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Faculty of Mechanical Engineering
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**FACULTY
OF MECHANICAL
ENGINEERING
CTU IN PRAGUE**

Fouling in Process Apparatuses

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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

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Faculty / Institute: **Faculty of Mechanical Engineering**
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II. Master's thesis details

Master's thesis title in English:

Fouling in process apparatuses

Master's thesis title in Czech:

Fouling in process apparatuses

Guidelines:

Make a literature and patent survey concerning the fouling in process apparatuses. Focus the survey on the description of this phenomenon and its influence on the design of industrial apparatuses (chemical industry, food industry, pharmaceutical industry, ...). Focus also on mathematical models of the fouling layer growth and try to find models suitable for specific materials, chemicals, foods, ... Finally focus on experimental methods used in this area, how the fouling is measured and studied in mixing apparatuses, heat exchangers, and so on. Sketch and describe your idea how to measure and study the fouling in our laboratory, considering the fouling layer is formed by glauberite.

Bibliography / sources:

Follows literature survey.

Name and workplace of master's thesis supervisor:

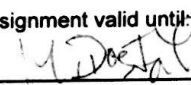
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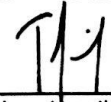
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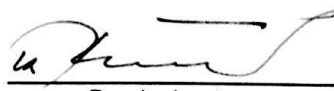
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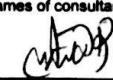

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

31 -10- 2017

Date of assignment receipt



Student's signature

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1. INTRODUCTION

Fouling is inevitable phenomenon of deposition unwanted material on the surface of process equipment either externally or internally to layer by layer in the presence of moist and air. Due to time the scaling of that layer increases even for regular water considered as working fluid, it has significant impact on thermal and hydronic performance due to fouling properties. The term of fouling usually refers to any type of fouling deposit matter on the heat transfer apparatus surface. The nature of the deposit strongly depends on the composition of the fluid treated by the exchanger. The fluid can be itself at the origin of the deposit, by organic decomposition under conditions of favorable temperature and pressure. But fouling can also come from solid or semi-solid materials in suspension in the fluid. According to Rima Harche^[2] in an idealized way, Fig.(1) shows these three major stages of a fouling mechanism.

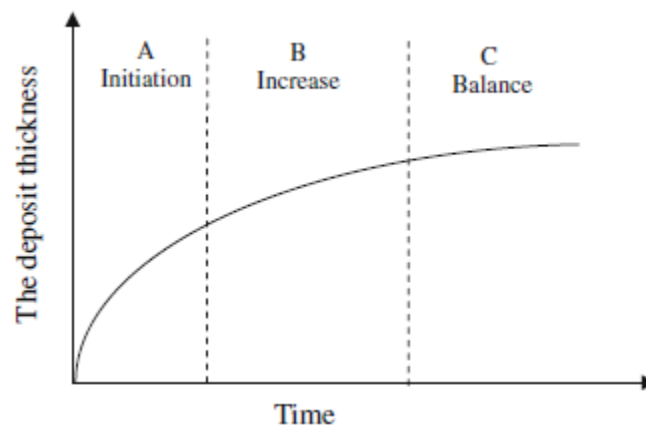


Figure 1 The deposition thickness [21]

The first starting part (A) phase is for initiation and mainly depends on types of deposit which varies periodically for few minutes for few weeks as an example of air-conditioning systems. While on other hand, part (B) relates to the increase in this deposit resulting from a competition between the mechanisms from deposit and wrenching. The fouling rate decreases gradually while wrenching increases. At last the second one leading that to a balance in (C) and a height fouling held constant. Amount of layer deposition has direct impact on heat transfer and pressure drop, as it effects on physical dimension of shell and tubes of heat exchanger.

2. TYPES OF FOULING

The deposit layer depends on the particular fluid and the conditions under which the process equipment operates. The deposit associated with cooling water, for instance, may include: corrosion products, particulate matter, crystals and living biological material on other hand for some components the deposit will depend on many factors including the origin of the water, its treatment and the processing conditions. Due to different condition it is possible that one component is dominant either scale formation or corrosion and the result leads to different fouling mechanisms in the development of techniques to mitigate the problem. Mainly there are six fouling mechanism which is reviewed by Bott et al. ^[23] in following categories:

2.1 Crystallization/Precipitation fouling

It occurs usually with the cooling water stream contain sulfates and carbonate, and referred to in water systems as scaling by shah et al. ^[24]. It is the crystallization of dissolved salts from saturated solutions, due to solubility changes with temperature, and subsequent precipitation onto the heat transfer surface. It generally occurs with aqueous solutions and other liquids of soluble salts which are either being heated or cooled. The deposition of inverse solubility salts on heated surfaces, usually called "scaling" and its deposited layer is hard and tenacious. The deposition of normal solubility salts on cooled surfaces usually has porous and mushy deposited layers and it is called "sludge", "soft scale", or "powdery deposit". Precipitation/crystallization fouling is common when untreated water, seawater, geothermal water, brine, aqueous solutions of caustic soda, and other salts are used in heat exchangers. The most important phenomena involved with this type of fouling include crystal growth during precipitation require formation of a primary nucleus. The mechanism controlling that process is nucleation, as a rule heterogeneous in the presence of impurities and on the heat transfer surface.



Figure 2 Crystallization fouling

It involves the formation of crystals from solution on the surface or deposition of crystals formed in the bulk liquid or in the laminar sub-layer due to decrease of solubility with increase in temperature.

2.2 Particulate fouling

It is the deposition of suspended particles in the process streams onto the heat transfer surfaces. If the settling occurs due to gravity as well as other deposition mechanisms, the resulting particulate fouling is called "sedimentation" fouling. Hence, particulate fouling may be defined as the accumulation of particles from heat exchanger working fluids (liquids and/or gaseous suspensions) on the heat transfer surface. Most often, this type of fouling involves deposition of corrosion products dispersed in fluids, clay and mineral particles in river water, suspended solids in cooling water, soot particles of incomplete combustion, magnetic particles in economizers, deposition of salts in desalination systems, deposition of dust particles in air coolers, particulates partially present in fire-side (gas-side) fouling of boilers, and so on. The particulate fouling is influenced by the following factors: concentration of suspended particles, fluid flow velocity, temperature conditions on the fouled surface (heated or non-heated), and heat flux at the heat transfer surface. It depends on the coming of discrete solid particles at the transfer surface. High velocity of fluid can minimize this effect. Particles may be small (i.e., $< 1 \mu\text{m}$) or may be large (i.e., several mm). Particulate fouling is common in both liquid and gas systems.



Figure 3 Particulate fouling

2.3 Biological fouling

Defined as the growth of living matter on heat exchanger surfaces commonly caused by micro-organisms. It is the attachment and growth of macro organisms and or microorganisms and their products on the heat transfer surface. It is usually called "Biofouling" and it is generally a problem in water streams. In general, biological fouling can be divided into two main subtypes of fouling: Microbial and Macrobial. Microbial fouling is accumulation of microorganisms such as algae, fungi, yeasts, bacteria, and molds, and Macrobial fouling represents accumulation of macro organisms such as clams, barnacles, mussels, and vegetation as found in seawater or estuarine cooling water. Microbial fouling precedes macrobial deposition as a rule and may be considered of primary interest. Biological fouling is generally in the form of a biofilm or a slime layer on the surface that is uneven, filamentous, and deformable but difficult to remove. Although biological fouling could occur in suitable liquid streams, it is generally associated with open recirculation or once-through systems with cooling water. Biological fouling may promote corrosion fouling under the slime layer. The phenomenon usually associated with water systems, e.g., cooling water, involves both microorganisms and microscopic marine organisms. Which include bacteria, fungi or algae, while the second-one includes mussels and barnacles.



Figure 4 Biological fouling

2.4 Chemical reaction fouling

Chemical reactions at or near the surface may give rise to this phenomena. This reaction is initiated with unsaturated organic compounds are heated or if they come directly to the hot metal tube wall. The effect of heat on a process fluid as it passes through the exchanger, may accelerate chemical reactions, e.g., cracking or polymerization reactions that can give rise to deposition of very tough plastic- like layer on the surface. The deposition in this case is the result of one or more chemical reactions between reactants contained in the flowing fluid in which the surface material itself is not a reactant or participant. However, the heat transfer surface may act as a catalyst as in cracking, coking, polymerization, and autoxidation. Thermal instabilities of chemical species, such as asphaltenes and proteins, can also induce fouling precursors. This fouling occurs over a wide temperature range from ambient to over 1000°C but is more pronounced at higher temperatures. The mechanism of this type of fouling is a consequence of an unwanted chemical reaction that takes place during the heat transfer process. Chemical reaction fouling is found in many applications of process industry, such as petrochemical industries, oil refining, vapor-phase pyrolysis, cooling of gas and oils, polymerization of process monomers, and so on. Furthermore, fouling of heat transfer surface by biological fluids may involve complex heterogeneous chemical reactions and physicochemical processes. The deposits from chemical reaction fouling may promote corrosion at the surface if the formation of the protective oxide layer is inhibited. In some instances the metallic surface of the heat exchanger acts as a catalyst thereby aiding the fouling process. Chemical reaction fouling is usually associated with liquids but it may also occur in vapor or gas streams.

2.5 Corrosion fouling

Some heat exchange materials of construction are subject to corrosion from the aggressive nature of the fluids or impurities in the fluids in contact with the surface. It involves a chemical or electrochemical reaction between the heat transfer surface itself and the fluid stream to produce corrosion products which, in turn, change the surface thermal characteristics and foul it. Corrosion may cause fouling in two ways. First, corrosion products can accumulate and adhere to the surface providing resistance to heat transfer. Second, corrosion products may be transported as particulate materials from the corrosion site and be deposited as particulate fouling on the heat transfer surface in another site of the system. For example, fouling on the water side of boilers may be caused by corrosion products that originate in the condenser or feed train. Corrosion fouling is prevalent in many applications where chemical reaction fouling takes place and the protective oxide layer is not formed on the surface. It is of significant importance in the design of the boiler and condenser of a fossil fuel-fired power plant. The result may be a protective layer, but more likely, the corrosion process produces a thick corrosion layer. It may be observed in both liquid and gas systems.



Figure 5 Corrosion fouling

2.6 Decomposition fouling

In case of organic compounds there may chance to decompose into other carbonaceous deposits while heating or it will come in contact with hot surface. While in cracking operations the hydrocarbon feedstock is the main objective but coke formation is also there which is undesired. Example for decomposition of organic compound is to tar and coke.

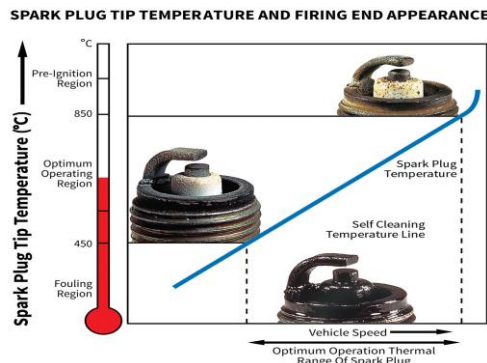


Figure 6 Decomposition fouling

Although the different mechanisms have been identified as leading to fouling, it is possible to consider fouling in an idealized, general way. If the deposit thickness due to fouling is plotted against time, three idealized curves may be visualized as shown in Fig.8.

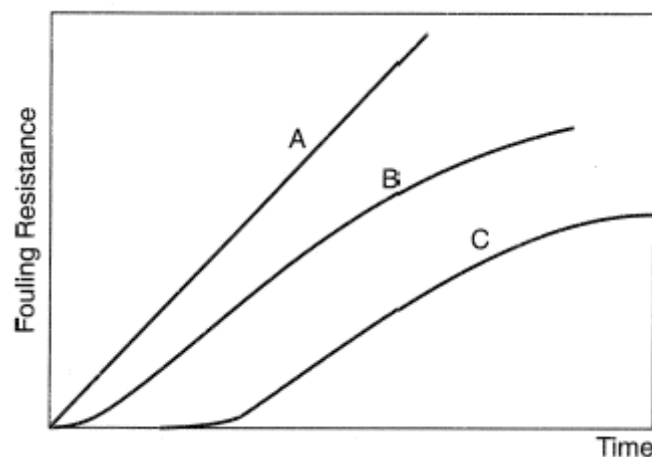


Figure 7 Idealized fouling curves

Curve A represents a straight line relationship as deposit thickness is proportional to time. Curve B is a falling rate curve with the rate of deposition declines with time. Curve C is the usual form of the relationship between deposit thickness (or thermal fouling resistance) and

time; it is an exponential or asymptotic curve. For a short time the heat exchanger fouls relatively slowly, but after a period of time the rate of deposition rapidly accelerates to be followed by a fall in the rate of deposition. Eventually the deposit thickness remains constant. The thickness of a deposit is a measure of the resistance of the deposit to the transfer of heat so that similar curves would result if foulant thermal resistance was plotted against time. The curves in Fig.7 are shown to develop from the origin. In some examples of fouling, an initiation or induction period is required before fouling begins. Induction periods may be extremely short, which tends a few seconds, or they may involve several weeks or months. The extent of the induction period depends on the nature of the heat exchanger surface, which relate to the material of construction and the surface roughness, together with the properties of the fluid and any impurities passing over the surface.

3. LITERATURE REVIEW

A detailed study of shell and tube heat exchanger with various mass flow rate and fouling factor has been provided in references. Thanhtrung Dang et al.^[1] gives idea about theoretical idea of shell and tube heat exchanger heat transfer rate and fouling thickness with two cases, when the thickness of substrate is 1.2mm and after it increase by 1.031 times to 2mm investigated in this study.

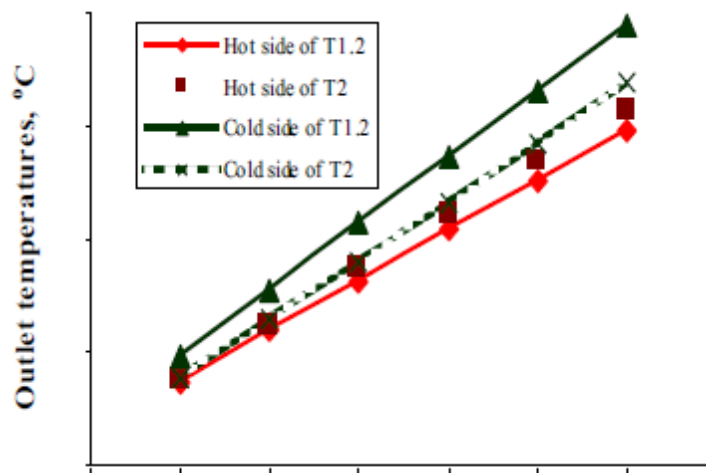


Figure 8 Inlet temperature of hot side.

When the thickness of substrate of the heat exchanger increases, its actual heat transfer rate decreases and with the increase of the inlet temperature of hot side the outlet temperatures also increases. However the accumulation of deposits rate describe by Rima Harcheon et al^[2] which effect the heat transfer surface and finally leads to a reduction of the energy transfer effectiveness.

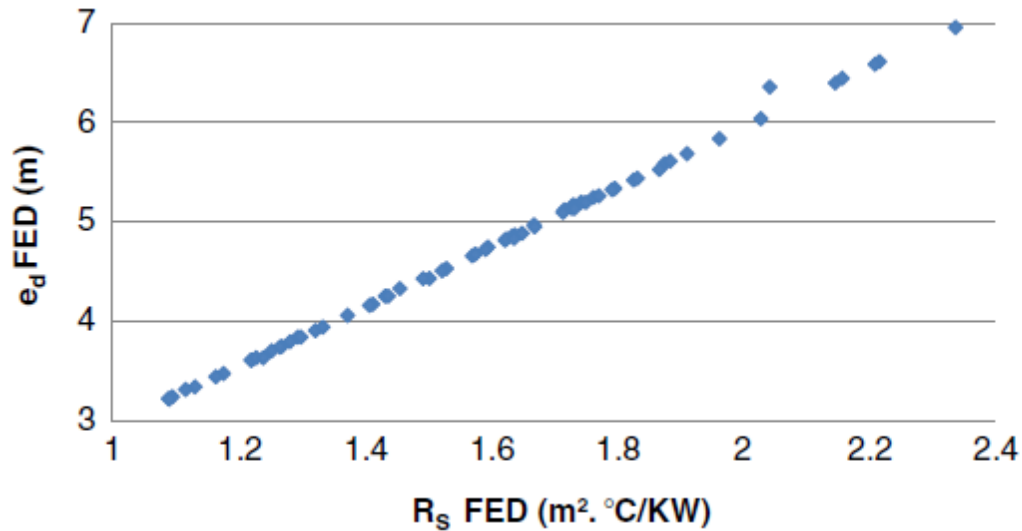


Figure 9 Variation of deposit thickness with fouling resistance

In Fig: one of result that the deposit thickness varies proportionally with the fouling resistance, which represents the variation of the deposit thickness according to the fouling resistance for the E101 FED exchanger battery. J.W. Suitor et al. ^[3] gives idea about theoretical developments by using kern method concluded that fouling resistance increases indefinitely with time. The deposition term is a complex function of velocity, water chemistry, the wall, scale surface and bulk fluid temperature. P.J. Frayer et al. ^[4] demonstrated the design of fouling resistance in which pulsates flow system may be effective in many cases, but that antifouling exchangers should not be designed without understanding the fouling mechanism. D. Gulley ^[5] Studied that, pressure drop is a big help in analyzing performance problems. They also provide a rough check of flow rates. Liljana Markovska et al. ^[6] Studied that, increased fluid velocities result in larger heat transfer coefficients and, consequently, less heat-transfer area and exchanger cost for a given rate of heat transfer. On the other hand, the increased fluid velocities cause an increase in pressure drop and greater pumping power cost. Kevin M. Lunsford^[7] presented some methods for increasing shell and tube heat exchanger performance. The method considers whether the exchanger is performing correctly to begin with, excess pressure drop capacity in existing exchanger, the re-evolution of fouling factor and their effect on exchanger calculations. K.C.Leong and K.C.To^[8] describes user friendly computer software(HTRI and HTFS) developed for the thermal and hydraulic design of shell and tube heat exchanger based on open literature Bell Delaware method. The use of this software will bridge the gap between engineering practice and teaching of shell and tube heat exchanger design. A rating, sizing and simulation can be performed in this computer software such as HTRI & HTFS. For estimation of optimal

operation condition of shell and tube heat exchanger these type of optimization software are very useful. D.I.Wilson et al.^[9] proposed a semi-empirical approach to quantify the effect of flow velocity on tube-side fouling in crude oils at high temperatures which pilot plant studies indicated that: (i) Fouling rates increased with increasing temperature – initially interpreted as film temperature, elsewhere as wall/deposit temperature. (ii) Fouling rates decreased with increasing flow velocity (figure 1) by using the fouling model and the concept of the fouling threshold fouling rate in heat exchanger can be predicted.

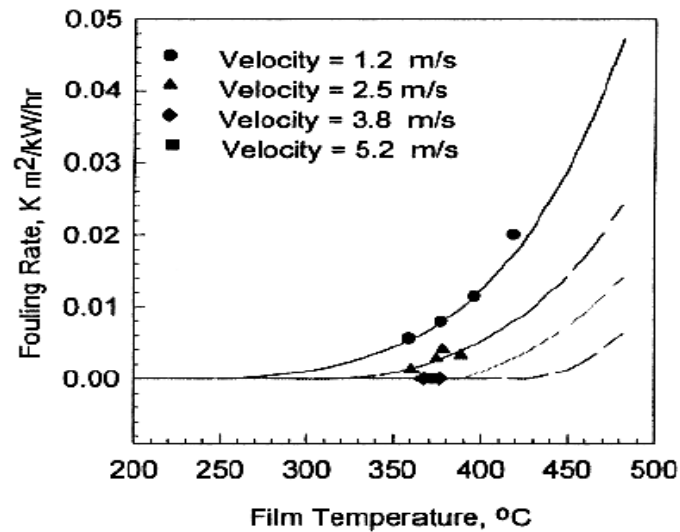


Figure 11: The Ebert-Panchal model ^[9]

John M. Nesta and Christopher A. Bennett^[10] showed the fouling layer is a conductive resistance to heat transfer that must be accounted for in the design heat transfer coefficient. Also, Fouling thickness and thermal conductivity both contribute to the resistance. Reduced cross-sectional flow area also increases pressure drop in the fouled region. M.S. Abd-Elhady et al.^[11] Studied the influence of flow direction with respect to gravity on particulate fouling of heat exchangers is investigated experimentally to determine the optimal flow direction to minimize fouling. Four orientations of flow have been investigated, horizontal flow, upward flow, downward flow and a flow under an angle of 45°. E.M.Ishiyama et al.^[12] presented an analysis of the thermal and hydraulic impacts of fouling. For fouling rate laws that incorporate the threshold fouling concept, characteristic times for fouling of an exchanger were identified, based on hydraulic or thermal limitations. D.H. Lister and F.C. Cussac^[13] showed the formulation mechanism for the effect of the bubbles on deposition in water under boiling condition. Paper describes the main mechanisms occurring during boiling and to determine how bubbles influence the deposition of iron oxide particles. Deposition, removal

and consolidation of the deposit are included in the model. The relation between heat transfer, bubbles formation near wall and fouling amount is studied. Su Thet Mon Than et al.^[14] evaluated design data for heat transfer area and pressure drop and checking whether the assumed design satisfies all requirement or not. The primary aim of this design is to obtain a high heat transfer rate without exceeding the allowable pressure drop. Arturo Reyes Leon et al.^[15] developed relationship between heat transferred and energy loss for turbulent flow and also identified the advantages of having the appropriate exchanger with working conditions, environmental conditions and economical aspects. In addition to thermal design, mechanical design of heat exchanger is also part of it. Rajiv Mukherjee ^[16] developed correlation for optimal condition of shell and tube heat exchanger. The optimized thermal design can be done by sophisticated computer software however a good understanding of the underlying principles of exchanger design is needed to use this software effectively.

4. FOULING INTO DESIGN OF PROCESS APPARATUS

The presence of a deposit on the surfaces of a heat exchanger gives rise to two major problems are, the efficiency of the heat exchanger is reduced in respect of heat transfer as a result of the thermal resistance of the deposit mentioned in Rima Harche^[2] In general, the thermal conductivity of deposits is very much lower than metals so that even a thin layer can cause significant thermal resistance. The fact that the surface of the foulant layer is rough compared to the original metal surface will, in general, increase the heat transfer due to the increased turbulence generated by the roughness elements. To some extent, this offsets the effects of increased thermal resistance across the heat exchanger. However, the benefits, due to the presence of the fouling layer, are usually relatively small compared to the restrictions to heat flow imposed by the insulating properties of the foulant.

The overall effect on heat transfer may be summarized by the following statement:

- Change in overall heat transfer coefficient is some function of
- Change due to the thermal resistance of the foulant layer
- Change due to the surface roughness of the deposit
- Change due to the increased velocity for a given volumetric flow rate, resulting from the restrictions on flow area imposed by the presence of the deposit.

Although the dependence has been cited regarding the heat exchanger as a whole, it is strictly applicable to local conditions. Still, the incidence and quality of a deposit is likely to vary with its location in the exchanger. Due to the roughness of the deposit and the restrictions of the flow area that are responsible for enhanced turbulence and heat transfer compared to the condition for the same flow rate, and according to Liljana Markovska, et al.^[6] the pressure drop also increases. Relatively the layers on the inside of a tube can, for instance, give rise to substantial increases in pressure drop. For example, a 1mm layer on the inside of a heat exchanger tube with a nominal internal diameter of 18mm increases the velocity for a given volumetric flow rate by a factor of $182/162 = 1.27$. Since pressure drop is a function of the square of the velocity, the pressure drop with the deposit in place, will be increased by a factor of 1.27² or around 1.6 times, i.e., a 60% increase as written in Shah et al.^[24] These calculations neglect the effect of deposit roughness so that, if it were possible to take the additional contribution to pressure drop into account numerically, the pressure drop through the exchanger under fouled conditions may approach double that for a clean exchanger. Reduced heat transfer and increased pressure drop under fouled conditions can have

significant implications for energy utilization on the process plant—namely reduced heat recovery that may have to be made good using primary energy, and increased energy requirements for monitoring the fluid through the exchanger. Both effects have implications in terms of cost of operation. The economic penalties of heat exchanger fouling on the financial performance include other effects that are due to the presence of deposits that may not always be recognized at the design stage, or during subsequent operation.

4.1 Preliminary calculation

The heat transfer surface fouls during operation, resulting in increased thermal resistance and often an increase in the pressure drop and pumping power. It is required to understand, how mass flow rate can effect on deposition rate of fouling layer inside the tube. The extra layer make the passage narrow which effect in the increase of fluid velocity at the axis of the tube and vice versa at the surface, which decrease the velocity due to roughness. In general the main consequences of this extra layer finally reduce the efficiency of any heating apparatus.

A selected shell and tube heat exchanger must satisfy the process requirements with the allowable pressure drops until the next scheduled cleaning of plant. The methodology to evaluate thermal parameters is explained with suitable assumptions. The following are the major assumptions made for the pressure drop analysis:

1. Flow is steady and isothermal, and fluid properties are independents of time.
2. Fluid density is dependent on the local temperature only or is treated as constant.
3. The pressure at a point in the fluid is independent of direction.
4. Body force is caused only by gravity.
5. There are no energy sink or sources along streamline; flow stream mechanical energy dissipation is idealized as zero.
6. The friction factor is considered as constant with passage flow length.

During the initial stages of heat exchanger selection when the basic concepts of the design are being considered, the problem of potential fouling will be a major concern. It is usual, after careful thought, to include additional thermal resistance over and above that for the clean conditions, to allow for the anticipated deposit accumulation. The result is an increase in heat transfer area for a given heat load and temperature change requirements. The increase in heat transfer area means increase in the size of the heat exchanger for a given specific duty which represents an increase in capital cost. The choice of the anticipated increase in heat transfer resistance due to the fouling is crucial to the ultimate cost of the heat exchanger. Where

excessive fouling is anticipated and a particular heat exchanger is vital to the process, it may be prudent to duplicate the heat exchanger in addition to allowing for deposit accumulation in the basic design, so that production can be maintained without the need to shut down the process. According to Bott et al. [23] duplication and oversizing, to allow for fouling, represents substantial additional capital costs. Where special materials of construction are required, due to the nature of the fluids passing through the heat exchanger, the additional cost may be considerable. Heat transfer or the size of heat transfer exchanger can be obtained from equation:

$$Q = U_o A_o \Delta T_m \quad (1)$$

The overall heat transfer coefficient U_o based on the O.D. of tubes can be estimated from the estimated values of individual heat transfer coefficients, the wall and fouling resistance and the overall surface efficiency using equation.

$$\frac{1}{U_o} = \frac{A_o}{A_i} \left[\frac{1}{\eta_i h_i} + \frac{R_{fi}}{\eta_i} \right] + A_o R_w + \frac{R_{fo}}{\eta_o} + \frac{1}{\eta_o h_o} \quad (2)$$

For the single tube pass, purely countercurrent heat exchanger, $F = 1.00$. For preliminary design shell with any even number of tube side passes, F may be estimated as 0.9

Heat load can be estimated from the heat balance as:

$$Q = (mC_p)_c (T_{c2} - T_{c1}) = (mC_p)_h (T_{h2} - T_{h1}) \quad (3)$$

If one stream changes phases:

$$Q = mh_{fg} \quad (4)$$

LMTD (Log Mean Temperature Difference Method) calculation:

If three temperatures are known, the fourth one can be found from the heat balance,

$$\Delta T_{lm} = \frac{(T_{h1} - T_{c2}) - (T_{h2} - T_{c1})}{\ln \frac{(T_{h1} - T_{c2})}{(T_{h2} - T_{c1})}} \quad (5)$$

Heat transfer area can be calculated from equation (1). Number of tubes of diameter (d_o), shell diameter (D_s) to accommodate the number of tubes (N_t), with given tube length (L) can be estimated.

$$A_o = \pi_e N_t L \quad (6)$$

One can find the shell diameter (D_s), which would contain the right number of tubes (N_t), of diameter (d_t).

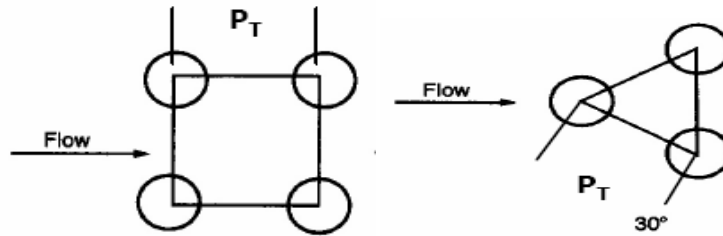


Figure 10 Square and triangular pitch tube layout^[17]

The total number of tubes can be predicted in fair approximation as function of the shell diameter by taking the shell circle and dividing it by the projected area of the tube layout (fig 10) pertaining to a single tube A_1 .

$$N_t = (CTP) \frac{\pi D_s^2}{4A_1} \quad (7)$$

Where, CTP is the tube count calculation constant that accounts for the incomplete coverage of the shell diameter by the tubes.

Based on fixed tube sheet the following values are suggested:

One tube pass: CTP = 0.93

Two tube pass: CTP = 0.90

Three tube pass: CTP = 0.85

$$A_1 = (CL) (P_T)^2 \quad (8)$$

Where CL is the tube layout constant:

CL = 1.0 for 90 and 45

CL = 0.87 for 30 and 60

Equation (7) can be written as:

$$N_t = 0.875 \left(\frac{CTP}{CL} \right) \frac{D_s^2}{(P_r)^2 d_o^2} \quad (9)$$

Where P_R is the Tube Pitch Ratio ($P_R = P_T/d_o$).

The shell diameter in terms of main construction diameter can be obtained as from equations (6) and (9).

$$D_s = 0.637 \sqrt{\frac{CL}{CTP}} \left(\frac{A_o (P_r)^2 d_o}{L} \right)^{1/2} \quad (10)$$

4.2 Tube side pressure drop

The tube side pressure drop can be calculated by knowing the number of tube passes (N_p) and length (L) of heat exchanger.

The pressure drop for the tube side fluid is given by equation

$$\Delta P_t = 4f \frac{LN_p}{d_i} \rho \frac{\mu_m^2}{2} \quad (11)$$

$$\Delta P_t = 4f \frac{LN_p}{d_i} \frac{G_i^2}{2\rho} \quad (12)$$

The change of direction in the passes introduction in the passes introduction an additional pressure drop due to sudden expansions and contractions that the tube fluid experiences during a return that is accounted for allowing four velocity head per pass

$$\Delta P_t = 4N_p \frac{\rho \mu_m^2}{2} \quad (13)$$

The total pressure drop of the side becomes:

$$\Delta P_t = \left(4f \frac{LN_p}{d_i} + 4N_p \right) \frac{\rho \mu_m^2}{2} \quad (14)$$

4.3 Pumping power and pressure drop

The fluid pumping power is proportional to the pressure drop in the fluid across a heat exchanger, the equation can give by Liljana Markovska et al. [6]

$$P = \frac{m\Delta P}{\rho\eta_p} \quad (15)$$

Where η_p is the pump or fan efficiency ($\eta_p = 0.80$ to 0.85)

The cost in terms of increased fluid friction requires an input of pumping work greater than the realized benefit of increased heat transfer. For gases and low density fluids and also for very high viscosity fluids, pressure drop is always of equal importance to the heat transfer rate and it has a strong influence on the design of heat exchangers. Pressure drop of shell and tube as well as pumping power can be calculated by these theories. Fouling factor, the effect of fouling on pressure drop and overall heat transfer coefficient estimation are also important factor to explain.

4.4 Effect of fouling on heat transfer

According to Su Thet Mon Than et al. [14] heat transfer rate can be given by,

$$Q = U_c A_o \Delta T_M \quad (16)$$

Where, U is based on outside heat transfer surface area of the exchanger. Fouling coefficient (U_f) can be related to the clean surface overall heat transfer coefficient (U_c) as:

$$\frac{1}{U_f} = \frac{1}{U_c} + R_{ft} \quad (17)$$

The heat transfer under fouling conditions (Q_f) can be expressed as:

$$Q_f = U_f A_f \Delta T_M \quad (18)$$

Overall heat transfer coefficient based on outer surface area under fouled conditions can be obtained by adding the inside and outside thermal resistances.

$$U_f = \frac{1}{\frac{A_o}{A_i h_i} + \frac{A_o}{A_i} R_{fi} + \frac{A_o \ln\left(\frac{d_o}{d_i}\right)}{2\pi kl} + R_{fo} + \frac{1}{h_o}} \quad (19)$$

4.5 Effect of fouling on pressure drop

There is a finite thickness of fouled surface which causes change in geometry due to fouling affects the flow field and the pressure drop. Fouling layer roughness of surface decreases the Inner Diameter and increases the Outer Diameter of the tubes.

$$\Delta P = 4f \left(\frac{L}{dl} \right) \frac{\rho u_m^2}{2} \quad (20)$$

The preceding dimensionless group involving Δp has been defined as the Fanning friction factor f .

$$f = \frac{\Delta p}{4 \left(\frac{L}{d_i} \right) \frac{\rho u_m^2}{2}} \quad (21)$$

$$f = 0.046 \text{Re}^{-0.2} \text{ for } 3 \times 10^4 < \text{Re} < 10^6 \quad (22)$$

$$f = 0.079 \text{Re}^{-0.25} \text{ for } 4 \times 10^3 < \text{Re} < 10^5 \quad (23)$$

The fouling layer decreases the inner diameter and roughens the surface, thus causing an increase in the pressure drop given by equation (20). Pressure drop under fouled and clean condition can be related as:

$$\frac{\Delta P_f}{\Delta P_c} = \frac{f_f d_c}{f_c d_f} \left(\frac{u_f}{u_c} \right)^2 \quad (24)$$

By assuming that the mass flow rate ($m = u_m \rho A$) under clean and fouled conditions is the same, equation (24) can be modified as:

$$\frac{\Delta P_f}{\Delta P_c} = \frac{f_f}{f_c} \left(\frac{d_c}{d_f} \right)^2 \quad (25)$$

The fouling factor can be related to the fouling thermal conductivity k_f and the fouling thickness t_f as:

$$R_f = \frac{t_f}{k_f} \text{ (For a plane wall)} \quad (26)$$

$$R_f = \frac{d_c \ln\left(\frac{d_c}{d_f}\right)}{2\pi k_f} \text{ (For a cylindrical tube wall)} \quad (27)$$

Inner diameter under fouled conditions, d_f , can be obtained by rearranging equation (27):

$$d_f = d_c \exp\left(\frac{-2\pi k_f R_f}{d_c}\right) \quad (28)$$

And the fouling thickness, t_f , is expressed as:

$$t_f = 0.5t_c \left[1 - \exp\left(\frac{-2\pi k_f R_f}{d_c}\right) \right] \quad (29)$$

These theories show the correlation between pressure drop clean and fouled condition. Effects of fouling on heat transfer is also discussed which will helpful in calculation of overall heat transfer coefficient. These fundamental logics are going to use in optimization process

5. FOULING PROCESS MECHANISMS

The overall fouling process is usually considered to be the net result of two simultaneous sub-processes; a deposition process and a removal or re-entrainment process. A schematic representation of fouling process is given in figure: 11. All sub-processes can be summarized as:

- Formation of foulant materials in the bulk of the fluid.
- Transport of foulant materials to the deposit-fluid interface.
- Attachment/ formation reaction at the deposit-fluid interface.
- Removal of the fouling deposit (spalling or sloughing of the deposit layer).
- Transport from the deposit-fluid interface to the bulk of the fluid.

A schematic diagram for the fouling processes is shown in figure:11. It must be noted that, some of these sub-processes may not be applicable in certain fouling situations such as corrosion fouling.

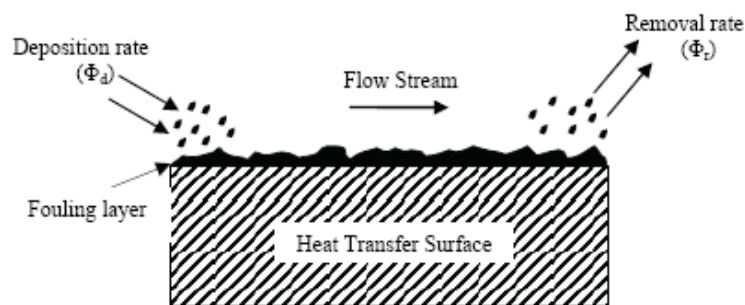


Figure 11 Fouling process ^[5]

In another way, three basic stages may be visualized in relation to deposition on surfaces from a moving fluid. They are:

1. The diffusion transport of the foulant or its precursors across the boundary layers adjacent to the solid surface within the flowing fluid.
2. The adhesion of the deposit to the surface and to itself.
3. The transport of material away from the surface.

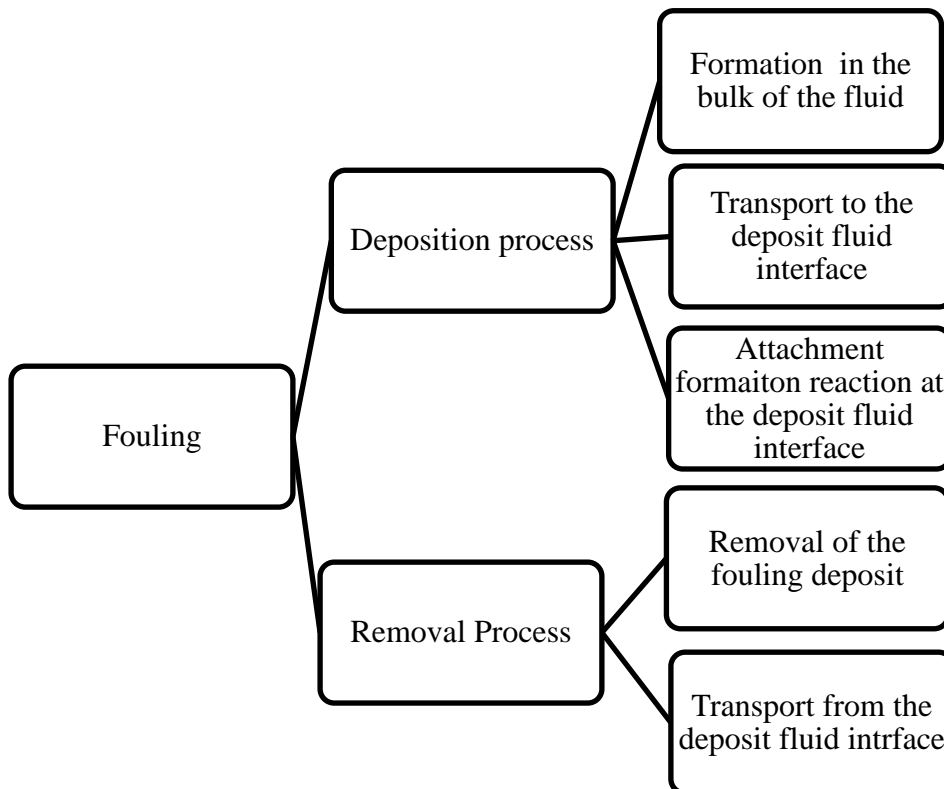


Figure 12 Fouling process ^[5]

From the empirical evidence involving various fouling mechanisms discussed, it is clear that virtually all these mechanisms are characterized by a similar sequence of events. The successive events occurring in most cases are illustrated in figure: 12. These events govern the overall fouling process and determine its ultimate impact on heat exchanger performance. In some cases, certain events dominate the fouling process, and they have a direct effect on the type of fouling to be sustained. The main five events can be summarized briefly as following:

1. Formation of foulant materials in the bulk of the fluid or initiation of the fouling, the first event in the fouling process, is preceded by a delay period or induction period, fouling layer thickness t_d as shown in figure:11, the basic mechanism involved during this period is heterogeneous nucleation, and t_d is shorter with a higher nucleation rate. The factors affecting t_d are temperature, fluid velocity, composition of the fouling stream, and nature

and condition of the heat exchanger surface. Low-energy surfaces (un-wettable) exhibit longer induction periods than those of high-energy surfaces (wettable). In crystallization fouling, t_d tends to decrease with increasing degree of supersaturation. In chemical reaction fouling, t_d appears to decrease with increasing surface temperature. In all fouling mechanisms, t_d decreases as the surface roughness increases due to available suitable sites for nucleation, adsorption, and adhesion.

2. Transport of species means transfer of the fouling species itself from the bulk of the fluid to the heat transfer surface. Transport of species is the best understood of all sequential events. Transport of species takes place through the action of one or more of the following mechanisms:

- Diffusion: involves mass transfer of the fouling constituents from the flowing fluid toward the heat transfer surface due to the concentration difference between the bulk of the fluid and the fluid adjacent to the surface.
- Electrophoresis: under the action of electric forces, fouling particles carrying an electric charge may move toward or away from a charged surface depending on the polarity of the surface and the particles. Deposition due to electrophoresis increases with decreasing electrical conductivity of the fluid, increasing fluid temperature, and increasing fluid velocity. It also depends on the pH of the solution. Surface forces such as London–van der Waals and electric double layer interaction forces are usually responsible for electrophoretic effects.
- Thermophoresis: a phenomenon whereby a "thermal force" moves fine particles in the direction of negative temperature gradient, from a hot zone to a cold zone. Thus, a high-temperature gradient near a hot wall will prevent particles from depositing, but the same absolute value of the gradient near a cold wall will promote particle deposition. The thermophoretic effect is larger for gases than for liquids.
- Diffusiophoresis: involves condensation of gaseous streams onto a surface.
- Sedimentation: involves the deposition of particulate matters such as rust particles, clay, and dust on the surface due to the action of gravity. For sedimentation to occur, the downward gravitational force must be greater than the upward drag force. Sedimentation is important for large particles and low fluid velocities. It is frequently

observed in cooling tower waters and other industrial processes where rust and dust particles may act as catalysts and/or enter complex reactions.

- Inertial impaction: a phenomenon whereby “large” particles can have sufficient inertia that they are unable to follow fluid streamlines and as a result, deposit on the surface.
 - Turbulent down sweeps: since the viscous sublayer in a turbulent boundary layer is not truly steady, the fluid is being transported toward the surface by turbulent downsweeps. These may be thought of as suction areas of measurable strength distributed randomly all over the surface.
3. Attachment of the fouling species to the surface involves both physical and chemical processes, and it is not well understood. Three interrelated factors play a crucial role in the attachment process: surface conditions, surface forces, and sticking probability. It is the combined and simultaneous action of these factors that largely accounts for the event of attachment.
 4. Removal of the fouling deposits from the surface may or may not occur simultaneously with deposition. Removal occurs due to the single or simultaneous action of the following mechanisms; shear forces, turbulent bursts, re-solution, and erosion.
 5. Transport from the deposit-fluid interface to the bulk of the fluid, once the deposits are sloughed, it may/may not transport from the deposit-fluid interface to the bulk of the fluid. This depends on the mass and volume of the sloughed piece and on the hydrodynamic forces of the flowing fluid. If the sloughed piece is large enough, it may move on the surface and deposited on another site on the system such as some corrosion products. All deposits which removed due to erosion effect will be transported to the bulk of the fluid. The removal process is not complete without this action. The important parameter affecting the deposit sloughing is the aging of deposits in which it may strengthen or weaken the fouling deposits.

5.1 FOULING CURVES ^[5]

The overall process of fouling is indicated by the fouling factor, according to Bott et al. ^[23] Fouling resistance (R_f) which is measured either by a test section or evaluated from the decreased capacity of an operating heat exchanger. The representation of various modes of fouling with reference to time is known as a fouling curve or fouling factor-time curve. Typical fouling curves are shown in figure 13.

Linear Fouling Curve: It is indicative of either a constant deposition rate, ϕ_d with removal rate, ϕ_r being negligible where ϕ_d is constant, ϕ_r is equal to 0 or the difference between ϕ_d and ϕ_r is constant. In this mode, the mass of deposits increases gradually with time and it has a straight-line relationship of the form ($R_f = at$) where “a” is the slope of the line.

Falling Rate Fouling Curve: Results from both decreasing deposition rate, ϕ_d with removal rate, ϕ_r being constant or decreasing deposition rate, ϕ_d and increasing removal rate, ϕ_r . In this mode, the mass of deposit increases with time but not linearly and does not reach the steady state of asymptotic value.

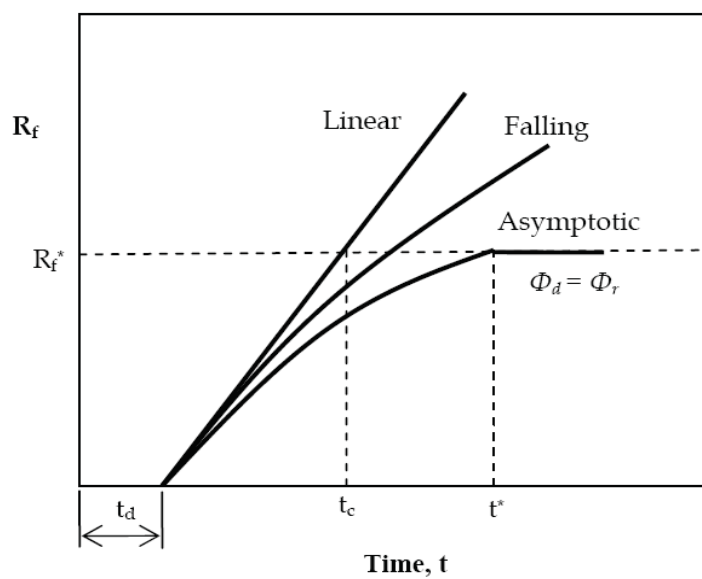


Figure 13 Fouling Curves ^[5]

5.2 Asymptotic Fouling Curve

It is indicative of a constant deposition rate, ϕ_d and the removal rate, ϕ_r being directly proportional to the deposit thickness until $\phi_d = \phi_r$ at the asymptote. In this mode, the rate of fouling gradually falls with time, so that eventually a steady state is reached when there is no net increase of deposition on the surface and there is a possibility of continued operation of the equipment without additional fouling. This mode is the most important one in which it is widely existed in the industrial applications. The pure particulate fouling is one of these types. The underlying mechanism involved in the accumulation of deposits on surfaces of heat exchangers may generally be considered to involve three stages. The foulant or the agents or impurities (e.g., bacteria, solid particles or corrosive agents) that lead to deposit formation, approach the surface from the bulk through the viscous sublayer adjacent to the

heat exchanger surface, across which the fluid is flowing. The principles of mass transfer apply. At the surface, adhesion can take place involving a number of factors including the interaction of surface forces, chemical reactions and structural orientation. Once deposited on the surface, the material may be subject to forces that compact or weaken the deposit. The quality of the deposit is likely to be time dependent. These three stages will be influenced by a number of system parameters, but principally these are associated with fluid flow, heat and mass transfer. As a consequence, the process whereby a surface becomes fouled and the deposit maintained, is complex resulting from the interaction of a number of factors. Although it is extremely rare for a single mechanism to apply, it is useful to examine separately the mechanisms briefly mentioned earlier in order to have an appreciation of the effects of the system variables involved.

5.2.1 Crystallization

The deposition or formation of crystals on a surface, sometimes referred to as scaling, is often associated with aqueous systems, e.g., cooling water circuits. Before crystallization can occur, it is necessary to have conditions of supersaturation, i.e., dissolved solid concentrations above the saturation solubility at a particular temperature. The supersaturation provides the "driving force" for precipitation to occur. In general, the degree of supersaturation involved is quite small; its location will depend very much on the temperature distribution within the heat exchanger between the bulk fluid and surface temperatures. Two solubilities of salts in water are recognized. First one is normal solubility salts such as NaCl or Na₂SO₄ which display increased solubility as the solution temperature is raised, so that when a saturated solution is cooled supersaturation can occur followed by precipitation. Fouling from normal solubility salts is likely when these solutions are cooled. Salts like CaCO₃, Mg₂(SO₄) which have inverse solubility and on the other hand, have reduced solubility as the temperature is raised. Consequently, as the temperature of a saturated solution increases, supersaturation and precipitation will occur. Fouling or scaling due to inverse solubility salts is probable when solutions of these salts are heated. Furthermore, the solubility of inverse solubility salts in general is quite low, so that relatively small temperature changes are likely to cause fouling problems. The problem is very prevalent in cooling water systems due to the so-called hardness salts usually present in the water. There are two contributory factors are, as the cooling process takes place the temperature of the water rises. If the water is already saturated even a small temperature rise leads to precipitation. In cooling water systems, the technique used to remove unwanted heat is to

evaporate some of the water in a cooling tower or spray pond. The loss of water vapor concentrates the dissolved salts so that saturation is soon achieved with the consequent increased possibility of precipitation of sparingly soluble salts. To offset this concentration effect, some of the saturated water is removed in the so-called "blow down" discharge, to be replaced with fresh "make up" water. The scale produced on heat exchanger surfaces as a result of crystallization from water is often tenacious and difficult to remove, although in some instances, it is soft, resembling a sludge that is more easily removed from the surface. The condition of the deposit very much depends on the conditions, particularly of temperatures that prevail close to the solid surfaces. The color of scale depends very much on the system involved. In purer forms, the color is near white, but color can be imparted to the scale from trace compounds in the system, e.g., oxides of iron that may give black (magnetite) or red (hematite) colors. Controlling scale formation in boilers is particularly important, since the accumulation of hardness salts on the heat transfer surfaces (e.g., the inside of water tubes) can lead to catastrophic failure. The presence of the scale can lead to excessive metal temperatures and consequently rupture.

5.2.2 Particle Deposition

Particle accumulation on heat exchanger surfaces is a common fouling phenomenon as mentioned by Rema et al. ^[2] A wide range of particle sizes may be involved in the deposition process. The origin of the particles varies. In some instances (e.g., water and crude oil), the particulate matter may be inherent in fluid stream. In combustion systems, particulate matter (e.g., the mineral matter in coal) may be released as the combustible components are burnt. The mineral particles go forward with the flue gasses and are deposited on the heat exchanger surfaces. It is also possible in combustion systems, that, if the combustion process is not adequately controlled, incomplete combustion occurs and particles of unburnt carbon are carried in the gas stream. The high temperatures prevailing in combustion systems may mean that some particulate matter is in the form of liquid droplets that solidify as they are cooled. Agglomeration and chemical reaction of the particles with gaseous components in the flue gas can add to the complexity of the fouling process. In some process streams, temperature effects lead to chemical reactions which produce large molecules (e.g., polymers) as particulate matter capable of being deposited on surfaces.

5.2.3 Biological Growth on Surfaces

Biofouling of heat exchanger surfaces is generally falls in two groups are macrofouling and microfouling. In general, aqueous environments are involved such as might be found in a cooling water system. Water originates from a natural source such as a river or the sea. Generally macro fouling is associated with living creatures such as mussels and barnacles. It is also possible for vegetation such as sea weed to become attached and grow on surfaces. Macro fouling is often experienced and although it is not exclusively occurred in the use of sea water. Micro fouling is the result of the attachment and growth of microorganisms on surfaces. As far as heat exchangers are concerned, the microorganisms involved are usually bacteria. Other microorganisms that may be found in cooling water systems include fungi and algae. Algae need a source of light. According to Shah et al. ^[24] In nature this is sunlight; so, these microbes are to be found in exposed regions, for example, the basin below a cooling tower. Fungi, on the other hand, may be found on the internal structure of a cooling tower. The structure of the tower can be damaged and destroyed by fungal activity. Although algae and fungi may not grow on heat exchanger surfaces, they may still be the source of deposits on the heat transfer surfaces. With the passage of time, either living or dead algae or fungi may become detached upstream of the heat exchanger only to deposit in the downstream equipment. Under the conditions, this organic material may provide a suitable nutrient for supporting bacterial activity. In general, the surface of heat exchangers in cooling water systems is ideal for microbial growth. The slime layer associated with fouling from microorganisms is characterized by a gelatinous, hydrated material often nearly transparent, but more usually colored by microorganisms, or by other contaminants in the water such as oxides or hydroxides of iron. Another common feature of biofilms is that they are uneven and deformable under the action of the water flow. Under certain conditions filamentous structures grow out from the surface and are free to oscillate within the flowing water. Biofilms are notoriously difficult to remove from surfaces, but if they spontaneously slough off the surface as does happen during operation, the lumps of biofilm can cause blockages downstream. Very thick biofilms with serious implications for heat transfer and pressure drop are possible under favorable conditions.

The presence of a biofilm on a metal surface may promote corrosion. The local conditions under the biofilm are likely to be different from those in the bulk flow, this is particularly applicable to the pH. The activity of the living material is likely to lower the local pH that could initiate corrosion. Furthermore, under a biofilm, due to the restrictions on ingress of

bulk fluid, galvanic cells may be established that enhances, perhaps only locally, the rate of corrosion.

5.2.4 Chemical Reaction Fouling

The accumulation of deposits may occur as the result of chemical reactions at or near a heat exchanger surface by Bott et al. [23] Because chemical reactions are usually enhanced by raised temperatures, chemical reaction fouling may be experienced where a reactive fluid is being heated. Under these circumstances, the slow-moving layers of fluid near the heat transfer surface are subject to relatively high temperatures. Fouling due to the incidence of chemical reactions can occur in a wide range of process streams and over a wide range of temperature, i.e., from near ambient to temperatures associated with combustion conditions. Processes where chemical reaction is responsible for deposit formation, include food processing in case of the pasteurization of milk, oil refining, preheating crude oil prior to primary distillation and chemical manufacturing that involves polymerization reactions. As in combustion also the impurities contained in the original fuel like coal or combustible waste may give rise to chemical reactions in conjunction with acid gases such as SO_2 and SO_3 contained in the flue gases. Incomplete combustion may lead to the generation of soot particles that deposit on heat transfer surfaces. Free radicals may be responsible for chain reactions in organic liquids that ultimately lead to deposit formation. These examples of chemical reaction demonstrate the wide range of substances that may be regarded as being deposits from chemical reactions. With effect the deposits may be soft and tender or tough and difficult to remove depending on the chemical reactions involved and the conditions.

5.2.5 Corrosion of Surfaces

Unlike other fouling mechanisms, in corrosion fouling the heat transfer surface itself degenerates to form a layer of lower thermal conductivity than the original metal. The resistance of many metals and alloys to corrosion is due to the presence of a thin layer of oxide on the surface that restricts the flow of electrons and ions usually necessary for corrosion to occur. A protective oxide layer may be regarded as controlled but desirable corrosion. At the same time it also represents a thermal resistance. In general, the thickness of the protective layer is such that the heat flow is not greatly impaired. If, however, conditions

are such that the corrosion of the surface is extensive, then the oxide layers (and probably hydroxide layers in aqueous systems) represent a fouling problem. It is also possible that corrosion is facilitated by the removal of protective oxide layers by aggressive chemical agents, e.g., acid attack. In combustion systems, inorganic salts deposited on heat transfer surfaces may be subject to such high temperatures that they become molten. The liquid condition may provide pathways for electron transfer that accelerates corrosion beneath the deposit. Corrosion fouling is very much dependent upon the material of construction from which the heat exchanger is fabricated. The problem of corrosion fouling can be eliminated by the correct choice of construction material, but in general, corrosion resistant alloys are expensive. Circumstances may be such that the high costs involved cannot be entertained. Other techniques must then be employed to restrict the incidence of corrosion.

5.2.6 Freezing Fouling

Freezing fouling as Shah et al. ^[24] mentioned may occur where the temperature in the region of the heat transfer surface is reduced to below the freezing point of the fluid being processed. The deposition of wax from waxy hydrocarbons by cooling is often considered to represent freezing fouling, but it is probably better defined as crystallization fouling. A good example of freezing fouling is the production of chilled water. If the temperature of the heat exchanger surface on the water side is at or below 0°C, then it is likely that a layer of ice will form on the surface. The thickness of the ice deposit will be very dependent on the magnitude of the temperature distribution between the coolant on the one side of the exchanger and the water on the other. The elimination of freezing fouling may be achieved by the choice of coolant temperature, so that the surface in contact with the liquid from which heat is being extracted is slightly higher than the freezing point of the liquid.

5.2.7 Mixed Mechanisms of Fouling

Although six mechanisms of fouling have been briefly described, it is rare for practical heat exchanger fouling to be the result of a single mechanism. In most process streams where fouling occurs, two or probably more mechanisms are involved. It is possible that one mechanism may be dominant and, from a practical standpoint, the other mechanisms present can be ignored when remedial action is being considered. In cooling water systems, it is likely that, in addition to microorganisms, the circulating water will contain dissolved solids, suspended particulate matter and, perhaps, also aggressive chemicals. The accumulated deposit on the equipment surfaces may therefore contain microorganisms, particles, scale and

products of corrosion. In fouling associated with combustion, the fouling on heat exchangers may be due to particle deposition, chemical reactions and corrosion as described earlier. It will be clear from these two examples that the process of fouling may be extremely complex necessitating, as it does, a rather empirical approach to its understanding and investigation.

6. EXPERIMENTAL METHODS

6.1 Scott Alan Sinquefield et al. ^[20]

According to the inventor Scott Alan Sinquefield et al. ^[20] the main objective of experiment is to reduce fouling by means of anti-foulant additives, which are commonly used in liquid processes to reduce or prevent the buildup of solids, often referred to as scale, on a surface of an apparatus. The apparatus prohibit the direct usage of precipitation of dissolved species and by the deposition of suspended solids within the process fluids and other liquids that pass through these devices, which may cause the scaling on the apparatus. All that example of the buildup of scale in the pulp process industries which usually results in lost revenue due to more frequent shut downs of paper-making machinery for cleaning, as well as increased steam demand (resulting in increased operating costs) to offset a loss in heat transfer efficiency, thereby maintaining good heat transfer rates and resulting in possibly fewer washing shut downs Anti-foulant additives can be a good alternative. However, mill trials for anti-foulants are costly, requiring several months due to infrequent shut downs for washing when scale can be observed. In addition, results integrated over several months are difficult to interpret because of process fluctuations and variations in the time since last cleaning. The experiments presented in this paper invention is directed to a process and apparatus for evaluating the effectiveness of one or more anti foulant additives used in the fluid streams of industrial heat transfer applications. More particularly, the present invention is directed to an apparatus and a process comprised of two or more cells plumbed in parallel in which the effectiveness of an anti-foulant may be tested, Wherein at least one of the cells serves as a reference to one or more test cells. A schematic of the experimental set-up is presented in Fig. 16 which is an illustration of one embodiment of testing apparatus of the present invention. A fluid sample is passed through a particulate filter 17 and into a means by Which the main stream is split into two streams, although multiple streams may be possible in further embodiments. At this splitting means 18, cleaning water passed through a ball valve 10 may be used to introduce cleaning or flushing water with or without the presence of the main stream. Each divided stream then continues to a flow regulating valve 7 before entering a flow meter 5. The fluid stream of the test cell then enters a tee pipe 4 for the introduction of an anti-foulant, which is introduced to the divided stream by the pump 6. This combined stream then passes through an in-line static mixer 3 before entering an insulated conduit for fluid flow 2. A heated rod 1 is placed into the insulated conduit 2 and is embedded with thermos couples 14. To the heated rod 1 and thermocouples 14 are attached a watt meter 15

and a temperature controller 16. The combined stream passes through the conduit 2 and over the heated rod 1 to a tee joint at which the combined stream may through one or both of a ball valve 8 for flushing the cell or a ball valve 9 for continuing to a pump 19 for reintroduction into the process. The fluid stream of the reference cell, after passing through the flow regulating valve 7, passes through an optional in-line static mixer 3 before entering the insulated conduit for fluid flow 2. A heated rod 1 is placed into the insulated conduit 2 and is embedded with thermocouples 14. To the heated rod 1 and thermocouples 14 are attached a Watt meter 15 and a temperature controller 16. The reference stream passes through the conduit 2 and over the heated rod 1 to a tee joint at which the reference stream may pass through one or both of a ball valve 8 for flushing the cell or a ball valve 9 for continuing to a pump 19 for reintroduction into the process. Data from the Watt meters 15 and thermocouples 14 are recorded by a computer 11 and manipulated for on-line display of results.

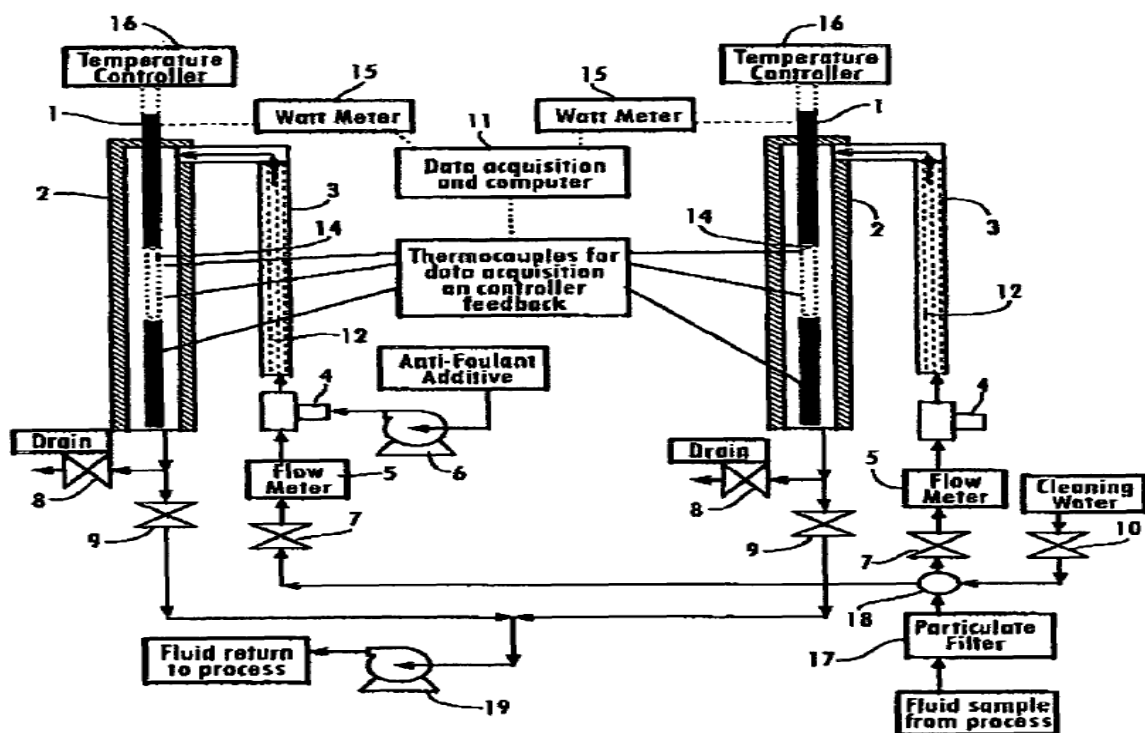


Figure 14 Fouling test apparatus and process for evaluation of anti-foulants ^[20]

The testing apparatus of that invention allows us for the evaluation of one or more anti-foulant additives used in heat transfer applications. In one embodiment, the fluid is any liquid

to which anti-foulant may be added during the course of an industrial fluid process. In another embodiment, the fluid to be tested ranges in temperature from about 200 to about 400° F. In a further embodiment, the fluid is any liquid to which an anti-foulant may be added during the course of a pulping process. In yet another embodiment, the fluid to be tested is the black liquor of a wood pulping digester. The apparatus is comprised of at least two cells. A cell, as used herein, provides for the series flow of a liquid through a combination of several described components. According to one method, the cell comprises a pipe assembly, comprising a heated probe placed within a conduit having both an entrance and an exit means for fluid flow while in other the conduit or pipe is insulated. In another embodiment, the heated probe is removable from the conduit such that probes of varying diameter, size or metal alloy may be used. In a further embodiment, the heated probe is a metal rod. In yet another embodiment, the heated probe is a square bar on an elongated plate heater. The cell may further comprise one or more means for measuring the surface temperature of the heated probe at one or more points along the heated probe. In one embodiment, the temperature measuring means is a thermocouple. In another embodiment, the temperature measuring means is a resistance temperature device (RTD). In a further embodiment, the temperature measuring means is a thermistor. The cell may additionally comprise a temperature controller for controlling the surface temperature of the heated probe, and one of the temperature measurements may serve as feedback to a temperature controller and additional measurements may be used as data. In one embodiment, the temperature controller maintains a constant temperature of the heated probe so that applied power may be measured. In another embodiment, the temperature controller applies constant power to the heated probe and the surface temperature of the heated probe is measured. The cell may also comprise a watt meter to measure the power applied to the heated probe. In one embodiment, the watt meter may be attached to the temperature controller. In another embodiment, the watt meter may be attached to the heated probe without a temperature controller. In a further embodiment, a watt meter and a temperature controller may be attached to the heated probe, with the watt meter further connected to a means for recording and/or manipulating the data. The cell may also comprise a means for measuring the fluid temperature leaving the conduit. In one embodiment, this temperature measuring means is a thermocouple. In another embodiment, this temperature measuring means is a resistance temperature device (RTD). In a further embodiment, this temperature measuring means is a thermistor. The cell may further comprise a means for measuring and controlling the flow rate of the fluid in the conduit. In one embodiment, the flow measuring and controlling means is a flow meter. The cell may

also comprise a mixer. In one embodiment, the mixer is a static mixer. In another embodiment, the mixer is a dynamic mixer, for example, an impeller driven by a motor. In an embodiment using a dynamic mixer, a drive shaft through the pipe Wall of the cell may be required. In a further embodiment, each cell comprises a static mixer. The cell may additionally comprise a means to inject and/or control the flow rate of an anti-foulant placed in series with, and up-stream of, an optional mixer. In one embodiment, the injection means is a metering pulp. In another embodiment, the injection means is a syringe pump. In some embodiments, the injection means may comprise a pipe tee. In further embodiments, the cell may comprise an injection means without comprising an optional mixer. The testing apparatus of the present invention additionally comprises an entrance and exit means used to pump the cells in parallel fluid flow. Data from the Watt meters 15 and thermocouples 14 are recorded by a computer 11 and manipulated for on-line display of results shows an example of test results of one embodiment of the apparatus of the present invention in which the surface temperature of each heated rod is held constant and at the same value for all cells.

6.2 M. Riihimaki et al. [27]

In that research M. Riihimaki et al. [27] a laboratory scale test apparatus is built for the experiments to study the fouling of heat transfer surfaces caused by mildly aggressive process fluids with a tendency to foul surfaces can be used in experiments. The fluids can contain solid particles or crystallizing salts. In the test section, a test piece of sheet metal (0.1x0.2m) can be replaced for analysis and that enables also the use of different surface materials and coatings in the experiments. The test area is a rectangle flow channel where constant heat flux is directed through the test piece. The controlled variables are flow rate, fluid temperature, heat flux, surface material and solution composition (conductivity or pH control). By the deposition of crystals or particles on the heat transfer surface the heat transfer decreases. This can be quantified from the evolution of the temperature measured from a test piece. This apparatus is used to obtain data for the kinetic fouling models, and to validate the results of CFD and to study different coatings. Fouling experiments are done with a slurry containing CaCO_3 particles using stainless steel AISI 316L 2B as the surface material. The bulk fluid temperature, heat flux, flow rate and solid content are varied in the experiments. The fouling is found to be induced by nucleating air at temperatures already below boiling temperatures. The nucleation of air was eliminated by increasing pressure in further experiments. The background electrolyte (MgCl_2) was found to have a strong effect on the dispersion properties and the fouling rate of particle slurry. Salt solution supersaturated with respect to

CaCO_3 was made of soluble salts CaCl_2 and NaHCO_3 . With this solution, fouling started after a delay period and so called induction time was obtained for non-coated and coated steels. Surface materials that have longer induction time than non-coated steel were regarded to mitigate fouling. The goal of this work is to increase new understanding of the fouling phenomena and to develop new design methods and coatings in order to decrease fouling. The goal is going to be reached by modifying the construction material of the heat exchangers, the surface composition of materials, and shape of flow channels. Further, a design framework for Heat Exchanger Thermal Analysis will be developed based on the determination of interaction forces (chemical, colloidal, hydrodynamic and turbulent) between surfaces and fluids and combining them into a computational fluid dynamics (CFD) model. A detailed CFD model for particulate fouling is developed using Eulerian two-phase model. The magnitude and the interaction regions of the forces acting on the particles in the vicinity of the fouling surface are evaluated. The most important forces affecting the particle transport to the near wall region and the adhesion of the particles on the wall surface are included into the CFD fouling model. The model will be used to estimate deposition formation in the heat transfer channels. The parameters for the models of different interaction forces (chemical, colloidal, hydrodynamic and turbulent) in the deposition formation are determined based on the materials used with the experimental studies. The validation of the fouling model is based on the experimental results obtained with the laboratory apparatus. The object is to develop a wall function model for particulate fouling. The fouling model will be further developed into a large scale CFD model that can be applied in modelling of fouling in an industrial heat exchanger. Molecular modelling was used to investigate the specific chemical interactions between surface materials used in heat exchangers and compounds causing deposition formation. Fouling mechanisms are defined at the molecular level by starting from a unit cell structure of materials, predicting the morphologies of the materials and then predicting an effect of the process fluid on selected surfaces. Typically the most important component of process fluid is water. Therefore, the dissociation behavior of water molecules on surfaces was studied, and then the study was continued with adsorption and reaction path calculations of fouling components. As a result, the formation mechanism with detailed intermediate steps of CaCO_3 deposition was received. The fouling happens via hydrogen carbonate intermediates, but the final deposition structure was found to vary between surfaces.

6.3 Richard C et al. ^[22]

In this patent Richard C et al. ^[22] present invention relates to the cracking of hydrocarbons that contain relatively non-volatile hydrocarbons and other contaminants to reducing fouling. Steam cracking, also referred to as pyrolysis, and has long been used to crack various hydrocarbon feedstocks into olefins, preferably light olefins such as ethylene, propylene, and butanes. Conventional steam cracking utilizes a pyrolysis furnace which has two main sections: a convection section and a radiant section. The hydrocarbon feedstock typically enters the convection section of the furnace as a liquid (except for light feedstocks which enter as a vapor) Wherein it is typically heated and vaporized by indirect contact with hot flue gas from the radiant section and by direct contact with steam. The heating of the hydrocarbon feedstock containing residue can take any form known by those of ordinary skill in the art. However, as seen in figure: 17, it is preferred that the heating comprises indirect contact of the hydrocarbon feedstock 10 in the upper (preferably farthest from the radiant section) convection section tube bank of heat exchange tubes 12 of the furnace 14 with hot flue gases from the radiant section 63 of the furnace. The heated hydrocarbon feedstock typically has a temperature between about 150 and about 260°C such as between about 160 to about 230°C. for example, between about 170 to about 220°C. The heated hydrocarbon feedstock is mixed with primary dilution steam and optionally, a fluid that can be a hydrocarbon (preferably liquid but optionally vapor), water, steam, or a mixture thereof. The preferred fluid is water. A source of the fluid can be low-pressure boiler feed water. The temperature of the fluid can be below or equal to, or above the temperature of the heated feedstock. The mixing of the heated hydrocarbon feedstock and the fluid can occur inside or outside the pyrolysis furnace 14, but preferably it occurs outside the furnace. The mixing can be accomplished using any mixing device known within the art for example, it is possible to use a first sparger 16 controlled by valve 17 of a double sparger assembly 18 for the mixing. The first sparger 16 can avoid or reduce hammering, caused by sudden vaporization of the fluid, upon introduction of the fluid into the heated hydrocarbon feedstock. In a preferred embodiment, the present invention uses steam streams in various parts of the process. The primary dilution steam stream 20 controlled by valve 21 can be mixed with the heated hydrocarbon feedstock as detailed below. In another embodiment, a secondary dilution steam stream 22 can be heated in the convection section and mixed with the heated mixture steam before the flash. The source of the secondary dilution steam may be primary dilution steam that has been superheated, optionally, in a convection section of the pyrolysis furnace. Either or both of the

primary and secondary dilution steam streams may comprise sour or process steam. Superheating the sour or process dilution steam minimizes the risk of corrosion, which could result from condensation of sour or process steam. In one embodiment of the present invention, in addition to the fluid mixed with the heated feedstock, the primary dilution steam 20 is also mixed with the feedstock. The primary dilution steam stream can be preferably injected into a second sparger 24. It is preferred that the primary dilution steam stream is injected into the hydrocarbon fluid mixture before the resulting stream mixture optionally enters the convection section at 26 for additional heating by flue gas, generally within the same tube bank as would have been used for heating the hydrocarbon feedstock. The primary dilution steam can have a temperature greater, lower or about the same as hydrocarbon feedstock fluid mixture but preferably the temperature is about the same as the mixture, yet serves to partially vaporize the feedstock fluid mixture. The primary dilution steam may be superheated before being injected into the second sparger 24. The thus-heated mixture stream leaves the convection section as a mixture stream 30 optionally to be further mixed with an additional steam stream.

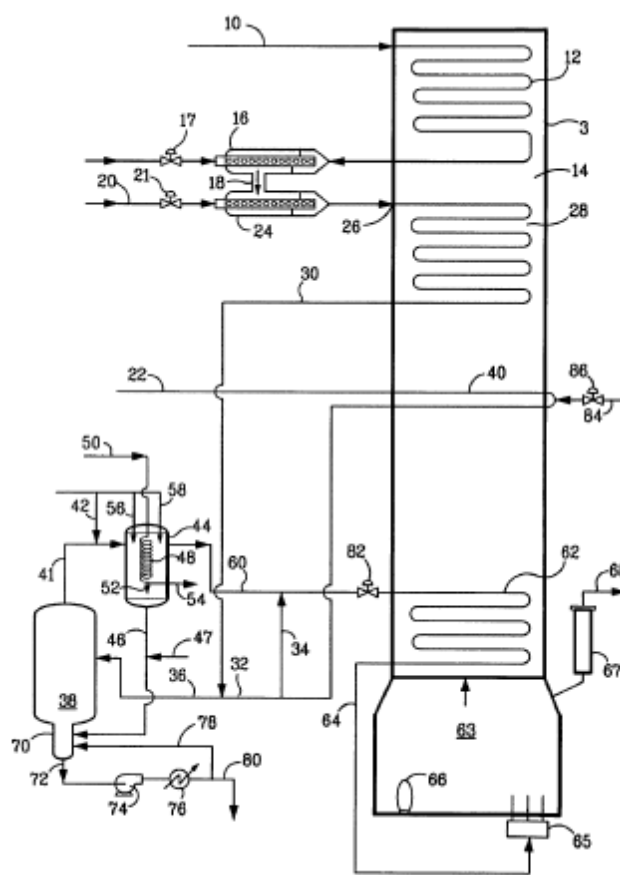


Figure 15 Apparatus for cracking a hydrocarbon feedstock containing residue. [22]

The vaporized feedstock and steam mixture is then introduced into the radiant section where the cracking takes place. The resulting products including olefins leave the pyrolysis furnace for further downstream processing, which include quenching. Conventional steam cracking systems have been effective for cracking high-quality feedstock which contains a large fraction of light volatile hydrocarbons, such as gas oil and naphtha. However, steam cracking economics sometimes favor cracking lower cost heavy feedstocks such as crude oil and atmospheric residue. Crude oil and atmospheric residue often contain high molecular weight, non-volatile components with boiling points in excess of 5900°C otherwise known as residues. The non-volatile components of these feedstocks lay down as coke in the convection section of conventional pyrolysis furnaces. Only very low levels of non-volatile components can be tolerated in the convection section downstream of the point where the lighter components have fully vaporized. Additionally, during transport some naphtha is contaminated with heavy crude oil containing non-volatile components. Conventional pyrolysis furnaces do not have the flexibility to process residues, crudes, or many residue or crude contaminated gas oils or naphtha which is contaminated with non-volatile components.

To address coking problems, which is incorporated herein by reference, discloses the use of an external vaporization drum for the crude oil feed and discloses the use of a first flash to remove naphtha as vapor and a second flash to remove vapors with a boiling point between 230°C and 5900°C. The vapors are cracked in the pyrolysis furnace into olefins and the separated liquids from the two flash tanks are removed, stripped with steam, and used as fuel, which is incorporated herein by reference, discloses a process to minimize coke deposition. It describes preheating of heavy feedstock inside or outside a pyrolysis furnace to vaporize about 50% of the heavy feedstock with superheated steam and the removal of the residual, separated liquid. The vaporized hydrocarbons, which contain mostly light volatile hydrocarbons, are cracked. Periodic regeneration above pyrolysis temperature is effected with air and steam.

6.4 Markus Riihimaki et al. ^[21]

The main objective of this work is to increase new understanding of the fouling phenomena and to develop new design methods and coatings in order to decrease fouling. The goal is going to be reached by modifying the construction material of the heat exchangers by changing the coating materials, the surface composition of materials, and shape of flow channels. Further, a design framework for Heat Exchanger Thermal Analysis will be developed based on the determination of interaction forces which are chemical, colloidal, hydrodynamic and turbulent and affect between surfaces and fluids and combining them into a computational fluid dynamics (CFD) model. According to author Markus Riihimaki et al. ^[21] a laboratory scale test apparatus is built for the experiments to study the fouling of heat transfer surfaces. Mildly aggressive process fluids with a tendency to foul surfaces can be used in experiments. The fluids here used in research is water which can contain solid particles or crystallizing salts. In the test section, a test piece of sheet metal (0.1x0.2m) can be replaced for analysis and that enables also the use of different surface materials and coatings in the experiments. The test area is a rectangle flow channel where constant heat flux is directed through the test piece. The controlled variables are flow rate, fluid temperature, heat flux, surface material and solution composition (conductivity or pH control). By the deposition of crystals or particles on the heat transfer surface the heat transfer decreases. This can be quantified from the evolution of the temperature measured from a test piece. This apparatus is used to obtain data for the kinetic fouling models, and to validate the results of CFD and to study different coatings.

6.5 Quan Zhen hua et al. [25]

In this research the author Quan Zhen hua et al. [25] created a new model of heat mass transfer to predict the fouling process of calcium carbonate on heat transfer surface which lead to the crystallization fouling and particle fouling on the heat transfer surface by the suspension particles of calcium carbonate. The experimental results of the fouling process, the deposition and removal rates of the mixing fouling were expressed with the coupling effect of temperature. That gives the idea of the fouling resistance varying with time which helps to describe the fouling process more accurately. By this research we can calculate for crystallization fouling and particulate fouling, the deposition and removal rates easily. And with this approach we are able to achieve good prediction of fouling process, and less than deviation of the experimental data. The new model is credible to predict the fouling process more precisely. According to Quan Zhen hua et al. [25] an on-line monitoring apparatus of fouling resistance was developed, in which fouling resistance can be measured on-line for different heat transfer surfaces. Figure 1 is a schematic diagram of the experimental set-up, which consists of a heat transfer test section, a hot water circulating loop, a cooling water circulating loop, a refrigerant water circulating loop, a set of measuring and controlling devices, and a microscopic-imaging system.

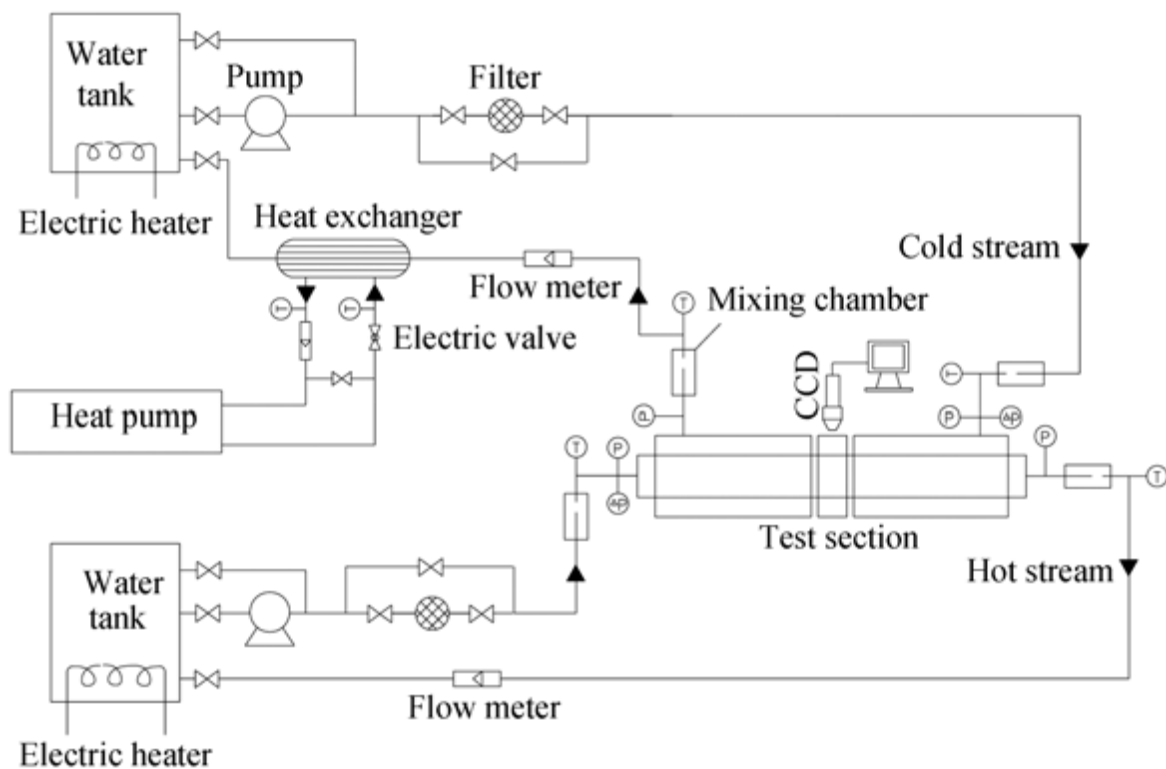


Figure 16 A schematic on-line monitoring apparatus of fouling resistance diagram

The set up consist test section which composed of two concentric tubes: the inner one is a copper tube, whereas the cooling water (test liquid) moves in the annulus gap between the two tubes in the opposite direction of the hot water like a counter-flow heat exchanger. Loops are created of cold and hot water and circulate through water tank, pump, flow meter, filter, valve, and are connected by sanitary stainless-steel pipes. The cooling water than moves to a shell-and tube heat exchanger for emitting heat and then returns to the water tank with the help of two electric heater of 15kW and 13kW. A self-regulates electric valve for flow rate, a controlled silicon is used to regulate power, a microscopic-imaging system was developed to observe scale crystals on the heat transfer surface online. Heat transfer performance was tested using smooth tube and with pure water as working fluid to monitor the fouling process of heat transfer surface. The main relation to determine the rate of deposition of CaCO₃, which was proposed by the ionic diffusion model mentioned by Quan Zhen hua et al.^[25]

$$m_c = \frac{kd[Ca^{2+}]}{2a} (-b \pm \sqrt{b^2 - 4ac})$$

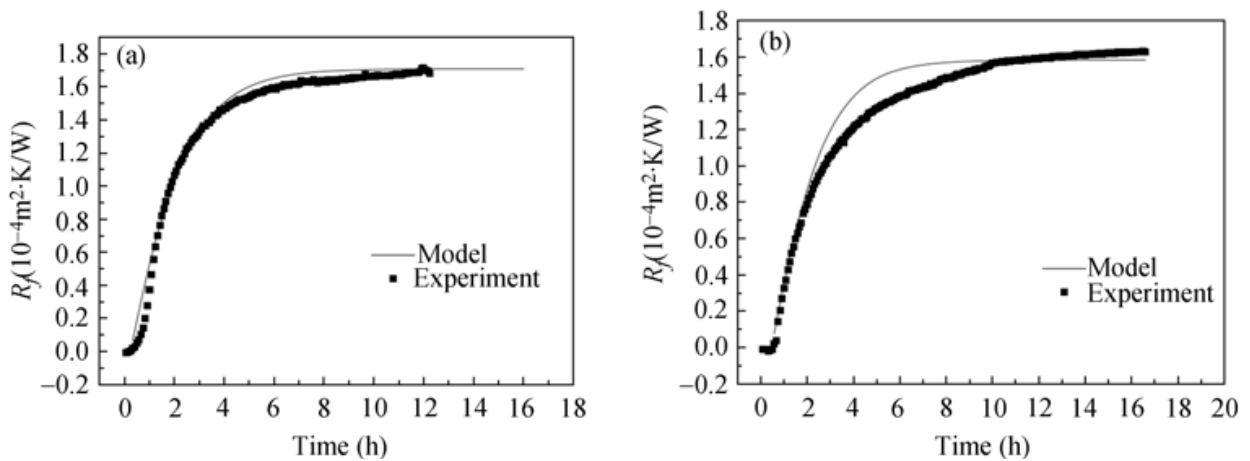


Figure 17 Comparisons of predictive results of present model and experimental data

(a) $C=500$ mg/L, $TA=500$ mg/L, $t_{h1}=70^\circ\text{C}$, $t_{c1}=22.2^\circ\text{C}$, $\text{pH}=7.95$, $V=1.2$ m/s; (b) $C=300$ mg/L, $TA=300$ mg/L, $t_{h1}=70^\circ\text{C}$, $t_{c1}=44.3^\circ\text{C}$, $\text{pH}=7.91$, $V=1.2$ m/s.^[25]

Above graph shows the comparisons of the model with experimental data. The results show that the present model could give a good prediction of fouling process, and the deviation is less than 15% of the experimental data in most cases.

6.6 S. D. Changani et al. [17]

In this research author S. D. Changani et al. [17] mention the problem of fouling from fluids of food which is very severe for apparatus and lead to the need for quick and effective cleaning processes. This type of fouling process happens as a result of very complex processes that occur at the time of heating of that fluid by the deposition of protein and minerals deposited on the surface. This research explained all the aspect of the chemical engineering factors that cause to deposition. The paper includes the data of fouling associated with milk process industries which have been reported for more than half a century. The research specifically focus on plant cleaning with the motive that the amount of fouling could be reduced by maintaining the parameters of milk at 75°C for 10 min. By keeping suggestion of fouling that it was happened due to denatured protein, solubility of milk salts and temperature change. S. D. Changani et al. ^[17] create a modeled of fouling is used for the calculation of data for the thermal behavior of β -lactoglobulin, which coupled with models for temperatures and flows of the process plant. Where rate of cleaning is always dependable to the deposit layer and with effect of which chemical treatment used for that specific process. Clearly, denaturation of whey proteins, especially β -lactoglobulin, during preheating reduces the amount of protein deposit later in the process. In practice, the selection of preheating temperatures is a matter of compromise between reducing downstream fouling without causing deposition in the preheating section. Many significant physicochemical factors are involved in dairy fouling. On heating, protein denaturation and aggregation reactions as well as the insolubilization of calcium phosphate and change in solution pH occur. Each reaction is important, and their effect appears interrelated.

Table 1 Composition of Cow's Milk

Component	% w/w
Water	87.0
Lactose	5.0
Lipids	4.0
Proteins:	
Caseins	2.5
β -Lactoglobulin	0.3

α -Lactalbumin	0.07
Other proteins	0.19
Minerals:	
Calcium	0.13
Sodium	0.05
Potassium	0.15
Phosphate	0.21
Chloride	0.10
Others	0.30

At the initial stage the processes is the governing means for that induction period and due to that there is possibility to extend it. The amount of fouling that make up the induction stage are thus important to demonstrate that fouling effect which begins at contact points between the plate of heat exchanger.

Table 2 Protein Deposits Analysis

<i>Composition (%)</i>	<i>Pasteurizer</i>	<i>Sterilizer A</i>	<i>Sterilizer B</i>
β -Lactoglobulin	50	62	—
	—	9	—
	18	—	27
β -Casein	—	—	50
	—	9	—
Immunoglobulins	23	9	—
Other	9	11	23

According to S. D. Changani et al. ^[17] number of techniques can be characterize that surfaces, including X-ray photoelectron spectroscopy, auger spectroscopy, secondary ion mass spectrometry, ion scattering spectroscopy, and Rutherford backscattering but in spite of this it is always difficult to obtain a full information of the fouling process with the help of only single technique that means there is possibility to use the combination of different techniques. In this paper author studied β -lactoglobulin adsorption onto chromium covered glass slides and found that, above the denaturation temperature, conformational changes of the protein

must take place before surface aggregation begins by maintaining lag phases of 500s and 1200s were found at 78°C and 76°C, respectively. The nature of the surface is unimportant at the time of adsorption of first fouling layer when a surface is covered and at that time only metal deposit surface interaction are considerable as coating of the heating surface affected the strength of adhesion but not the amount of deposit with effect of its interfacial energy is the main factor affecting adhesive strength.

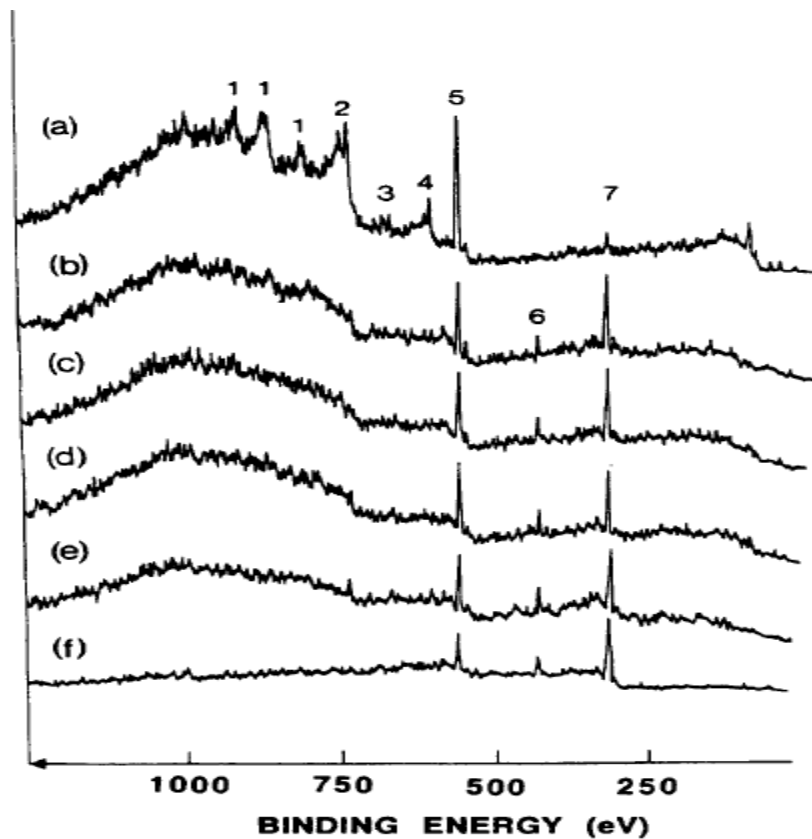


Figure 18 X-ray photoelectron spectra [17]

While on other side final deposit contains calcium phosphate concentrated at the deposit-metal interface. But there is still conflict that in-between minerals and proteins which one is adsorbed first and somehow it was found, by using X-ray photoelectron spectroscopy on different test fluids, that proteins were the main species to adsorb first but, though it was not the one. Whey protein concentrate (WPC) is dependent on the presence of calcium and magnesium ions which promote thermal denaturation and aggregation. That increase and a decrease in calcium concentration compared with that of normal milk increased fouling, with effect of amount of casein. According to Figure of the X-ray photoelectron spectra, which, was obtained by the adsorption of the deposit WPC at 73°C of fluid inlet temperature and the contact times of 4 and 150s, together with the spectrum of a clean un-fouled stainless-steel

surface? Protein was followed mainly through carbon and nitrogen peaks of binding energy appropriate to the peptide bond. Inserts 1 and 2 correspond to the carbon is spectrum for unfouled and fouled surfaces.

7. FOULING MODELS

Overall fouling model many fouling models are based on the approach of Shah et al. ^[24] who defined the net rate of the formation of deposits because of two competing processes, i.e. the formation and removal of deposits. Irrespective of different type of fouling process, the principal characteristic feature of fouling is the same and depend on the net mass fouling rate means the rate of change of deposition of mass on the heat transfer surface is proportional to difference between the foulant deposit rate m_d and the foulant re-entrainment rate m_r .

$$\frac{dm}{dt} = m_d - m_r \quad (30)$$

where dm/dt is the overall mass deposition rate and m_d and m_r mass deposition rate with rate of deposition removal. The formation of the deposits may involve the following sub-processes: processes in the bulk fluid, transport to the heat transfer surface, and attachment of the deposits to the surface. The removal may involve dissolution, re-entrainment, or spalling of the material from the surface. The general fouling models, need case-specific reformulation, in which all of the relevant phenomena occurring in the studied case, and information of physical properties and kinetic data, are included. Before combining the sub-processes described in the previous section into an overall fouling model, it is important to evaluate the relative importance of each sub-process to determine if the mass deposition rate is limited by one of the sub-processes. If one sub-process limits the fouling process, it is said to control the fouling. Many researchers have found that crystallization fouling is controlled by surface integration. In contrast, J.G Knudsen et al. ^[26] found that mass transfer controls the crystallization fouling of tap water. Some researchers have proposed that mass transfer controls fouling at low flow velocities, and that the control shifts to surface integration as the flow velocity increases by Rima Harcheon et al[2]. Overall, it is clear that both the operating conditions and the process fluid affect the controlling mechanism. The controlling step in crystallization fouling can be found by plotting the mass deposition rates at the constant surface temperature as a function of flow velocity. When the mass transfer rate is low compared to the rate of surface integration, and the mass transfer controls fouling process, increasing the velocity increases the mass deposition rate. On the other hand, when the mass

transfer rate is much higher than the rate of surface integration the mass deposition rate remains constant or even decreases as the flow velocity increases. The decreasing mass deposition rate with an increasing flow velocity, may be attributed to the increased removal at higher flow velocities, or to the decreasing residence time of the fluid at the wall, which reduces the probability of the attachment to the surface Thanhtrung Dang et al. [1]. It is proposed in the literature J.W. Sutor et al. [3] that the mass transfer controls fouling at low flow velocities, and at some flow velocity, the maximum in the fouling rate is achieved. The fouling rate begins to decrease after the maximum point as the flow velocity is increased. The maximum fouling rate is higher the higher the wall temperature is, because the attachment of the foulants to the surface at a certain flow velocity is more probable at higher wall temperatures. The maximum point of the fouling rate occurs at the higher flow velocity the higher the wall temperature is, because the higher the fouling rate is, the shorter residence time is required to overcome the effect of the wall temperature on the fouling rate.

7.1 Surface integration controlled fouling model

If surface integration controls crystallization fouling, the mass transfer term can be neglected in the model. In the surface integration controlled fouling, the interfacial concentration (C_i) is assumed to correspond to the bulk concentration (C_b) because mass transfer from bulk fluid to the surface is assumed to be infinite. Since modeling of these phenomena in detail would be complicated, the integration of the ions to the crystal lattice is usually described by a temperature dependent chemical reaction given by Bott et al. [23] which is driven by the nth order of the concentration difference between the interfacial (C_i) and the saturation (C_{sat}) concentrations as follows

$$m_d = k_r(C_i - C_{sat})^n \quad (31)$$

where k_r is the rate coefficient for the surface integration, which is often described by the Arrhenius type rate equation Bott et al. [23]

$$k_r = k_0 e^{\frac{-E_a}{RT_i}} \quad (32)$$

where k_0 is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, and T_i is the interfacial temperature. Therefore, the following model for the surface integration controlled mass deposition rate is obtained

$$m_d = k_r(C_b - C_{sat})^2 = k_0 e^{\frac{-E_a}{RT_i}} (C_b - C_{sat})^2 \quad (33)$$

Where m_d is the total deposition rate of calcium carbonate particulate, $\text{kg}/(\text{m}^2\cdot\text{s})$

7.2 Factors that affect the incidence of fouling

A number of system variables affect the incidence of fouling on heat exchange surfaces, but three generally carry more importance than all others including: fluid temperature and that associated with the temperature distribution, stream velocities and as would be expected the concentration of all foulant or foulant precursors that are contained in the fluid streams. Variables of less general importance, but which may assume significance in certain examples, include: pH, material of construction and associated surface condition. Attention to the magnitude of these variables, associated with all mechanisms of fouling, can go a long way to mitigating particular fouling problems, although it has to be said that certain problems may not respond as well as others.

Guidelines associated with temperature that is useful for the initial design and subsequent operation of heat exchangers suggest:

Low temperatures will:

- Reduce the effects of chemical reaction and corrosion since rates of reaction are generally temperature sensitive, high temperatures favor accelerated reactions.
- Reduce the activity of micro and macro organisms.
- Reduce the opportunity for supersaturation conditions to occur for inverse solubility salts.
- High temperatures will reduce the incidence of biofouling where the temperature is for optimum growth.
- Avoid conditions that could lead to freezing fouling;
- Reduce the opportunity of supersaturation conditions to occur with dissolved salts with normal solubility.

In addition to temperature effects that influence the fouling process, temperature may also be a factor in the long term retention of the deposit on the surface. Over a period of time it is more than likely that a particular deposit will age. The aging process may be influenced by temperature. The effects could be beneficial or detrimental to the continued operation of the heat exchanger. It is possible that, due to internal chemical reactions, the deposit becomes more tenacious and difficult to remove. For other encrustations, the effect of changed

temperature distribution as the deposit grows in thickness, planes of weakness and inconsistencies in the deposit lead to fracture and spalling. The temperature effects are, in general, associated with the temperature distribution across the heat exchanger. For a given temperature difference between the hot and cold streams within the equipment, the growth of deposit occur usually on both sides which will affect in the phenomena of transfer of that total force which help to distribute that temperature, so that the metal of wall separating fluids will experience a changing temperature. The deposits themselves will also be affected in terms of their respective temperatures. For large temperature differences and thick deposits, there is likely to be a considerable temperature difference across the deposit with implications for the quality of the deposit. For instance, the chemical reactions involved when the deposit is relatively thin, may be quite different from those associated with thick deposits. Such conditions, for instance, on the flue gas side of coal combustion equipment, may give rise to stratified deposits and chemical transformations as time passes. Although the temperature of the streams within a heat exchanger will be specified, there is some flexibility open to the designer to modify the temperature distribution. By investigating changes in velocity that affect the thermal resistance in the respective streams, it is possible to change, beneficially, the various interface temperatures. The changes in velocity have implications in their own right. Some comments on the effects of velocity have already been made, namely, the effects on temperature distribution and pressure drop by Rema et al. [2] The latter is closely linked to fluid shear: increasing velocity increases fluid shear at the interface between a solid surface and the fluid flowing across it. High shear forces may result in foulant removal, that tends to maintain a static fouled condition, i.e., near the asymptotic or equilibrium fouling condition. Under these circumstances the velocity controls the deposit thickness. Increasing velocity may appear attractive for minimizing the effects of deposits, but for a particular deposit, the necessary velocity may be unacceptably high leading to high pumping costs and possibly problems of erosion. It also has to be remembered that increasing velocity will increase turbulence, so that where the fouling process is mass transfer controlled, deposition is facilitated. In biological fouling, for instance, higher velocities, although leading to enhanced removal opportunities, will also facilitate nutrient transfer to the living matter colonizing the particular surface.

The choice of velocity, therefore, is very much a compromise depending on the particular system under consideration. As a rough guide velocities of the order of 2m/s for liquid flows in tubes will have some controlling effect without excessive pumping costs. On the shell side

mean fluid velocities for liquids across the tube bank of around 1 m/s may be regarded as a suitable guide. In gas systems much higher velocities are possible but it is difficult to provide reliable guidelines. In general, the higher the concentration of foulant or deposit precursor, the greater the fouling of surfaces is likely to be, since the mass transfer driving force, i.e., the concentration gradient towards the target surface is enhanced. It is usually not in the gift of the heat exchanger designer or operator, to influence the concentration of foulant precursors in the stream handled by the exchanger. Often the potential fouling problem is not recognized at the design stage; it may only be discovered during subsequent operation as trace constituents of the flow stream. It may be possible to limit the deposit precursor, for example particulate matter or unreacted species, by improved control of processes upstream from the exchanger. In certain exceptional circumstances it may be necessary to reduce, or remove altogether, the components responsible for the fouling process.

7.3 Fouling Resistance Concept

The usual method of allowing for the incidence of fouling in heat exchanger design is to employ resistances that account for the fouling on both sides of the exchanger. Sometimes these fouling reactions are referred to as "fouling factors". The latter description is not altogether satisfactory since the term "factor" is usually applied to a multiplier.

The thermal resistance due to fouling is additive as illustrated in the following equation which sums all the thermal resistance between the two fluids. If the Overall Heat Transfer Coefficient is U_1 then:

$$\frac{1}{U_1} = R_1 + R_2 + R_w + \frac{1}{\alpha_1} + \frac{D_1}{D_2} \cdot \frac{1}{\alpha_2} \quad (34)$$

where R_1 and R_2 are the fouling resistances associated with fluid streams 1 and 2, respectively. R_w represents the thermal resistance of the metal wall separating the two fluids. In general, this resistance is quite small and often it can be neglected altogether due to the high thermal conductivity of metals, α_1 and α_2 are the heat transfer coefficients at the metal wall for fluids 1 and 2, respectively, and D_1 and D_2 are the inner and outer diameter of the tube through which fluid 1 is passing. Fluid 2 passes over the outside of the tube. It will be seen that, in reality, the equation is not mathematically sound except for steady state conditions, i.e., when the deposit thickness on both sides of the exchanger remains constant. Under these conditions it is likely that the asymptotic fouling resistance has been attained.

The earlier discussion has shown that fouling development is transient so that the steady state condition does not apply. In order to help designers and others, tables of fouling resistances are published, e.g., the TEMA (Tubular Exchanger Manufacturers' Association) fouling resistances as mentioned by Shah et al. [24]. The data are classified according to the fluid and process and the figures are based on the experience of recognized experts in the field. Although the information is a useful guide, it has to be treated with caution in the light of the earlier discussion on the influence of temperature, velocity and foulant precursor concentration. In general, the tables do not specify any of the variables so that it becomes difficult to relate them to a particular set of conditions. It also has to be understood that the published fouling resistances are only applicable to shell and tube heat exchangers and may not be used in the design of plate heat exchangers for instance. Furthermore, it has to be remembered that by taking into account the anticipated fouling resistance, a clean (newly on stream) heat exchanger will over perform. To compensate, adjustments to the fluid flow rate(s) will be made that could encourage the fouling process so that the fouled condition prediction is self-fulfilling. The data on fouling resistances relating to the actual process streams and the conditions of velocity and temperature pertaining to the particular possible design should be used for assessment purposes. But generally these data are not to hand. The choice according to Bott et al. [23] becomes one of experience and judgement with guidance from published figures. In this connection, it has to be appreciated that the increased capital cost of a heat exchanger over and above the clean condition to allow for fouling, may very well depend upon the arbitrary choice of fouling resistance.

7.4 Mitigation of Fouling

To control the degree of fouling a wide range of online mitigation techniques used according to J.G Knudsen et al.[26] and they generally fall into two groups, namely, physical methods and by the use of chemical additives named chemical treatment method. Physical methods as name suggest use mechanical methods of removal. Some examples are given in the following table:

Table 3 Mechanical control techniques ^[24]

Techniques	Application
Circulation of Sponge Rubber Balls	In power industry
Brush and cage system	Heat exchangers(inside of pipe)
Backwashing	Valves, pump, piping and tank.
Air or gas injection	Heat exchanger(surface)
Soot blowing	Combustion systems
Acoustics	Removal of deposits.
Shot impingement	Cleaning mineral deposit
Use of inerts	Heat exchanger tubes

While on other hand chemical technique includes reduce of fouling layer by means of some chemical, additives, anti-foulant etc. besides there are several new design enhancement methods which can handle fouling. Following examples of the use of additives are given below in table:

Table 4 Chemical additives for different fouling conditions ^[24]

Fouling type	Additive Type	Additive Chemistry
Biofouling	Biocides, biodispersants, bio stats(to reduce fouling activity)	Chlorine, bromine, chlorine dioxide, ozone.
Crystallization	Dispersant, crystal modifier, chelating agent.	EDTA(ethylene diamine tetra-acetic acid) PH control by addition of acid HEDP(I-hydroxyethyl dine-I, I-bisphonic acid)
Particulate	Dispersant or coagulator for settling.	EDTA, various polymers.
Corrosion	Inhibitor or surface filming	Orthophosphates,

		Polyphosphates, Azoles
--	--	------------------------

Some additives have capability to adhere the particles on surface that it will remain away from the surface for longer time. According to Bott et al. ^[23] That means the concentration of the additive is small relative to normal condition, i.e., up to 100 mg/l but in many applications the concentration may be as low as 1 mg/l. To maintain cost effectiveness the concentration of additive must be kept as low as possible. Sometimes use of chemicals are necessary to protect the life of the heat exchanger by maximizing heat transfer ability of equipment.

8. Conclusions

The thesis conclude combined effect of fouling and there reducing technique. With the help of certain experiment of fouling apparatus processes this chapter shows clearly the diversity and complexity of topics related to fouling processes clearly. But due to space limitation, however, has prevented the authors from thoroughly covering many equally important aspects of fouling in heating transfer devices. According to fouling apparatus research of I paper which covered the usage of anti-foulant additives which are frequently effective in reducing buildup scale on surface, thereby maintaining good heat transfer rates and resulting in possibly less washing shut downs occur.

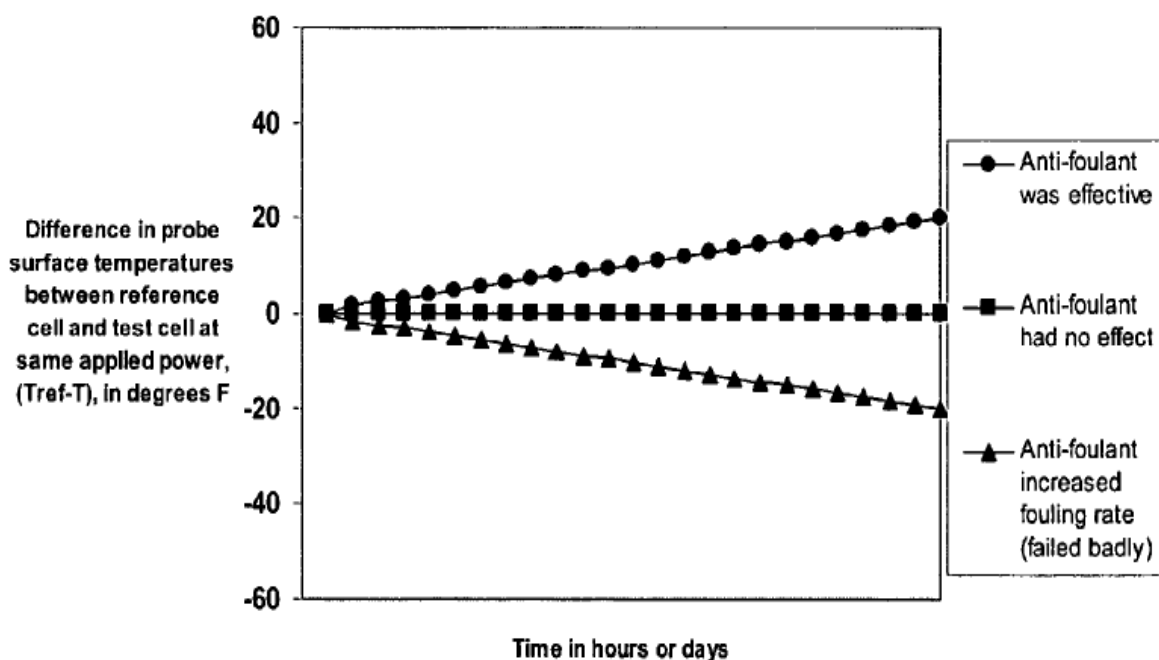


Figure 19 Graph showing the difference in surfaces temperatures between the probe of a reference cell and the probe of a test cell

With the result of it we found that if anti-foulant is effective, the reference rod will accumulate scale faster than the test cell rod, resulting in more power applied to the reference cell to maintain the same surface temperature and heat transfer rate thoroughly. If the anti-foulant has no or little effect, then the cells will require the same or approximately the same

power input at time progresses. Fig: 19 also show an example of the results of another method of the apparatus of the present invention. As scale accumulates on the rods it acts as an insulating layer and the surface temperature decreases with time. But this process cost large amount as compare to other techniques as the process require several months due to infrequent shutdowns for cleaning when scale start to appeared. In addition, results is time consuming as it took over several months and are difficult to interpret because of process fluctuations and variations in the time since last cleaning and to use the additive note preferable for food process apparatuses as it may affect the properties of food nutrients or may contaminate the quality of it. While on the other process mentioned in which is coating the heat exchanger surface method non-fouling properties are verified in industrial scale testing in the connection with an industrial process by using small heat exchanger unit parallel to the industrial process unit. Thus, the results by modelling, laboratory scale tests and industrial scale tests of the work can be utilized in order to choose suitable surface materials for industrial equipment which decreased the fouling and controlled fouling of heat exchangers which leads to economic savings for processes. As compare to prior one it help to reduced capital and maintenance costs, energy savings, and smaller heat transfer units. It is also preferable for crude oil industry but again for food process it may require to be check properly. Therefore it is economically feasible and environmental friendly as there is non-fouling equipment involved. But in some applications, this overdesign accelerates fouling because of the lower-than-design value of the fluid velocity in the exchanger. Next result covered the most important phenomena which is rare to consider generally. In this research they found, with the help of a heat mass transfer model, a research was developed to predict the fouling process of calcium carbonate on heat transfer surface. But by taking into account the coupling effect of temperature with the fouling layer. In addition, the deposition and removal rates of the compound fouling were calculated including crystallization fouling and particulate fouling. And the fouling parameters according to experimental results were applied to the model. The comparative results of the model shows less deviation which is almost less than 15% and with good prediction of the fouling process with experimental data showed that the present model. Thus the new model is credible to predict the fouling process. Both prevention and protection must be included in design consideration. Basic information on corrosion types, locations in heat exchangers, and control ideas are presented in the text. Some of the important considerations are the desired structural strength and fatigue characteristics based on the operating pressures, temperature, corrosiveness, and chemical reaction of fluids with material, proper selection of the materials and the method of bonding

of various components, and problems during operation such as transients, dynamic instability, erosion and freezing. The phenomena that control the fouling processes are complex in nature, and a comprehensive general theory cannot be defined. Most often, the influence of fouling is included through an overdesign. In some applications, this overdesign accelerates fouling because of the lower-than-design value of the fluid velocity in the exchanger. Fouling has a significant detrimental effect on heat transfer in liquids and on pressure drop which affect fluid pumping power in gases. In this chapter, various fouling mechanisms are discussed that have been identified and investigated particularly with the emphasis on fouling in single-phase liquid and gas sides and in compact heat exchangers. After providing details on the sequential events in fouling, modeling of a fouling process is presented. However, if fouling is a surface process, to modify the exchanger surface, it is necessary to determine which species are deposited first and design the surface to resist such deposition or to extend the induction period for as long as possible. The work described above suggests that it may be possible to use protein-resistant coating to prevent the first layer of adhesion. However, the processing temperatures are such, particularly in that calcium phosphate will still precipitate and adhere to the surface. In selecting surfaces, both fouling and cleaning must be considered; any fouling-resistant system must still be capable of being cleaned because of possible bacterial contamination or equipment breakdown, so the surface must be capable of resisting cleaning. Developments in the process plant will evolve as a result of advances in the understanding both of the chemistry of the milk system and of the way in which that chemistry is affected by the flows and temperature that occur in the process plant. Type A deposit appears to be formed by adhesion to the wall of proteins that have reacted in the bulk of the fluid either by unfolding or partial aggregation. Preheating can give aggregates that have fewer tendencies to adhere. However, the interaction between proteins and calcium phosphate in deposition is still unclear, as are the processes that control adhesion and the rate of adhesion. The controlling kinetic step in fouling is not known. There is a number of modified milk products that have not been well studied whose behavior may be significantly different from those discussed here. More work is needed in a number of areas as there are a number of processes, such as evaporation, that have not been thoroughly studied for which the mechanism of fouling is not known.

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List of Symbols

Heat duty/Heat Transfer Rate	$Q(W)$
Overall heat transfer coefficient	$U_o(W/m^2 \cdot K)$
Overall surface efficiency	η_o
Log Mean Temperature Difference	$\Delta T_{ln}(^{\circ}C)$
Mass deposition Rate	$m_c(kg/(m^2 \cdot s))$
Fouling Resistance	$R_f(m^2 \cdot K/W)$
Heat transfer Coefficient	$h(W/m^2 \cdot K)$
Mass Transfer Coefficient	$k_d(m/s)$
Universal gas Constant	$R(J/kg \cdot K)$
Activation energy	$E(J/kg \cdot mol)$
Thermal Conductivity	$\lambda (kW/m^{\circ}C)$
Deposit Thickness	$t_d(m)$
Surface area of Heat Transfer	$A(m^2)$
Pressure Drop	$\Delta P_t(bar)$
Pumping Power	$P(W)$
Specific Heat	$c(J/kg \cdot K)$

Heat Capacity	$C(\text{W/K})$
Temperatures of Hot side	$T_{h1}, T_{h2}(\text{°C})$
Temperature of Cold side	$T_{c1}, T_{c2}(\text{°C})$
Diameter of shell	$D_s(\text{m})$