room temperature (i.e., below 30°C), easily removable with weak hydrochloric acid, is less adherent than aragonite, and has a hexagonal crystal shape with a specific gravity of 2.71 [1]. Aragonite is formed at high temperature (i.e., above 30°C) and is difficult to remove, having an orthorhombic crystal shape and a specific gravity of 2.94 [1]. Aragonite is a more troublesome form of calcium carbonate than calcite because it forms a harder and denser deposit than calcite in boilers and other heat transfer equipment [1]. It has been of interest to see whether calcium carbonate scales produced in water treated by a PWT device is calcite or aragonite.

C. DEVICES FOR PHYSICAL WATER TREATMENT

In order to prevent or mitigate the fouling problem, various physical water treatment (PWT) methods have been applied using one of the following means: magnetic fields, electric fields, alteration of surface charges, mechanical disturbance such as ultrasound, vortex flows, and sudden pressure changes. Magnetic devices in particular have a long and controversial history in their efficacy and efficiency [1,2,10]. Numerous researchers investigated the feasibility of using a permanent magnet for reducing mineral fouling [22–31]. Some of them reported that magnetic treatment changed water properties and/or produced nucleation sites in a bulk solution, whereas others reported that it did not work.

Two most common types of permanent magnets are clamp-on magnets (see Fig. 3a) and magnets positioned at the center of a pipe (see Fig. 3b) such that water flows through an annulus gap between the pipe and magnets. Permanent magnets often have magnetic field strength ranges from 2000 to 6000 gauss (0.2–0.6 T). When charged molecules or ions pass

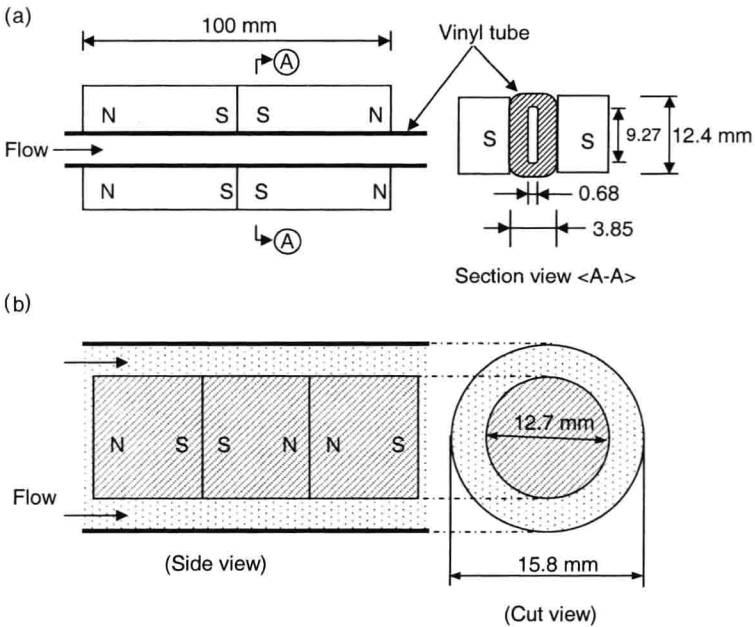


FIG. 3. Sketches of two common geometries of permanent magnets used for PWT. (a) PMDU (permanent magnet made at Drexel University), test results obtained with this magnet is identified as MWT(A) in Section 5. Total four permanent magnets were used, an arrangement that maximized the magnetic treatment on water. The maximum strength of the magnetic field was measured to be 0.16 T (or 1600 gauss) by using an Alphalab DC Magnetometer, from Salt Lake City, UT. (b) MWT(B), water moves through annulus gap between pipe wall and cylindrical magnets.

through a region under magnetic fields, electric fields are induced, which can be expressed as [32,33]:

$$E = V \times B \quad (1)$$

where E is an induced electric field [V/m], V is a flow velocity vector, and B is a magnetic field strength vector [Wb/m^2]. The magnitude of the electric field induced by permanent magnets at a water velocity of 3.0 m/s becomes $(3 \text{ m/s}) \times (4000 \text{ gauss}) = 1.2 \text{ V/m}$.

Figure 4 shows a sketch of a solenoid coil device, and a method to measure the induced electric field inside a tube. As shown in Fig. 4a, a solenoid coil was wrapped over a plastic tube, used only for forming the solenoid coil into a cylindrical shape; the plastic material has no affect on the electromagnetic field due to its non-ferrous composition.

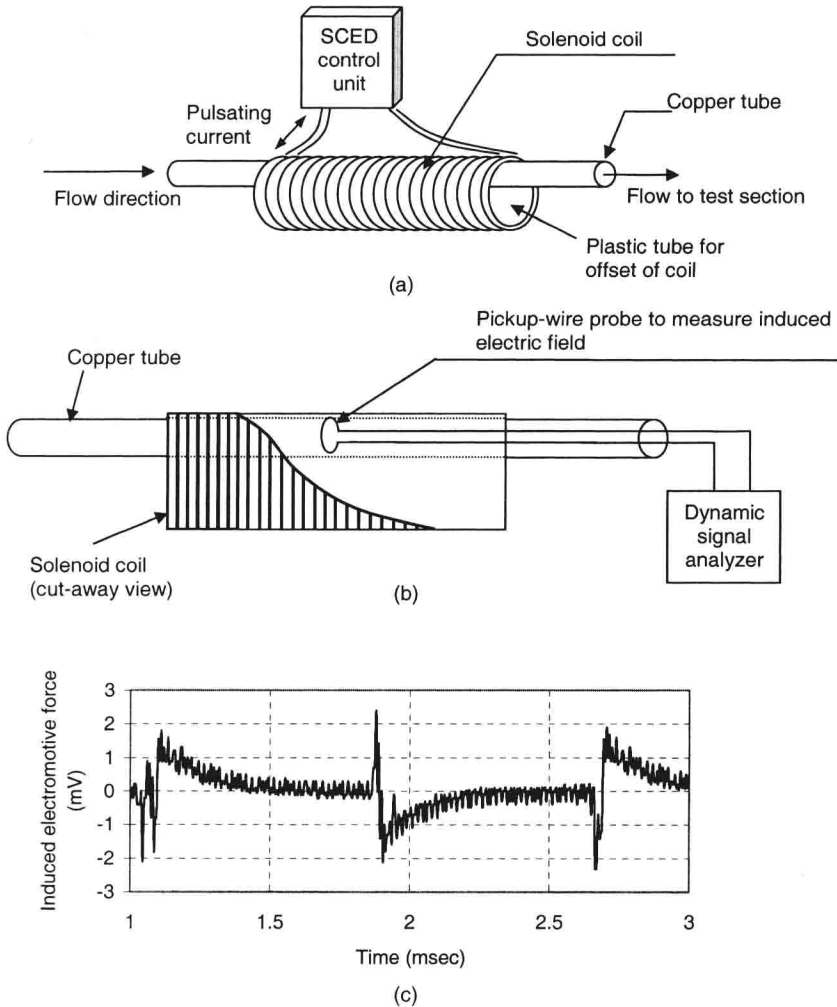


FIG. 4. (a) Installation of an EAF unit and a solenoid coil; The solenoid coil was wrapped over a plastic tube with an outside diameter (O.D.) of 50 mm. 14-Gauge wire was wound with 80 turns. Two ends of the solenoid coil were connected to a SCED-control unit. (b) Measurement of an induced electric field inside a copper tube; (c) Induced electromotive forces generated by a time-varying electric current.

Two ends of the solenoid coil were connected to an electronic control unit. The copper tube was located at the off-centered position relative to the solenoid coil since the strength of the induced electric field had a maximum value at the surface of the coil and a minimum value at the