

Minimizing Fouling in Heat Exchanger Design

Fouling dynamics of heat exchangers – an analysis of the prevention methods.

Constantine Sandu and Daryl Lund, Department of Food Science, University of Wisconsin-Madison

Introduction

Pritchard recently [1] editorialized on the dilemma of fouling research, that is, "prevention or cure?". In our opinion, the effort of fouling research has to be channeled toward optimum design and operation. This is the most realistic approach to solutions that are applicable in many industrial areas: petroleum refineries, petrochemical operations, saline water conversion, steam generation (boilers), cooling water systems, ocean thermal energy conversion, geothermal energy, chemical industry, food and pharmaceutical industry, etc.

In this review, emphasis is given to the successes in minimizing/preventing fouling of heat exchangers accomplished through proper design and operation. These successes can be attributed to engineering inventiveness in dealing with fouling as an industrial problem, despite the fact that usually the fundamentals of specific fouling processes are not known. We do not present quantitative information for the designer of heat exchangers. Rather we concentrate on the main issues which, in our opinion, are under the control of the design and operation engineers.

To understand the relationship between fouling-dynamics and design of heat exchangers, it is necessary to summarize both the parameters affecting fouling dynamics and the process of designing heat exchangers [2]. Although fouling is too complex to be considered in a general framework, its dynamics are influenced by the following parameters: nature of the industrial fluid; nature of the heating surface; fluid velocity and flow regime; design of the heat exchanger; mode of heat transfer; temperatures of the fluid and heating surface; and nature of fouled layer. On the other hand, the process of designing heat exchangers starts from a set of general data and goes through a series of stages: thermal and mechanical design; specific design; system operating and control requirements; and cost analysis. If the designing process is considered step by step, it can be shown that fouling-dynamics and the design of heat exchangers are intimately connected [2].

All correspondence should be addressed to: Daryl Lund, Department of Food Science, University of Wisconsin, Madison, WI 53706.

A general series of "reactions" (chemical, physicochemical, and physical processes) may be formulated to describe the process of fouling [3]. This series of "reactions", called *fouling kinetics*, encompasses: bulk reaction; induction reaction; fouling reaction; back diffusion; aging reaction; dissolution, erosion and spalling of fouled layer. Fouling of a heating surface can be physically and analytically described by defining every heat exchanger as a complex flow reactor in which chemical kinetics and interface processes are coupled with momentum, heat and mass transport. If one/some of the processes in fouling kinetics can be influenced, then fouling is likely to be minimized. Chemical (physicochemical) and physical treatments can change the nature of bulk, fouling, aging, or induction reactions. The construction material of heat transfer surface influences the type and rate of induction reaction, the resistance to corrosion fouling, and the adhesion strength of fouled layer. Forced convection and induced turbulence act upon the deposition and removal (erosion) mass fluxes. Mechanical erosion increases the removal mass flux.

Whereas chemical and physical treatments usually must be specific to each industrial fluid passing a heat exchanger, the design concepts are rather versatile. If forced convection and induced turbulence can be successful in saline water conversion, for instance, this concept also has potential in food and pharmaceutical industries.

Chemical Treatments

From an early patent (1869) dealing with the use of tannin and starch products to prevent fouling of steam boilers [4]—to the discoveries in the 1930s that extremely small amounts of sodium hexametaphosphate would prevent the depositions of calcium carbonate and magnesium hydroxide [4]—modern antifouling treatments are based upon thousands of chemicals [4]. This vast diversification is the result of increasing efforts to minimize fouling of heat exchangers and of changing regulations to protect the environment from the hazards produced by disposal of the effluents created with these chemicals.

Many chemical species which are prone to fouling or which catalyze different steps of fouling kinetics may be

removed from the fluid. Chemical treatments such as softening (chemical precipitation), demineralization (desalting), acidification, and sequestering (chelating) are frequently used as pretreatments in cooling water systems to remove fouling compounds. Because these chemical treatments require considerable addition of chemicals (usually more than the stoichiometric ratios), their application to large volumes of water, or to waters having high concentrations of fouling compounds (saline waters, geothermal brines, petroleum industry waters) becomes too expensive. In this case the use of fouling inhibitors (crystal modifiers) is much more economical because they are effective at concentration levels far below the stoichiometric ratio. The most frequently used fouling inhibitors are inorganic polyphosphates, organophosphorus compounds and organic polymers.

Coagulation (flocculation) treatments of waters (followed by clarification processes) make use of chemical agents to remove finely divided solids that are usually too small to settle. Most of the coagulants are used as seeds. Seeding provides a more extensive and favorable surface for fouling to occur on, rather than the heat transfer surface. This technique is widely used in saline water conversion. Calcium carbonate sludge has been recirculated as seeding sludge to prevent deposition of calcium salts on heating surfaces.

Most industrial fluids have corrosion tendencies. Preventing corrosion of heat exchangers minimizes corrosion by-products fouling and its influence on fouling kinetics. Chromate-based water treatment is generally considered the most effective fouling and corrosion inhibitor.

Industrial fluids in petroleum refineries, petrochemical operations and chemical plants are usually treated with antifoulants (in most cases, proprietary chemistry) which are multifunctional [5, 6]. The antifoulant is composed of an ashless, nonmetallic dispersant and various inhibitor chemicals (antipolymerants, corrosion inhibitors, oxygen scavengers, metal deactivators, etc.).

Heat exchangers in cooling water systems, ocean thermal energy conversion, nuclear plants, and saline water conversion, have to be protected from biological fouling (microbiological and macrobiological). The presence of biological fouling may also promote corrosion. At the same time, biological fouling can adversely affect antifouling treatments of waters. Bactericides, fungicides and algicides are presently used to control biological fouling. Among these chemicals, chlorine is the most popular. The concentration of chlorine and the frequency of application depend upon the chlorine demand of water, temperature, and flow rate. Removal of established microorganisms requires high concentrations but, even at high levels, the chlorine cannot penetrate the slime film, and the effect may be incomplete [7].

All aspects of chemical and physicochemical treatments are far too complex to treat here. An excellent presentation of the subject can be found in the monograph of Cowan and Weintritt [4] and other papers [8-21]. Fouling Prevention Research Digest lists many of the publications describing antifouling treatments since 1979.

In many American states [4], and in other countries, laws now severely restrict the discharge of potentially pollutant wastes. This must be considered in any review of chemical treatments. The discharge of polyphosphates has been

banned completely in Canada because of eutrophication of aquatic plant life [22], and some American states have a total ban of phosphates [4]. In some cases, polyphosphates are replaced with more stable phosphonates, phosphate esters, and polyelectrolytes. Nevertheless, phosphorus compounds can be removed from effluents by treatments based on bacteria, lime, polyelectrolytes, activated carbon and membrane filtration [4].

Chromate-based corrosion inhibitors are currently affected by pollution control standards in the U.S.A. [4]. Hexavalent chromium is known to be carcinogenic and also deleterious to sewage plant operation [23]. In many countries, the discharge of heavy metals into the ecosystem is controlled. This makes the corrosion inhibitors based on chromium, zinc, molybdate no longer useable, unless they are replaced/removed from effluents [4, 23]. Nitrite-based corrosion inhibitors are also suspected of adverse effects on the environment [22].

Biocides like chlorinated cyanurate, copper sulfate, sodium arsenite, sodium pentachlorophenate, etc. are subject to legislative requirements [4]. Apparently, chlorine (1 mg/liter), hypochlorine, and chlorine dioxide are not restricted by pollution control standards. Stupian [24] estimates that an anti-biofouling treatment of an OTEC (ocean thermal energy conversion) plant would require the release of 5 metric tons/hr of chlorine. What would the environmental impact be upon the marine life with this amount of chlorine? Ozone treatment as a substitute for chlorine in fouling control has the advantage that it leaves no byproducts, but it is expensive [25]. New developments in ozone generation systems claim costs less than chlorine treatment costs [25]. Also, ferrates, as powerful oxidants seem to be another substitute for chlorine because they are unstable and can co-precipitate heavy metals or phosphates used in fouling control [25].

Chemical treatments have two major disadvantages. First, the increase in the process cost due to transport, controlled handling and in-line addition, and treatments and/or disposal of the effluents. Second, some industrial fluids like those in the food and pharmaceutical industry prohibit chemical treatments because of safety or product quality considerations. However, the successful experience in chemical treatments as well as the search for new achievements in this area must be continued.

Physical Treatments

A water stream entering a heat exchanger can be treated by distillation, reverse osmosis, or electrodialysis. The heat exchanger will not foul, but this merely transfers the fouling problem from the heat exchanger to a different place. Many closed systems (e.g., closed recirculating cooling-water-systems) are using purified water through one of these methods to prevent fouling.

In waste heat recovery, gaseous streams (steam, air) are passing scrubbers/washers to remove the dust. This will improve the antifouling tendencies of the streams, but it may very well generate a fouling problem in the scrubbers. Wet scrubbers may also lead to microbial fouling, a potential problem in cleaning air from food spray drying operations.

Mechanical treatments are widely applied to remove

solid particles or liquid droplets from many industrial fluids. Settling, filtration, flotation, centrifugation, cyclones, hydrocyclones, abruptly changing the flow direction, oil traps, etc. are only some of the techniques used to make fluids less prone to fouling. Most mechanical treatments are used in connection with chemical treatments. However, settlers, filters, etc. may also experience problems with their own fouling and the disposal of sludges/deposits.

There are special physical treatments such as oxygen stripping of feedstocks in petroleum refineries, using inert gas blanketing. Also, forewarming of food fluids is mentioned as a method of reducing fouling.

Currently there are several "gadgets" on the market which claim to reduce fouling [26-28]. The principles they claim to use include magnetic treatment, electric treatment, radiation treatment and catalytic treatment [29]. Hasson and Bramson [28] described a controlled test of a magnetic water conditioner whose results showed no effects on the fouling rate or the hardness of the deposit. There is still research interest in applying magnetic treatment, because some success is claimed in improving the functioning of water cooling systems [25]. The adhesion of curd to the walls of cheese vats has been successfully prevented by an electrostatic charging of the walls [30, 31]. Burton [32], using the same principle, showed clearly that milk fouling of heat surfaces cannot be prevented; on the contrary, the fouling of a heated tube having an applied voltage was more severe than that of an uncharged tube. There is, however, an effect on the apparent density and adhesiveness of the deposit.

Heat-Exchanger Design Concepts

Most heat-exchanger design concepts used to prevent/minimize fouling do not originate with the fouling problem itself, but with the concern of designers to enhance the heat/mass transfer and to optimize the heat exchange plants or heat transfer processes. As a result, it is not surprising that efficient heat exchangers, like plate heat exchangers and fluidized bed heat exchangers, experience less fouling problems. On the other hand, very efficient heat exchangers, like compact heat exchangers, are almost incompatible with fluids (especially gases) carrying a heavy fouling load. Some external treatments have to be used to clean the fluids before they enter the heat exchanger.

Reduction in fouling via heat exchanger design concepts has evolved through trial and error. The concepts generally fall into four categories: (a) construction material of heat transfer surface, (b) forced convection and induced turbulence, (c) mechanical erosion of fouled layer, and (d) "non-surface" heat transfer. For forced convection, both the deposition mass flux and the removal mass flux (erosion) are influenced by velocity or turbulence. For mechanically assisted erosion, hydrodynamics play a minor role because the removal mass flux is mainly accomplished by wiping/scraping/scrubbing the fouled deposit.

Construction Material

If thermal conductivity was the only criterion for se-

lecting an alloy as material of construction, stainless steel would not be frequently selected; its thermal conductivity is lower than that of other metals and alloys [33]. For long-term service, however, the overall heat-transfer performance of stainless steel may prove superior because of its resistance to corrosion [33]. In stainless steel plate heat exchangers, a mirror finish is available, which may contribute to reduced fouling [34]. Applying a special manufacturing process (whose final operation is electropolishing), stainless steel tubes with extremely high surface finish (TUBEC tubes) have been produced [35]. Their use in evaporators in the pulp industry showed excellent antifouling capability.

The problem of erosion corrosion has surfaced in heat exchangers working with fluids that have a high content of suspended sand (ocean thermal energy conversion, saline water conversion) and those using mechanical erosion of fouled layer. Some published data show that copper-nickel alloys in sea water containing sand can be ranked in the following order of increasing resistance to erosion corrosion [36, 37]: C70600, C71500, C72200, and C71640. Aggressive chlorine treatment, accompanied by continuous tube cleaning, was found to increase erosion corrosion of 90/10 Cu/Ni and Alclad 3003 aluminum in sea water [38]; under the same conditions, titanium performed very well [39]. All these examples demonstrate that corrosion resistance of alloys depends upon the formation and strength of passive, protective films on the metal surfaces. Fouling kinetics, as well as antifouling treatments, can remove the protective film, resulting in different forms of corrosion (pitting, crevice corrosion, erosion corrosion).

Titanium, in spite of its high energy surface, is known for its non-wetting tendency and, therefore, for its ability to resist fouling. Gaunt [40] and Nosetani et al. [39] reported the industrial application of titanium with good results in heat exchangers used with sea water.

The well-known toxicity of Cu^+ ion in solution [41] is why copper and copper-nickel alloys exhibit anti-bio-fouling properties. These materials must dissolve at a sufficient rate to maintain a toxic concentration at their surfaces. Stupian [24] estimates that an OTEC heat exchanger plant will discharge 272 metric tons of copper per year. The environmental impact of this amount of copper upon marine life has not been assessed.

Heat exchange surfaces from non-metallic materials (glass, graphite, and Teflon) have been successful with regard to fouling, especially in high corrosive fluid applications. Heat exchangers of glass tubes have been designed for heat recovery systems with gases carrying solid particles. Equipment made of glass-lined tubes have found utility in the chemical and petroleum industries [42]. However, technical problems in such equipment procedures (sealing of tube end, welding the joints, glass-coating) are not easily solved.

Hills [43] described the design and applications of graphite heat exchangers—shell-and-tube type, rectangular block type, immersion type. The graphite has good antifouling/anticorrosion qualities, high thermal conductivity and good machining properties, but can not handle substances that exhibit strong oxidizing characteristics. The principal limitation of graphite is connected with the decomposition of the synthetic resins (used both for im-

pregnation and as a laminate) at temperatures over 356°F. Improvements to overcome these disadvantages have been made [43].

Teflon is the most successful non-metallic material to be used as a heat exchanger surface because it is unaffected by essentially all industrial chemicals and has excellent antifouling properties [44-46]. The designers offset the low thermal conductivity of teflon by using thin-wall tubes with small diameters. Therefore, considerably more heat transfer surface area is available per unit of volume of shell. The disadvantages of these heat exchangers are that they exhibit a large pressure drop, since tube sizes range from 0.08 to 0.20 in. ID (wall thickness 0.02 to 0.05 in.). Additionally, teflon tubing is temperature-pressure sensitive (e.g., 225 psig at 70°F and only 50 psig at 300°F) [44].

Teflon-, silicone-, and polystyrene-based coatings of metal surfaces have been widely used since they exhibit low surface free energy and can be applied in very thin layers (0.001 in.), minimizing the effect on heat transfer. Recently, France [47] reported a silicone-based coating designed for high temperatures (300 to 1,400°F). The major disadvantages of non-metallic coatings are their limited service lifetime [24, 47] and the application of coatings inside tubes is difficult.

Toxic paints based on Cu_2O have been used to prevent marine biofouling of OTEC heat exchangers [24]. Their service life, however, is limited because of continuous leaching of the toxic ingredient. For this reason, the coating layer is quite thick, resulting in high thermal resistance [24].

Forced Convection

There are some heat exchangers where fouling can be suppressed by increasing the velocity or the turbulence of the fluid, but in other heat exchangers this is not possible. If the velocity level to suppress fouling requires conditions beyond certain boundary conditions (allowable pressure drop, tube erosion, tube vibrations, etc.), then suppression of fouling through turbulence cannot be achieved.

As design concepts to suppress fouling, forced convection and induced turbulence result from the influence of momentum transport upon fouling dynamics. With increasing velocity, a point may be reached when the accumulation of chemical species prone to fouling at the liquid-solid interface becomes so small that fouling reaction rate decreases substantially, resulting in a reduced deposition mass flux. In addition, the erosion effect upon the fouled layer increases with increasing velocity, thus increasing the removal mass flux. This picture, describing suppression of fouling, results from the fundamental aspects of fouling dynamics [3].

Induced turbulence by different means has practically the same effect on fouling dynamics as high-velocity forced convection. The best example of this is the corrugated plates of plate heat exchangers [34, 48]. Induced turbulence can be achieved through other means such as spiral plate [49], finned tubes [50-52], ultrasonics [7, 19, 53-56], air rumbling, etc., and the result may be a decrease in fouling of heat exchangers. For instance, fouling of finned tubes depends upon the allowable pressure drop, as well as shape, pitch, and density of the fins [57-59]. The

influence of ultrasonically induced turbulence on fouling has not been clearly defined. Some studies show a reduction of deposition [54, 55], or at least formation of a loose deposit [53]. Research on cooling water systems reported positive results using ultrasonics [19] to prevent fouling, but the attempts to prevent biofouling ultrasonically did not prove successful [7].

Mechanical Erosion

Some of the most successful design concepts to prevent fouling are based upon mechanical erosion of fouled layer. Mechanically agitated thin-film evaporators, continuous tube cleaning systems, and fluidized bed heat exchangers all exhibit increased removal mass flux at levels which cannot be achieved by forced convection alone. Thin-film evaporators and fluidized bed heat exchangers induce large turbulence at the heat transfer surface. In addition, the rotor blades, fluidized particles and the continuous cleaning brushes/balls result in mechanical erosion of the fouled layer.

Mechanically agitated thin-film heat exchangers (evaporators, dryers, reactors) [60] have rotor blades with adjustable clearance (including zero clearance) which wipe/scrape the heat transfer surface at 3000 rpm. Two other heat exchanger types, the spring loaded scraper unit and the Votator, work on a similar principle, but rotate at much slower speeds (30 to 60 rpm) [61]. In this case, the processed fluid does not form a thin film at the heating surface. Fouling is not a problem for these heat exchangers, and heat sensitive as well as viscous liquids can be handled. Very high heat transfer coefficients and low residence times are particular advantages of mechanically agitated thin-film equipment. It is important to properly utilize them because of the relatively higher cost *vis-a-vis* more conventional exchangers [60]. Newer concepts suggest using radiative heat transfer in combination with mechanically agitated thin-film equipment, where the processed liquid is directly heated by infrared radiation [62].

There are two major types of continuous tube cleaning systems used to prevent fouling of heat exchangers: a flow-driven brush cleaning system marketed as MAN cleaning system, and a flow-driven ball cleaning system marketed as Taprogge or Amertap cleaning system. The MAN cleaning system consists of plastic baskets permanently fixed to the ends of each tube. A brush made of a titanium core and plastic bristles shuttles between the baskets by means of flow reversing at different time intervals. The Amertap cleaning system [63] uses sponge rubber balls (sometimes carborundum balls) that are injected in a closed loop, which includes the heat exchanger. At the discharge from the exchanger, they are caught in a screen installed directly in the line. The balls are then rerouted through a collector back to the ball-injection nozzles to ensure that the balls are uniformly distributed into heat exchanger tubes. The Amertap system has high cleaning frequency, automation, and variability of abrasiveness through selection of ball materials. To control fouling, continuous cleaning systems are applied to heat exchangers in cooling water systems, saline water conversion, and ocean thermal energy conversion [7, 19, 24, 38, 39, 63-65]. The largest Amertap system is on an 800,000 gpm heat exchanger at the San Onofre, Calif., nuclear power plant [24].

It is likely that a continuous cleaning system like Amertap is not economical when designed for a small capacity exchanger. There are also other limitations: (a) random tube cleaning that can be affected by changes in balls due to wear and contamination, (b) pressure losses due to collection screens, and balls themselves, (c) complex equipment for automatically sizing, sorting and counting balls, (d) short ball life, and (e) applicability only inside smooth wall tubes. There are two other aspects of particular interest. The balls and brushes increase erosion corrosion of alloys. Evidence exists that accumulation of a plaque on heat exchanger surfaces following extended periods of continuous cleaning may present a serious problem [7, 39]; neither the nature of the plaque nor the conditions of formation are known.

Fluidized bed heat exchangers represent a promising development in prevention of severe fouling. When a fluid prone to fouling flows inside the tubes, the heat exchanger is vertically mounted and when fouling occurs on the shell side, the horizontal configuration is preferred. Fluidized solid particles (glass or steel particles with diameter of a few millimeters) are able to induce high heat transfer coefficients as well as self-cleaning effects at low superficial liquid velocities inside tubes (about 0.3 to 0.6 ft/sec) [66]. Because of these low velocities, a so-called stationary fluidized bed exchanger requires a large number of tubes and a large shell diameter, increasing the cost [66]. Klaren [66] has described an improved design of circular fluidized bed heat exchangers, which in pilot or industrial plants have effectively been applied to reduce fouling from such severe fouling fluids as sea water, geothermal brine, river water, protein, fat and starch solutions, black liquor, and oil [66, 67]. Allen et al. [68] reported using a horizontal fluidized bed heat exchanger with silica sand particles (a few millimeters diameter) to prevent fouling of geothermal brines on the shell side. The tubes are surrounded by a fluidized bed or particles that scrub the heat transfer surface. The fluidized geothermal brine is directed from one stage to the other by a series of baffles. The report concludes that a fluidized bed heat exchanger, used in this application, would require less than half the heat transfer tube surface of a conventional shell-and-tube exchanger, but the shell size would be 50% larger.

The most impressive implementation of the fluidized bed concept in heat transfer is fluidized bed combustion [69-71]. Generally, these systems have heat exchangers immersed in a fluidized bed of sand, silica, alumina, or ash (and limestone), which is the place of combustion and heat transfer as well. Corrosion and fouling are minimal, but erosion of heat transfer surfaces can be a serious problem. The degree of erosion depends on the orientation of surfaces, the abrasiveness of the bed material, and the fluidization velocity. Obviously, the entire technology needs to be optimized, but its worldwide acceptance, with regard to flexibility, efficiency, emissions control, and antifouling, makes it a technology of the future [70].

Reay [57] mentions a fluidized bed technique in connection with heat-pipe heat exchangers, to reduce fouling and to increase heat transfer. He also describes a moving-granular-bed heat pipe exchanger designed to operate

with fouling gases, as would prevail in almost all equipment employed in steel making plants. The bed of granules is in continuous, slow-motion, by gravity, scrubbing the outside surface of the tubes and preventing any deposit. At the base of the heat exchanger, a vibrating screen cleans the granules of powder and dust, and a bucket elevator returns them to the top of heat exchanger for recycling. The idea of using falling balls or granules to clean the external surface of horizontal or vertical tubes operating with fouling gases has a long history of applications.

The application of ultrasonics to prevent fouling has already been mentioned. We assume that ultrasonics act by induced turbulence, especially when applied to liquid systems. Nevertheless, when applied to gaseous systems, ultrasonics and infrasonics are supposed to have a mechanical erosion effect, rather than induced turbulence. Freund and Matthews [72] describe applications of infrasonics to clean gas side heat transfer surfaces.

The injection of slurries (fine sand particles, etc.) has been suggested to prevent fouling of heat exchangers through mechanical erosion of fouled layer [7]. Slow moving scrapers in batch reactors, spray dryers, etc. actually remove the fouled layer mechanically from the wall of equipment. Slow rotating drums and discs having adjustable scrapers are designed to keep heat transfer surfaces clean [73]. Continuous (or intermittent) cleaning of the dust deposited upon smooth heat transfer surfaces working in gas-gas exchange has been designed using falling films of water as a means of mechanical erosion [59].

"Non-Surface" Heat Transfer

There are industrial processes of heat transfer where the presence of a heat exchange surface (usually, a metal surface) is not necessarily required. If the heat transfer can take place by admixture between two media, obviously no fouling occurs, however, the walls, nozzles, pipe connections, etc. can accumulate deposits. Classical examples of "non-surface" heat transfer are: direct steam injection, submerged combustion [74], wet scrubbing [59], spray drying, flash evaporation, spray-tower cooling, and turbulent-pipe mixing.

Yufin et al. [75] reported using various hydrophobic substances (unsaturated hydrocarbons, paraffin waxes, fluorinated oils) as heating agents in "tubeless" desalination plants. Hasson [76] examined the possibility of preventing fouling from an aqueous solution, flowing inside a heated tube, by covering the tube surface with an annular film of kerosene. Boehm and Jacobs [77] discussed the possibility of using geothermal brines in direct contact heat exchange with pentane or Freon in spray towers, sieve plate towers, baffle towers, mechanically agitated towers, wetted wall towers, and turbulent-pipe mixers. The results showed that baffle towers and mechanically agitated towers were best suited for highly fouling brines, whereas sieve towers were reasonable for low fouling brines.

In a different development, heat transfer by radiation to falling, free films and sprays has been suggested [62] in connection with concentration and drying of fluids prone

to fouling in the food and pharmaceutical industries.

Conclusions

It became common practice to consider that the failures produced by fouling in industrial operation of heat exchange plants were the result of training fouling resistances as time-independent values. On the one hand, all sources are cautious to state that these values are intended as a crude guide, and that economic factors have to prevail in the decision of choosing a fouling resistance value. On the other hand, practical experience shows that engineers can find a solution to optimize heat exchange plants when they are aware of the transient behavior of fouling and take into account the design and operation parameters influencing fouling dynamics. Engineers are able to experimentally determine the fouling dynamics and then decide whether it can be economically suppressed or not, and what optimization procedure is suitable in each case.

Actually, three basic procedures deserve more attention to minimize fouling costs: (1) economical suppression of fouling resistance, (2) optimum production-cleaning cycle, and (3) bypassing heat exchangers. These procedures have been analyzed by Sandu and Lund [2], with particular reference to shell-and-tube heat exchangers, evaporators and plate heat exchangers. The mathematical models associated with optimization procedures were briefly described. A survey on heat exchanger design and optimization was included to identify some of the main problems faced by the design engineers with regard to the computational procedures [2]. Establishing the design variables, objective function, and design constraints, as well as the suitable optimization techniques for a heat exchanger, is a complex process requiring sound engineering judgments.

Suppression of fouling means achieving an asymptotic fouling resistance on the magnitude of other resistances to heat transfer in the system. Suppression of fouling can be accomplished not only by forced convection (and induced turbulence), but by mechanical erosion (mechanically agitated thin-film exchangers, continuous tube cleaning systems, fluidized bed heat exchangers, etc.), construction materials, and chemical/physical treatments as well. Finally, whether fouling can be economically suppressed or not is completely determined by the relationships between fouling dynamics and design, within an optimization procedure of balancing the operating and maintenance costs against the installed costs [2].

More than any other standard source in the literature, the new issue of Heat Exchanger Design Handbook [78] gives special attention to fouling of heat exchangers (shell-and-tube, annular and plate heat exchangers; evaporators; and reboilers). Some of the main parameters affecting fouling dynamics (nature of the surface, fluid velocity, design of the heat exchanger, mode of heat transfer, and temperature of the heating surface) are mentioned, as well as suppression of fouling resistance to minimize the effects of fouling. However, the approach of this remarkable book still remains "classical", as far as the solutions to fouling of heat exchangers are concerned. Thus, constant fouling resistances are used in heat exchanger design and no attempt is made to deal with these resistances in a different way.

In our opinion, the concept of fouling resistance is outdated. It should be replaced by the concept of fouling dynamics which ultimately yields the time-dependence of the fouling resistance and pressure drop in the heat exchanger. Although there are some empirical models describing fouling as a function of time [2], there is a need for studies which characterize fouling dynamics for design purposes. An attempt should be made to introduce fouling dynamics as a basic concept so that researchers present information in a more universal form. The final goal is a better understanding of fouling and, ultimately, an improvement in operating heat exchange plants.

By the time this review was completed, a report by Garrett-Price et al. [79] (prepared for the U.S. Department of Energy) was released which addressed a series of practical aspects of fouling in heat exchangers. Specifically, aspects like fouling by air and combustion gases, mitigation and accommodation techniques currently used by different industries (food, textile, pulp and paper, chemical, petroleum, cement, glass and primary metals), mitigation technology trends (based on a patent analysis), and types and magnitude of costs associated with fouling are presented. In addition, the report is complete with information about: companies offering cleaning equipment, chemicals and cleaning services; manufacturers and suppliers of equipment for preventing and minimizing fouling; and a summary of heat exchanger manufacturers regarding their practical experience in industrial fouling.

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Constantine Sandu graduated as an engineer from the University of Galatz in Romania. He worked as a plant engineer in the canning industry and in teaching and research at the University of Galatz. He followed this with research and development work at the Federal Research Center for Nutrition in Karlsruhe, West Germany, and the Society for Heating and Engineering Ltd., in Krefeld, West Germany. He is presently a Ph.D. candidate at the University of Wisconsin-Madison majoring in Food Engineering and minoring in Chemical and Mechanical Engineering.

Daryl Lund holds a Ph.D. degree in Food Science with a minor in Chemical Engineering from the University of Wisconsin-Madison. He is currently a Professor of Food Engineering and Chairman of the Food Science Department at the University of Wisconsin-Madison. His main interests are food process engineering, fouling dynamics and simultaneous heat and mass transfer in foods.
