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Investigation into fouling factor in compact heat exchanger

***Masoud Asadi*[1] *and Dr. Ramin Haghighi Khoshkhoo*[2]**

[1]Department of Mechanical Engineering,
Azad Islamic University Science and Research branch,
Tehran, Iran

[2]Department of Mechanical Engineering & Energy engineering,
Power and Water University of Technology,
Tehran, Iran

ABSTRACT: Fouling problems cannot be avoided in many heat exchanger operations, and it is necessary to introduce defensive measures to minimize fouling and the cost of cleaning. The fouling control measures used during either design or operation must be subjected to a thorough economic analysis, taking into consideration all the costs of the fouling control measures and their projected benefits in reducing costs due to fouling. Under some conditions, nearly asymptotic fouling resistances can be obtained, and this suggests a somewhat different approach to the economics. Fouling is a generic term for the deposition of foreign matter on a heat transfer surface. Deposits accumulating in the small channels of a compact heat exchanger affect both heat transfer and fluid flow. Fouling deposits constricting passages in a compact heat exchanger are likely to increase the pressure drop and therefore reduce the flow rate. Reduced flow rate may be a process constraint; it reduces efficiency and increases the associated energy use and running costs. Maintenance costs will also increase. Fouling remains the area of greatest concern for those considering the installation of compact heat exchangers. The widespread installation of compact heat exchangers has been hindered by the perception that the small passages are more strongly affected by the formation of deposits. In this paper different types of fouling and treatment are presented.

KEYWORDS: Compact Heat exchanger, Fouling Factor, Fouling Resistance.

1 INTRODUCTION TO FOULING IN COMPACT HEAT EXCHANGERS

Obviously, compact heat exchangers are unsuitable for fluids containing large particulate material or debris. However, the high shear forces, low wall superheat and homogeneous flow distribution typical of compact heat exchangers reduce the formation and adhesion of deposits on the heat transfer surfaces. Also, the use of more corrosion resistant materials with smoother heat transfer surfaces further reduces the formation of deposits [1].

Section 2. examines the generic types of fouling that can occur in heat exchangers and outlines possible solutions. Section 3. examines the effects of fouling in more detail for different exchanger designs and section 4. provides further information on minimizing the risk of fouling at the specification stage. It is assumed that the specifier of the heat exchanger will have knowledge of the nature of the process stream. However, this will not always be the case, as plant and stream changes can occur sometime after units have been installed.

The adoption of heat exchangers has been affected by the perception that those with small channels are likely to foul [2]. Care should be taken when selecting compact heat exchangers for use in situations where mechanical cleaning is impossible. In these cases provision for chemical cleaning must be made. However, gasketed plate heat exchangers are frequently easier to clean than shell and tube types, provided other parameters permit their use [3].

Corresponding Author: Masoud Asadi (masoud2471@gmail.com)

There are two primary problems associated with the small flow passages used in most types of compact heat exchanger:

- The possibility of the heat exchanger acting as a filter for large particles, with these particles forming a filter cake at the inlet to the exchanger.
- The rapid increase in flow resistance resulting from the deposition of only a small thickness of material on exchange surfaces that might pass unnoticed in conventional shell and tube heat exchangers [2].

Fig. 1. Crystalline Fouling on a Plate and Frame Exchanger

The risk of partial blockages turning into complete blockages is also very much higher for compact heat exchangers than for shell and tube heat exchangers, and the difficulty of clearing such blockages, either by mechanical or chemical treatment, is also greater [4]. However, the ability of a compact heat exchanger to filter out material has proved useful in certain applications. In some gas-gas units, the small channel size has caused fibres to collect on the front face of the heat exchanger, instead of in the core where they would be more difficult to remove.

The effect of fouling depends on the deposit location. This, in turn, depends on the fouling mechanism and so on fluid composition. The effects of fouling are likely to be more important for fluid flow than for heat transfer.

For a fluid flow the factors that influence the effect of fouling are:

- The narrowness of the passages, which are relatively easily blocked by particles and fibres.
- The fact that only a small amount of material is required to achieve blockage.
- The difficulty of removing any blockage (although this depends on experience). Judging the effects of fouling on heat transfer need to take into account:
- The thickness of the deposit, its nature and the area covered.
- The relationship between the clean heat transfer coefficient and deposit resistance.
- The implications for design fouling resistance and the irrelevance of TEMA [14] values.

2 TYPES OF FOULING AND TREATMENT

For convenience, fouling is generally classified under one of the following six headings, depending on the mechanism causing the deposition [5-8]:

- Crystallization or Precipitation Fouling.
- Particulate Fouling (Silting).
- Biological Fouling.
- Corrosion Fouling.
- Chemical Reaction Fouling.
- Freezing or Solidification Fouling.

2.1 CRYSTALLISATION OR PRECIPITATION FOULING

Crystallization or precipitation fouling occurs when a solute in the fluid stream is precipitated out and crystals are formed, either directly on the heat transfer surface or in the fluid, and subsequently deposited on that surface. When the fluid concerned is water, calcium or magnesium salts are deposited, frequently referred to as scaling. Figure.1 shows a plate fouled by crystalline calcium phosphate deposits.

For normal solubility salts (e.g. sodium chloride), this type of fouling decreases with increasing heat transfer surface temperature, as the solubility increases. For the more troublesome inverse solubility salts (e.g. Calcium sulphate, calcium phosphate, calcium silicate, calcium carbonate, magnesium hydroxide and magnesium silicate), the solubility decreases with increasing temperature [8]. Hence, these salts are prone to forming deposits on surfaces where heat is transferred to water, either during cooling or evaporation.

It is important to identify the highest cooling water temperature that is likely to occur in a heat exchanger with narrow channels to determine the appropriate water strategy.

Solution

Crystallization or precipitation fouling is normally avoided either by pre-treating the fluid stream (e.g. by adding acid to cooling water to remove bicarbonate) or by the continuous addition of chemicals to reduce or eliminate deposit formation.

If deposits do form, they can often be removed by treatment with appropriate chemicals, e.g. by adding acid to remove carbonates. Care must be taken to ensure that the cleaning chemicals are compatible with the construction materials used for the exchanger.

Mechanical methods, such as the high-pressure lances that are often used to clean shell and tube heat exchangers, are unlikely to be of use for compact heat exchangers because of their small passage size.

2.2 PARTICULATE FOULING (SILTING)

Particulate fouling (or silting) occurs when solid particles from the fluid stream are deposited on the heat transfer surface. Most streams contain some particulate matter, originating from a variety of sources. Small particles are less likely to be removed from the surface than large ones. The combination of particles with condensation or other sticky forms of fouling can produce a deposit that is much more adhesive and difficult to remove than the individual components on their own. An example would be a combination of paper fibres and polymer adhesive from ink in a printing works heat recovery unit.

A particulate deposit may also provide a mechanism for keeping a surface wet. This may have implications for corrosion (e.g. the formation of an acid condensate from combustion gases).

Solution

Purely particulate fouling can be reduced by the use of sufficiently high fluid velocities. If the deposit also contains matter that acts as an adhesive, a solvent or other chemical treatment will be required to remove the adhesive. Chemical dispersants that affect the surface charges on solids can also assist in avoiding deposit formation.

Mechanical removal, e.g. by brushes, may be feasible, if access is available. Air rumbling, i.e. the temporary addition of air or of nitrogen to the liquid stream is frequently used to dislocated particulate or biological deposits.

Larger particles can easily be filtered out, and a suitable strainer could be located upstream of a compact heat exchanger where such particles are expected. The application of a severe pressure pulse can remove silting, but its effect on the mechanical strength of the exchanger must be considered.

Several other factors alleviate fouling in compact heat exchangers. The use of corrosion resistant materials minimizes fouling by upstream corrosion products and the specific design of compact heat exchangers gives high wall shear stresses. Designers should ensure that there are no flow dead spots.

2.3 BIOLOGICAL FOULING

The deposition and growth of organisms on surfaces cause biological fouling. The organisms most likely to cause problems in compact heat exchangers are bacteria, which can thrive even if the concentration of nutrients in the water is less than one part per million.

Bacteria grow over a wide range of temperatures. Bacterial growth may physically constrict flow passages or can generate a corrosive environment (e.g. sulphate reduced to hydrogen sulphide is corrosive to most materials, including common stainless steels).

Solution

Biological fouling is best controlled by treatment with biocides. Non-oxidising biocides are normally alternated to prevent the development of bacterial deposition. Certain biocides kill the bacteria, but do not remove the biofilm accumulation, but some are available with detergent properties that disrupt the film. Oxidising biocides, such as chlorine and ozone, oxidise the biofilm as well as killing the bacteria and may therefore require higher concentrations to be effective.

Compared with a conventional shell and tube exchanger, the relatively low surface area and the lower fluid inventory in a circuit with a compact heat exchanger should reduce the amount of biocide required. The well-defined flow in the small channels also aids rapid diffusion of the treatment chemical to the biofilm.

Fig. 2. Reaction Fouling (Protein Deposition) on a Plate and Frame Exchanger Plate

2.4 CORROSION FOULING

Corrosion fouling results from either a chemical reaction involving the heat transfer surface, or the transportation of corrosion products from elsewhere in the circuit and their deposition in the heat exchanger. Corrosion can also take place under the deposits, e.g. as a result of the formation of electrolytic oxygen concentration cells.

Solution

Corrosion fouling is best minimized at the specification stage by choosing materials that are resistant to corrosion in the fluid stream whenever possible. Alternatively, it is possible to dose with corrosion inhibitors, although the environmental impact of this approach must be considered. Cathodic protection can also be used, but care must be taken to ensure that the conditions do not form cathodic scales (calcium and magnesium salts) in hard waters and brines [9].

If a stainless steel heat exchanger is stored in a moist, salt-laden environment, measures should be taken to protect the surfaces. Amounts of salt as low as 1.0 mg/l could result in stress corrosion cracking.

Compact heat exchangers are usually made of the more corrosion-resistant materials. Several types have nodissimilar metals or other materials present, making corrosion attack on the heat exchanger surfaces predictable, unless unforeseen impurities are present in the fluid streams [10].

2.5 CHEMICAL REACTION FOULING

Chemical reaction fouling occurs when one or more constituents in the process fluid react to form a viscous or solid layer on the heat transfer surface, which is not itself involved in the chemical reaction. Such reactions are mostly polymerizations, and the deposit that is initially formed may turn from a tar to a hard coke or similar material that is more difficult to remove. Figure 2. shows protein fouling of a plate exchanger from the dairy industry.

Solution

The rate of chemical reactions increases exponentially with temperature, making it possible to minimise chemical reaction fouling by careful control of fluid and surface temperatures and by reducing residence times at high temperatures. Temperatures should not be increased to achieve the required heat transfer as this will make the fouling problem rapidly worse. It should be much easier to control chemical reaction fouling in a compact heat exchanger than in a conventional shell and tube exchanger because of the high degree of temperature control and low residence times. Compact heat exchangers have lower hold-up and residence times than conventional shell and tube exchangers.

2.6 FREEZING OR SOLIDIFICATION FOULING

Freezing or solidification fouling occurs when the temperature of the process fluid is reduced sufficiently to cause freezing at the heat transfer surface.

Solution

This type of fouling is the easiest to control, particularly in compact heat exchangers, where the small mass and low fluid inventory allows rapid clearance of the fouling by increasing the temperature to melt the deposit. In some cases, channels may be incorporated in the exchanger to allow a hot fluid stream to be introduced to melt material, such as hydrates. Compact heat exchangers offer a closer temperature approach and greater control over stream temperature.

3 THE FOULING RESISTANCE (R_F)

In the thermal design of heat exchangers, fouling is conventionally taken into account by using an additional thermal resistance value, $R_{f,}$ called the ‘fouling factor’ or ‘fouling resistance’, when calculating the overall heat transfer coefficient. Fouling reduces the overall heat transfer and, for a given duty, extra surface has to be provided to ensure that the required heat transfer is achieved [7].

In most cases fouling resistance is time dependent, with zero fouling initially. Frequently fouling resistance builds up to an equilibrium point where the rate of fouling removal is equivalent to the rate of deposition. Depending on the value of this ‘asymptotic’ fouling resistance, this may or may not allow continuous operation without cleaning. Alternatively, fouling resistance may continue to increase necessitating a cleaning action at some point.

Thermal resistance values are often taken from the standards recommended by TEMA [14]. These are dedicated to shell and tube heat exchangers and, as such, are generally not applicable to compact heat exchangers. Using the TEMA [14] values is likely to result in excessively high additional surface requirements. This is because the implied deposit thickness may give very high pressure drops in small channels. It is generally found that much lower fouling resistances than those recommended by TEMA [14] can be used for plate and frame heat exchangers. Measures such as filters to avoid compact heat exchanger blockages have encouraged some industries (e.g. the cryogenics industry) to adopt fouling resistance values of zero. Some manufacturers may add 10 - 25% extra surface to allow for uncertainties in design codes and other factors, of which fouling may be one. This should not be used as an excuse to reduce the flow velocity.

3.1 FOULING IN PLATE AND FRAME EXCHANGERS

Plate and frame heat exchangers were originally developed for the dairy industry. However, their application in the chemical process industry is increasing rapidly, where they begin to replace tubular heat exchangers in several traditional applications. While there is plenty of information about the governing equations for clean operation, information for fouling conditions is scarce. As shown in the following equation the percentage excess surface area increases with increasing clean heat transfer coefficient for a given heat duty [11].

$$\frac{A_f}{A_c} = 1 + U_{clean}\, R_f$$

Where

A_f : is the surface area after fouling

A_c : is the clean surface area

U_{clean} : is the clean heat transfer coefficient

R_f : is the fouling resistance

This puts a heavy penalty on compact heat exchanger types such as plate and frame heat exchangers if, because of ignorance or because of cautiousness, the TEMA[14] fouling resistances for shell and tube heat exchangers are used. Typical clean overall heat transfer coefficients for plate and frame heat exchangers are about 3000 W/m^{2}K, for shell and tube heat exchangers about 1000 W/m^{2}K. A design fouling resistance of 0.3 m^{2}K/kW corresponds to 30% overdesign for a shell and tube heat exchanger and to 90% overdesign for a plate and frame heat exchanger. Most manufacturers of plate and frame heat exchangers recommend that the excess surface should not exceed 25% of the heat transfer surface area calculated for the clean duty.

The fouling resistances listed in Table.1 have been recommended for plate and frame heat exchangers. Due to the non-uniformity of flow distribution and deposit formation, measured pressure drop increases are significantly higher than values predicted using an average deposit thickness calculated from the fouling resistance.

Table 1. Fouling Resistances for Plate and Frame Heat Exchangers

Fluid (Water)	**Fouling Resistances(m^2K/KW)**
Demineralized or distilled	0.009
Hard	0.043
Soft	0.017
Treated cooling tower water	0.034
Coastal sea water	0.043
Ocean sea water	0.026
River water	0.043
Engine jacket	0.052
Lubricating oil	0.017 - 0.043
Vegetable oil	0.017 - 0.052
Organic solvents	0.009 - 0.026
Steam	0.009
General process fluids	0.009 - 0.052

Effect of Process Parameters on Fouling

Cooper [2] investigated cooling water fouling using a plate heat exchanger. The water was chemically treated before entering the heat exchangers. Some of the important results of this investigation are given in Figure 3.

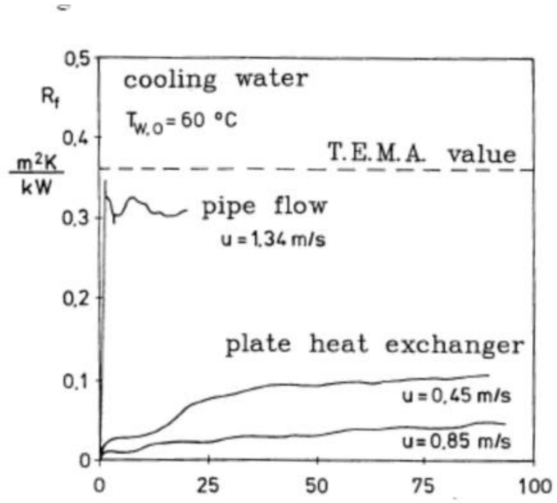

Fig. 3. Comparison of Fouling in Plate and Frame, and in Shell and Tube Heat Exchangers (after Cooper) [2]

The fouling resistance in the plate and frame heat exchanger is significantly lower than in the shell and tube heat exchanger, despite the typically lower flow velocities. If the flow velocity is increased, the fouling resistance decreases similarly as it is found for shell and tube heat exchangers [12]. This is also demonstrated in Figure.4 which shows the asymptotic value as a function of the surface temperature halfway up the plates.

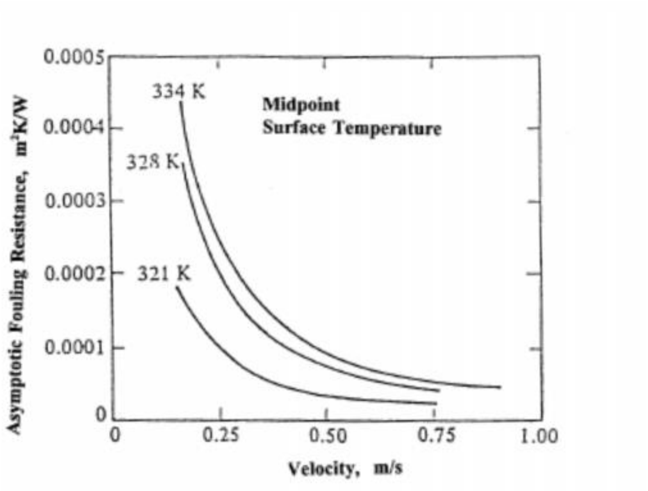

Fig. 4. Fouling Resistance in a Plate and Frame Heat Exchanger as a Function of Flow Velocity and Temperature

Novak [3] studied the fouling behavior of Rhine River water near Mannheim (Germany), and of Öresund seawater in Sweden. For both waters, mainly biological fouling was observed. The fouling resistances increased almost linearly over the period observed. Table 2. summarizes the effects of flow velocity on fouling rates.

Table 2. Fouling Rates of Rhine River Water for a Surface Temperature of 25°C [3]

Type	u m/s	t Pa	dR_f/dt $10^4m^2K/kWh$
Plate heat exchanger	0.13	6.7	7.4
Plate heat exchanger	0.19	14.5	4.3
Plate heat exchanger	0.77	190.0	0.6
Spiral plate exchanger	0.43	7.5	5.0

For constant flow velocity, Novak [3] found that maximum fouling occurred at a surface temperature of about 35°C, due to the preferred living conditions of biological matter. Bansal and Müller-Steinhagen[4-6] investigated pure crystallisation fouling from $CaSO_4$ in various plate heat exchangers. The rate of deposition increases with increasing wall temperature and bulk concentration and decreasing velocity. With increasing flow velocity, both the initial fouling rate as well as the absolute value of the fouling resistance decreases. Due to blockage of the outlet flow distribution area, the increase in pressure drop may be significantly higher than the increase in thermal fouling resistance. Chemical reaction fouling is strongly affected by the surface temperature that determines the reaction rate.

Effect of Plate Design

Two low velocity zones exist in the plate channels, opposite to the inlet and outlet ports. In these zones, shear forces are at a minimum and the wall temperature is close to the temperature of the heating medium. Both conditions promote the formation of deposits. The extent of the stagnant zones depends on the design of the flow distribution section. It decreases with increasing flow velocity.

Kho [7] studied the various possibilities of providing excess heat transfer surface area for fouling. Figure.5 shows that minimum fouling occurs if the 20% excess surface area is provided by a two-pass arrangement of the original plates, followed by the use of larger plates with the same width, followed by larger plates with standard width/height ratio. The poorest performance is obtained when the excess surface is simply added as parallel plates. The actual plate geometry (angle, amplitude and wavelength of corrugations) affects the formation of deposits. Delplace et al. [8] found that deposition from whey protein solutions on herringbone plates is only half of that of straight corrugations, for otherwise identical conditions.

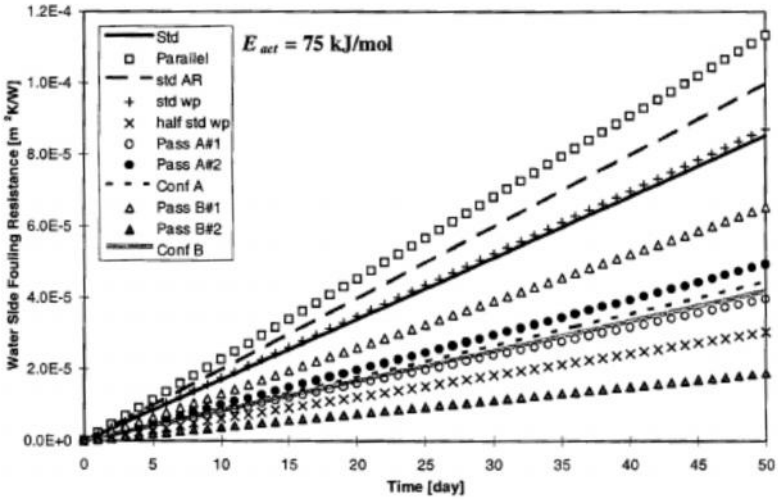

Fig. 5. Effect of Plate Arrangement on Fouling

Plate heat exchanger designs with extra-wide plate gap are available for applications with significant particulate content or severe fouling.

For all types of fouling, the delay time decreases with an increase in surface roughness. Heat exchanger plates usually have smoother surfaces than pipes, because of the manufacturing process itself and because the lower area requirement allows more expensive surface preparation. Electropolished plates with a surface roughness below 0.5 µm are commercially available, and are commonly used in food processing industries. Investigations with plate surfaces modified by Magnetron Sputtering, Physical Vapor Deposition and other technologies which can provide low surface energies are presently underway [9-10].

3.2 FOULING IN PLATE-FIN HEAT EXCHANGERS

Plate-fin heat exchangers are brazed/welded compact heat exchangers with a heat transfer surface density of about ten times that of tubular heat exchangers. Typical applications are cryogenic, chemical/petrochemical and hydrocarbon offshore installations. Molecular sieves and 100 µm filters are used in cryogenic installations to remove particulate matter or components that may freeze-out on the heat transfer surfaces.

Systematic investigations have been performed on particulate fouling [11] and on river water fouling [12].

For 3 µm ferric oxide particles suspended in water, no blockage of plain fin or wavy fin channels was observed. Wavy fin channels fouled more than plain fin channels. All experiments showed asymptotic behavior. Higher deposition rates were obtained for non isothermal conditions and at higher bulk temperatures. Maximum deposition occurred at a Reynolds number of about 1500.

Fibrous and biological material partially blocked the inlet of the aluminum plate-fin test sections when used with river water that was filtered through a 1 mm mesh. Some deposition was found at locations where corrosion of the aluminum had occurred. In the wavy fin test section, a thin, uniform deposit of fine mud was observed. Pressure drop for the plain finning increased linearly with time, whereas asymptotic behavior was found for the wavy finning. The initial slope of the relative pressure drop versus time curves was $5.8x10^{-8}$ s^{-1} for the plain fins and $1.71x10^{-7}$ s^{-1} for the wavy fins. For the latter, an initial deposition rate of $4.8x10^{-12}$ and an asymptotic fouling resistance of $6x10^{-6}m^2K/W$ were measured.

4 PREVENTING FOULING EFFECTS

4.1 DESIGN STAGE

Identify at an early stage the extent to which process streams are likely to cause fouling. The following points give general guidance.

Circuit Configuration

Closed loops are unlikely to present significant fouling problems. Working fluids in refrigeration or power cycles, for example, should not cause any fouling in a well-engineered and maintained system. Open loops are prone to fouling, and may require the installation of filters to remove particles, fibres etc., as well as regular chemical treatment to prevent biological growth, the deposition of scale, and corrosion. In open systems, check the possibility of using self-cleaning strainers and of installing systems for biocide dosing, the application of scale inhibitors, etc., to control fouling [13].

Once-through streams need to be examined on a case-by-case basis and appropriate action taken if the stream warrants it. If water treatment is constrained by environmental concerns, consider installing an untreated primary cooling water circuit with a secondary clean circuit serving the plant. The other benefits of compact heat exchangers may make this worthwhile. Where a closed cycle system is not an option, consult with the equipment supplier(s) and give detailed consideration to:

- Fouling margins.
- Optimal flow rates.
- Control of heat exchanger operation.
- Upstream fouling prevention.
- In-exchanger fouling control/removal.

Alternatively consider a specific compact exchanger design able to handle the fouling projected.

Performance Monitoring

On larger installations, or where an exchanger duty is critical for a process, exchanger monitoring can give early indication of cleaning thresholds or failure conditions. Monitoring can either be continuous or intermittent as necessary. Progressive fouling will become evident by increases in the pressure drop through the heat exchanger. It is also essential to measure the stream flow rate because a pressure drop increase may be compensated by reduced flow. Inlet and outlet stream temperatures may also be measured. In some cases it may be useful to calculate heat transfer coefficients on a regular basis from the parameters measured above.

Fluid Velocity

Fluid velocity has an effect on fouling. Any reduction in velocity associated with a lower throughput may increase fouling and necessitate more frequent heat exchanger cleaning. Take this into account when considering the operational flexibility necessary for the process.

Modular Design

Wherever possible, adopt a modular design that uses relatively small heat exchangers. These units can be individually removed for cleaning without total process shutdown. Installing multiple heat exchangers will have economic implications to be considered during design and specification including additional piping complexity.

Cleaning

Where a compact heat exchanger cannot be disassembled for mechanical cleaning (e.g. welded, brazed or diffusion bonded heat exchanger cores), install filtration equipment upstream. Another alternative is to consider chemical cleaning, possibly using a separate cleaning loop. If chemical cleaning is to be used, ensure that:

- The system is designed to allow the introduction and complete removal of the cleaning fluids used (no dead-legs).
- The cleaning fluids are compatible with the compact heat exchanger and associated pipework over the full temperature range.

In extreme circumstances small exchangers can be baked in an oven enabling the burnt fouling to be removed by rinsing with water or a detergent. Baking to remove serious fouling is unusual, as heating temporarily to such high temperatures will damage most heat exchangers.

Hydraulic Measures

Pulsating flows, reversing the fluids, or stopping the cold fluid intermittently can inhibit some types of fouling, but expert advice should be taken before adopting such techniques, as they can make some fouling problems worse. Air rumbling, i.e. the temporary addition of air or of nitrogen to the liquid stream is frequently used to dislocate particulate or biological deposits.

Cleaning-in-Place Plants

Automatic cleaning-in-place (CIP) plants can be linked to a process plant for cleaning pipes, tanks and heat exchangers internally. Figure 6. shows the layout of a typical CIP plant.

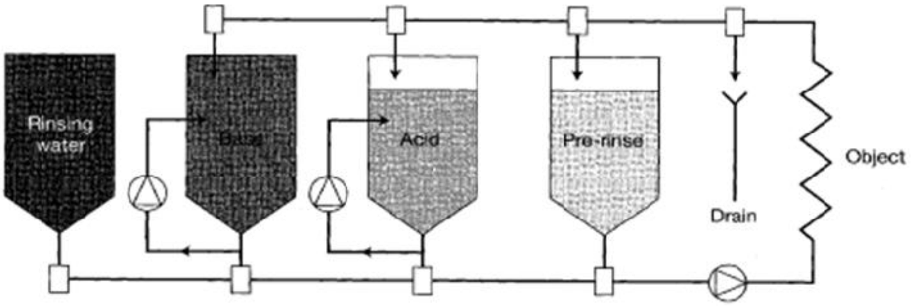

Fig. 6. Layout of a Typical CIP Plant

A typical CIP procedure takes place in five stages:

- A pre-rinse with cold water, helping to displace the product in the system.
- A rinse in an alkaline solution at approximately 80°C.
- A rinse in cold water.
- A rinse in acid solution at approximately 70°C.
- A rinse in cold water.

The cleaning time required depends on the equipment being cleaned and the fluids and temperatures used: it varies from thirty minutes for tanks to five hours for evaporators. In some cases, cleaning time may be reduced by introducing a short acid rinse prior to the alkaline cleaning, thereby helping to remove possible mineral deposits. Single-pack chemicals are also available that remove protein and mineral deposits at the same time.

CIP may be used for removing many types of fouling, including biological slime, rust, scale and organic matter. An example of the efficiency of CIP in removing cooling water deposits is shown in Figure.2. In this example, biological fouling from Rhine river water was removed by a slowly circulating alkaline solution at 60°C [3].

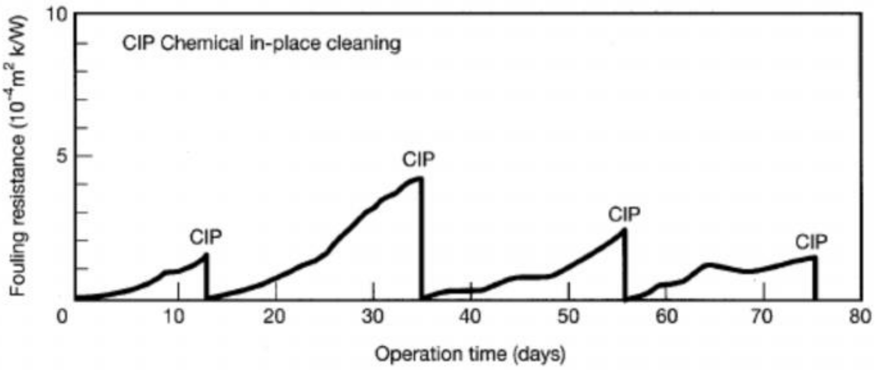

Fig. 7. Reduction of Fouling Resistance by CIP (after Novak)

Typically spent CIP solutions must be treated before release to the environment or recovered for reuse.

4.2 INSTALLATION

If fouling is likely to reduce the run time of a compact heat exchanger, consider installing two identical units in parallel. If one becomes fouled, the flow can be diverted through the other. The principle is the same as incorporating a bypass on a waste heat recovery unit to permit cleaning or to avoid plant shutdown in the event of a failure. Take extra care when installing, hydraulically testing and commissioning to avoid fouling and possibly corrosion.

4.3 OPERATION AND MAINTENANCE

Effective operational experience includes the following.

Check Design Limitations

Be aware of the design limitations of the selected compact heat exchangers. A tight design can limit operational flexibility, and optimum performance and minimum fouling will only be achieved when the unit is operated at, or near, its design conditions. For instance any reduction in the velocity of a cooling water stream may increase fouling.

Adequate Training

Make sure that all staff are fully trained in compact heat exchanger operation. Failures have occurred where non-specialists in heat exchangers were unaware of operating practices and experience.

Routine Preventive Maintenance

Compact heat exchangers are more vulnerable to the effects of fouling or blockage than conventional shell and tube heat exchangers. Therefore, give the same high priority to the relevant preventive measures - filters, chemical dosing etc. - as to ensuring that equipment, such as the main pumps, remains serviceable.

Failure or Blockage Procedures

Establish clear procedures for failure situations. When a failure occurs during operation, the general rule is to contact the manufacturer as soon as possible. Mechanical failure during operation may occur because liquids freeze or because of over pressurization, explosion, damage etc. If any of these occur, contact the manufacturer to discuss the possibilities of repair.

Decide on contingency plans for dealing with a blocked compact heat exchanger, such as cleaning in situ, blocking off the affected layers of a plate-fin heat exchanger, or switching to standby/replacement units.

The mechanical failure of one or more layers in a plate-fin heat exchanger or similar type of compact design need not involve complete replacement. Layers may be blanked off to allow continued operation. In some designs up to 10% of the layers may be blanked off. However, you should consult your equipment supplier before proceeding in this way.

Overhaul Procedures

Establish clear maintenance and overhaul procedures. Some compact heat exchangers can be sent off-site to be overhauled. This is particularly beneficial in the case of gasketed plate heat exchangers, as the gaskets are refitted to manufacturers' standards. If heat exchangers with gaskets are reassembled on site, ensure uniform gasket compression to minimize the risk of leaks. Use gaskets supplied by the heat exchanger manufacturer. With all reassembly, it is important to ensure that the manufacturer's recommendations are followed.

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