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Fouling in Heat Exchangers

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1. Introduction

Fouling is generally defined as the deposition and accumulation of unwanted materials such as scale, algae, suspended solids and insoluble salts on the internal or external surfaces of processing equipment including boilers and heat exchangers (Fig 1). Heat exchangers are process equipment in which heat is continuously or semi-continuously transferred from a hot to a cold fluid directly or indirectly through a heat transfer surface that separates the two fluids. Heat exchangers consist primarily of bundles of pipes, tubes or plate coils.



Figure 1. Fouling of heat exchangers.

Fouling on process equipment surfaces can have a significant, negative impact on the operational efficiency of the unit. On most industries today, a major economic drain may be caused by fouling. The total fouling related costs for major industrialised nations is estimated to exceed US\$4.4 milliard annually. One estimate puts the losses due to fouling of heat exchangers in industrialised nations to be about 0.25% to 30% of their GDP [1, 2]. According to Pritchard and Thackery (Harwell Laboratories), about 15% of the maintenance costs of a process plant can be attributed to heat exchangers and boilers, and of this, half is probably caused by fouling. Costs associated with heat exchanger fouling include production losses due to efficiency deterioration and to loss of production during planned or unplanned shutdowns due to fouling, and maintenance costs resulting from the removal of fouling deposits with chemicals and/or mechanical antifouling devices or the replacement of corroded or plugged equipment. Typically, cleaning costs are in the range of \$40,000 to \$50,000 per heat exchanger per cleaning.

Fouling in heat exchangers is not a new problem. In fact, fouling has been recognised for a long time, and research on heat exchanger fouling was conducted as early as 1910 and the first practical application of this research was implemented in the 1920's. Technological progress in prevention, mitigation and removal techniques in industrial fouling was investigated in a study conducted at the Battelle Pacific Northwest Laboratories for the U.S. Department of Energy. Two hundred and thirty one patents relevant to fouling were analysed [3]. Furthermore, great technical advance in the design and manufacture of heat exchangers has in the meantime been achieved. Nonetheless, heat exchanger fouling remains today one of the major unresolved problems in Thermal Science, and prevention or mitigation of the fouling problem is still an ongoing process. Further research on the problem of fouling in heat exchangers and practical methods for predicting the fouling factor, making use in particular of modern digital techniques, are still called for. One significant and clear indication of the relevance and urgency of the problem may be seen in the current international patent activity on fouling (Table 1).

Country	No. of Patents	% of Patents
U.S.A.	147	63.6
Germany	22	9.5
Japan	21	9.1
Sweden	9	3.9
Switzerland	8	3.5
Other	24	10.4
Total	231	100.0

Table 1. International Patent Activity [4]

Major detrimental effects of fouling include loss of heat transfer as indicated by charge outlet temperature decrease and pressure drop increase. Other detrimental effects of fouling may also include blocked process pipes, under-deposit corrosion and pollution. Where the

heat flux is high, as in steam generators, fouling can lead to local hot spots resulting ultimately in mechanical failure of the heat transfer surface. Such effects lead in most cases to production losses and increased maintenance costs.

Loss of heat transfer and subsequent charge outlet temperature decrease is a result of the low thermal conductivity of the fouling layer or layers which is generally lower than the thermal conductivity of the fluids or conduction wall. As a result of this lower thermal conductivity, the overall thermal resistance to heat transfer is increased and the effectiveness and thermal efficiency of heat exchangers are reduced. A simple way to monitor a heat transfer system is to plot the outlet temperature versus time. In one unit at an oil refinery, in Homs, Syria, fouling led to a feed temperature decrease from 210°C to 170°C. In order to bring the feed to the required temperature, the heat duty of the furnace may have to be increased with additional fuel required and resulting increased fuel cost. Alternatively, the heat exchanger surface area may have to be increased with consequent additional installation and maintenance costs. The required excess surface area may vary between 10-50%, with an average around 35%, and the additional extra costs involved may add up to a staggering 2.5 to 3.0 times the initial purchase price of the heat exchangers.

With the onset of fouling and the consequent build up of fouling layer or layers, the cross sectional area of tubes or flow channels is reduced. In addition, increased surface roughness due to fouling will increase frictional resistance to flow. Such effects inevitably lead to an increase in the pressure drop across the heat exchanger, which is required to maintain the flow rate through the exchanger, and may even lead to flow blocks. Experience with pressure drop monitoring has shown, however, that it is not usually as sensitive an indicator of the early onset of fouling when compared to heat transfer data; thus pressure drop is not commonly used for crude preheat monitoring. In situations where significant swings in flow rates are experienced, flow correction can be applied to both pressure drop and to heat transfer calculations to normalise the data to a standard flow.

Different fouling deposit structures can lead to under-deposit corrosion of the substrate material such as localised fouling, deposit tubercles and sludge piles. The factors that are most likely to influence the probability of under-deposit corrosion include deposit composition and its porosity and permeability. Even minor components of the deposits can sometimes cause severe corrosion of the underlying metal such as the hot corrosion caused by vanadium in the deposits of fired boilers [5].

Fouling is responsible for the emission of many millions of tonnes of carbon dioxide as well as the use and disposal of hazardous cleaning chemicals. Data from oil refineries suggest that crude oil fouling accounts for about 10% of the total CO₂ emission of these plants. Wastes generated from the cleaning of heat exchangers may contain hazardous wastes such as lead and chromium, although some refineries which do not produce leaded gasoline and which use non-chrome corrosion inhibitors typically do not generate sludge that contains these constituents. Oily wastewater is also generated during heat exchanger cleaning.

The factors that govern fouling in heat exchangers are many and varied. Of such factors some may be related to the feed properties such as its chemical nature, density, viscosity, diffusivity, pour and cloud points, interfacial properties and colloidal stability factors. The chemical nature of the feed in particular can be an important factor affecting to a large degree the rate and extent of fouling. This includes the chemical composition of the feed and the stability of its components and their compatibility with one another and with heat exchanger surfaces as well as the presence in the feed of unsaturated and unstable compounds, inorganic salts and trace elements such as sulphur, nitrogen and oxygen. The feed storage conditions and its exposure to oxygen on storage in particular can in most cases also affect materially the rate and nature of fouling.

Other factors of equal importance to the feed properties may be related to operating conditions and equipment design, such as feed temperature, bulk fluid velocity or flow rate, heat exchanger geometry, nature of alloy used and wettability of surfaces where fouling occurs. The rate of fouling is feed temperature dependent with different rates of fouling between the feed inlet and outlet sides of the heat exchanger. In a shell and tube heat exchanger, the conventional segment baffle geometry is largely responsible for higher fouling rates. Uneven velocity profiles, back-flows and eddies generated on the shell side of a segmentally-baffled heat exchanger results in higher fouling and shorter run lengths between periodic cleaning and maintenance of tube bundles.

All these and other factors that may affect fouling need to be considered and taken into account in order to be able to prevent fouling if possible or to predict the rate of fouling or fouling factor prior to taking the necessary steps for fouling mitigation, control and removal.

2. Fouling mechanisms and stages

Fouling can be divided into a number of distinctively different mechanisms. Generally speaking, several of these fouling mechanisms occur at the same time and each requires a different prevention technique. Of these different mechanisms some represent different stages in the process of fouling. The chief fouling mechanisms or stages include:

1. Initiation or delay period. This is the clean surface period before dirt accumulation. The accumulation of relatively small amounts of deposit can even lead to improved heat transfer, relative to clean surface, and give an appearance of "negative" fouling rate and negative total fouling amount.
2. Particulate fouling and particle formation, aggregation and flocculation.
3. Mass transport and migration of foulants to the fouling sites.
4. Phase separation and deposition involving nucleation or initiation of fouling sites and attachment leading to deposit formation.
5. Growth, aging and hardening and the increase of deposits strength or auto-retardation, erosion and removal.

Detailed analysis of deposits from the heat exchanger may provide an excellent clue to fouling mechanisms. It can be used to identify and provide valuable information about such mechanisms. The deposits consist primarily of organic material that is predominantly asphaltenic in nature, with some inorganic deposits, mainly iron salts such as iron sulphide. The inorganic content of the deposits is relatively consistent in most cases at 22-26% [6].

Deposit analysis is performed by taking a sample and extracting any degraded hydrocarbon oil by using a solvent, such as methyl chloride, that is effective at removing hydrocarbon oils and low molecular weight polymers that may have been trapped in the deposit.

The remaining material from this extraction will consist of any organic polymers, coke, and inorganic components. The basic analysis of the non-extractable material involves ashing in which organic and volatile inorganic compounds are lost. By this means, volatile inorganics such as chlorides and sulphur compounds which are lost on ashing, may be determined. The detection of iron sulphide or other volatile inorganic materials determines the cause of inorganic fouling. These values can be compared throughout the exchanger train [6]. The non-volatile material or ash will include all oxidised metallic salt-type materials or corrosion products. The presence of iron in the ash may indicate corrosion in tankage in an upstream unit or in the exchanger train itself. This basic analysis indicates if the deposits are primarily organic or inorganic.

Special techniques and tools such as the use of optical microscopy and solubility in solvents may be used for the analysis of the non-extractable material. Infrared analysis can identify various functional groups present in the deposit which may include nitrogen, carbonyls, and unsaturated paraffinic or aromatic compounds which are polymerisation precursors, identified in feed stream characterisation [6]. The carbon and hydrogen content of the non-extractable deposit can be determined by elemental analysis. If the carbon to hydrogen ratio is very high, it may indicate that the majority of the organic portion of the deposit is coke. The coke may have been particles entrained in the stream or material which has been thermally dehydrogenated in the heat exchangers. The carbon to hydrogen ratio also indicates whether the deposit is more paraffinic or aromatic. This information helps identify the polymers formed [6].

In Table 2 analytical results are shown from deposits obtained from the four chain feed/effluent heat exchangers in which the hot product effluent is used for pre-heating the cold naphtha feedstock for a naphtha hydrotreater plant at the Homs Oil Refinery [7]. This plant is one of the most important units at the Homs Refinery, with an annual capacity of 480,000 tons/yr. It is used to remove impurities such as sulphur, nitrogen, oxygen, halides and trace metal impurities that may deactivate reforming catalysts. Furthermore, the quality of the naphtha fractions is also upgraded by reducing potential gum formation as a result of the conversion of olefins and diolefins into paraffins. The process utilises a catalyst (Hydrobon) in the presence of substantial amounts of hydrogen under high pressures (50 bars) and temperatures (320°C) (Fig. 2). A major fouling problem was encountered early on in the heat exchangers, indicated by an increased pressure drop, decreased flow rate and lower temperatures at the heat exchangers outlet.

Particulate fouling

Particulate fouling, which is the most common form of fouling, can be defined as the process in which particles in the process stream deposit onto heat exchanger surfaces. These particles include particles originally carried by the feed stream before entering the heat exchanger and particles formed in the heat exchanger itself as a result of various reactions, aggregation and flocculation. Particulate fouling increases with particle concentration, and typically particles greater than 1 ppm lead to significant fouling problems.

Heat exchanger	A	B1	B2	C	D
Loss at 105°C (wt %)	1.17	1.03	1.05	1.15	1.14
Loss at 550°C (wt %)	79.70	95.10	90.17	94.42	57.17
Loss at 840°C (wt %)	80.00	95.29	90.19	94.48	57.99
Ash (wt %)	20.00	4.71	9.81	5.52	42.01
Chloride (wt %)	170	435	0	664	508
Sulphur (wt %)	17.00	13.50	13.80	10.20	13.00
Ammonium (ppm)	42	1184	43	134	4969
Iron (wt % of ash)	19.30	2.83	1.70	2.80	15.58
Sodium (ppm of ash)	1473	1047	825	3301	914
Calcium (ppm of ash)	459	179	78	377	1431
Magnesium(ppm of ash)	90	41	19	102	1341
Chromium (ppm of ash)	231	107	1166	196	1096
Copper (ppm of ash)	511	319	74	443	126
Nickel (ppm of ash)	378	129	63	90	52

Table 2. Analysis of deposits on heat exchanger surfaces [7].

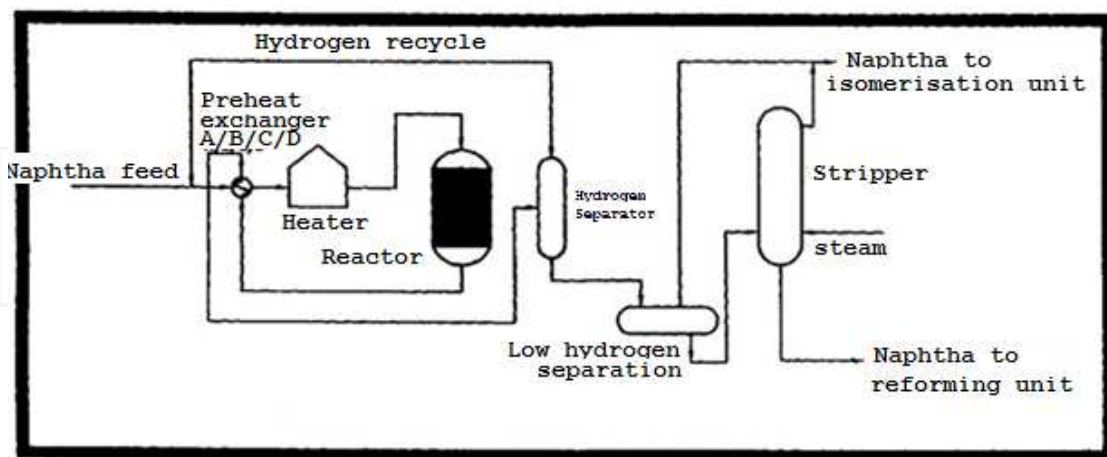


Figure 2. Naphtha hydrotreating unit

2.1. Particles in the feed stream

Particles in the fluid feed stream are solid particles which are entrained or contained in the feed stream before entering the heat exchanger and which can settle out upon the heat

exchanger surfaces. These solid particles are for the most part insoluble inorganic particles such as corrosion products (iron sulphide and rust), catalyst particles or fines, dirt, silt and sand particles, and other inorganic salts such as sodium chloride, calcium chloride and magnesium chloride. The feed streams may also contain some organic particles that may have been formed during their storage or transport.

Many streams including cooling water and other product streams from different units or plants may contain solid particles. In particular, streams from such oil refinery units as vacuum units, visbreakers, and cokers may have more particulates and metals than straight-run products due to the heavier nature of the feeds processed. Streams can also be purchased from other refiners. Due to the increased transit time and exposure to oxygen before being fed to the unit these feeds may have higher particulate levels as a result of polymerisation reactions and corrosion [6].

Particles in the fluid stream, regardless of whether they are organic or inorganic in nature, fall in general into two classes: basic sediment and filterable solids.

Typically, particles in the fluid stream greater than 1 ptb (pounds per thousand barrels) lead to significant fouling problems in the unit. Their effect on fouling can be avoided however if these particles are removed by solid-liquid filtration, sedimentation, centrifugation or by any of various fluid cleaning devices. The only particles that need to be considered in this regard are those that are not filterable or those particles that are left to proceed to the heat exchanger.

The amount of filterable solids in the stream, reported in ptb or wt% (weight percent), may be determined by filtration of the unit feed. Filterable solids analysis can evaluate a stream deposition potential by indicating the type of materials that could contribute to fouling if allowed to pass through to the heat exchanger.

Table 3 shows the analysis of filterable solids in the naphtha feed stream to the heat exchangers of the hydrotreater unit at the Homs oil refinery. The feedstock for this unit is a blend of light and heavy straight-run naphtha fractions from four different topping units. The resulting blend is left in a blending tank for a sufficient period of time to allow for equilibrium conditions to be established [8]. To evaluate the quantity of particulate solids which are entrained with the naphtha stream before entering the heat exchangers, a number of samples of the naphtha feed were filtered and the amount of entrained particles determined. Two samples of the filterable solids were taken, one sample was taken from the feed entering a macrofilter on the unit boundary and the other from a second macrofilter on the feed pump suction. The nature of the materials entrained was then determined by ashing and analysing these two samples (Table 3). The size distribution of the filterable solid particles was also determined (Table 4).

Examination of the deposit analysis for heat exchanger D (Table 2), where the deposits are a mixture of inorganic (42%) and organic (58%) deposits, indicate particulate and polymerisation fouling. The nature of particulate fouling in D is confirmed by the variation

of fouling factor with time, with no induction time or delay period indicated (Fig. 3). The fouling factor curve is linear with saw-tooth shape, where both the fouling factor and the deposition rate increase with time. This means continuous build up of the fouling layer followed by break off periods [9].

2.2. Particle formation

Chemical particle formation is the basic mechanism of particle formation in heat exchangers fluid streams, although organic material growth and biological particle formation, or biofouling, may occur in sea water systems and in types of waste treatment systems. Biofouling may be of two kinds: microbial fouling, due to microorganisms (bacteria, algae, and fungi) and their products, and macrobial fouling, due to the growth of macroorganisms such as barnacles, sponges, seaweeds or mussels. On contact with heat-transfer surfaces, these organisms can attach and breed, reducing thereby both flow and heat transfer to an absolute minimum and sometimes completely clogging the fluid passages. Such organisms may also entrap silt or other suspended solids and give rise to deposit corrosion. Corrosion due to biological attachment to heat transfer surfaces is known as microbiologically influenced corrosion. For open recirculating systems, bacteria concentrations of the order of 1×10^5 cells/ml and fungi of 1×10^3 cells/ml may be regarded as limiting values [10].

	Feed filter	Pump filter
Loss at 105°C (wt. %)	10.0	0.1
Loss at 550°C (wt. %)	28.3	25.3
Loss at 840°C (wt. %)	30.4	26.7
Ash (wt. %)	69.5	73.2
Carbon (wt. %)	2.6	6.4
Sulphur (wt. %)	36.9	19.7
Sulphates (wt. %)	55.8	50.7
Chloride (ppm)	-	281
Ammonium (ppm)	-	52
Iron (wt. % of ash)	45	58
Sodium (ppm of ash)	-	9
Calcium (ppm of ash)	-	161

Table 3. Analysis of two samples of the filterable solids.

Mesh size (μm)	< 90	90	125	355
Particle distribution (%)	24	8	36	32

Table 4. Size distribution of the filterable solid particles

Chemical particle formation can be the result of either corrosion or decomposition and polymerisation reactions. Trace contaminants present in the fluid stream can have a

significant effect on the fouling encountered in certain chemical processes. Such contaminants may include oxygen, nitrogen, NH_3 , H_2S , CN , HCN , Hg , unsaturates, organic sulphides and chlorides, and heavy hydrocarbon compounds such as paraffin wax, resins, asphaltenes, and organometallic compounds. Individual metals, which may exist as metal salts in the feed stream, can catalyse different polymerisation reactions. The concentrations of such metals are typically very low, not exceeding few ppms. However, small concentrations of certain metals can have a significant effect on catalysing different fouling-related polymerisation reactions. Metal detectors on unit feed samples can detect individual metals in the stream at less than 1 ppm.

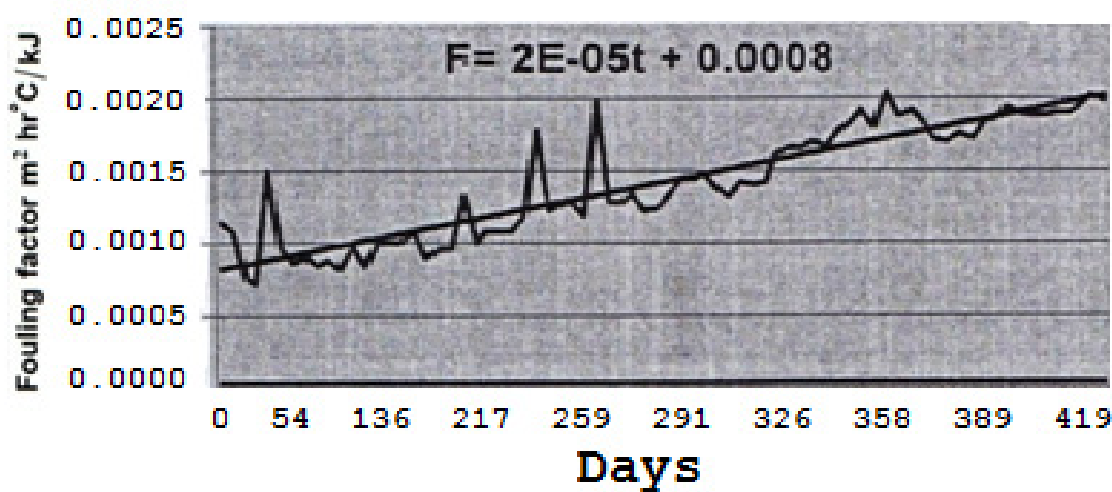
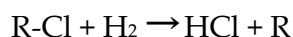


Figure 3. Variation of fouling factor in exchanger D in 2001.

Corrosion fouling is fouling deposit formation as a result of the corrosion of the substrate metal of heat transfer surfaces. This type of corrosion should not be confused, however, with the under-deposit corrosion, referred to earlier, which is one of the aftereffects of fouling.

Corrosion fouling is a mechanism which is dependent on several factors such as thermal resistance, surface roughness and composition of the substrate and fluid stream. In particular, impurities present in the fluid stream can greatly contribute to the onset of corrosion. Such impurities include hydrogen sulphide, ammonia and hydrogen chloride. In crude oil, for example, sulphur and nitrogen compounds are two very common contaminants which are mostly decomposed in certain situations to hydrogen sulphide and ammonia respectively. Chlorides which may be found in oil streams are converted to hydrogen chloride by the following reaction.



The chlorides may enter the refinery as salt with the crude. Chlorides in the oil stream may also be derived from various chemicals used in the oil industry which can contain high levels of chloride. Such chemicals include tertiary oil recovery enhancement chemicals and solvents used to clean tankers, barges, trucks and pipelines. As the crude oil is processed,

some of these chemicals and solvents, which are thermally stable and not soluble in water, pass overhead in the main tower of the atmospheric distillation unit along with the naphtha.

In the hydrotreater feed stream, chloride levels as high as 50 wt. ppm have been reported. High levels of chloride were detected with the filterable solids in the naphtha feed stream to the heat exchangers of the hydrotreater unit at the Homs refinery (Table 3) and in the deposits obtained from the heat exchangers (Table 2). Furthermore, the makeup hydrogen from the platforming unit will always contain trace quantities of hydrogen chloride. In order to maintain catalyst performance, modern platforming catalysts require a small, but continuous dosage of chloride, some of which is always stripped and leaves the platforming unit in the net gas stream that supplies the hydrotreater with makeup hydrogen.

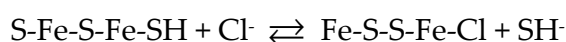
In a hydrogen sulphide environment the sulphur reacts with the exposed iron to form iron sulphide compounds. This happens in both the hot and cooler sections of the unit. The sulphur effectively corrodes the plant. However, once reacted, the iron sulphide forms a complex protective scale or lattice on the base metal, which inhibits further corrosion. The sulphide lattice would remain in equilibrium with its surroundings and the corrosion rate would be minimal if no other impurities were present in the system. The presence of other impurities, however, can accelerate corrosion as these impurities interact with the sulphide lattice.

Of the impurities that contribute to corrosion and fouling, hydrogen chloride may be the most important. By itself hydrogen chloride does not cause a problem. It will not foul equipment or corrode the carbon steel in the unit. Chloride corrosion and fouling, however, take place when hydrogen chloride, ammonia, and water all interact in the colder sections of the unit to defeat the protective sulphide lattice. The extent of the damage depends on their concentration and is directly dependent on pH, with the corrosion rate increasing rapidly with pH decrease.

Hydrogen chloride will become corrosive when it comes in contact with free water, i.e. water that is not in the vapour phase or is not saturated in the liquid hydrocarbon. Oil products are almost always saturated with water, and entrained water, even if it is less of a problem, does occur in most cases. Furthermore, continuous water wash at key locations is recommended as part of the solution to minimise the effects of chloride corrosion and fouling and this further contributes to the total water in the system.

Hydrogen chloride is highly soluble in water, and in a free water environment, any hydrogen chloride present in the vapour or hydrocarbon liquid will be quickly absorbed by the water, thus driving the pH down to approximately 1.

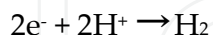
If the iron sulphide lattice is intact this chloride competes with the bisulphate ion (SH^-) for the iron ions in the lattice:



With a high concentration of hydrogen chloride present the reaction shifts to the right. As more and more bisulphate is released from the sulphide lattice, it eventually dissolves

leaving the base metal exposed. The reaction rate is then only limited by the chloride ion concentration in the solution at low pH. Loss of wall metal takes place very rapidly.

In water the chloride ions react directly with any exposed iron to form FeCl_2 .



As the chloride concentration in water is reduced by removing the source, diluting with additional water or neutralising with a base, the pH will increase. Hydrogen sulphide will begin to react with the exposed iron and start building a new protective layer. This sulphide lattice gets stronger as the pH increases to 6 and above. The corrosion rate falls off to a minimum.

Hydrogen chloride will also cause serious fouling problems if ammonia is present in the system. The ammonia reacts with hydrogen chloride to form ammonium chloride which may cause fouling and plugging problems. In the cooler parts of the unit, the ammonium chloride will condense from the vapour phase and solidify and deposit directly and accumulate on the walls. The salt can also break away from the walls and be carried downstream to eventually deposit somewhere else. If free water is present, ammonium chloride will be absorbed directly from the vapour phase into the water and no solid salts will form on the equipment. Another problem associated with ammonium chloride salt deposits is under deposit pitting corrosion as the hygroscopic nature of the salt will result in a wet environment at the wall under the deposit. The chloride ions will react with the iron to form iron chloride causing serious localised corrosion, the reaction rate accelerating in the presence of hydrogen sulphide. The sulphide ion as part of an ammonium sulphide salt will react with the iron chloride to form iron sulphide, thus releasing the chloride ion to start over.

Any excess ammonia available may react with the disulphide ions present in the solution to form ammonium sulphide salts, but only after most of the chloride has been neutralised. While hydrogen sulphide is only slightly soluble in the water, its salt is highly soluble. Therefore, as the pH is raised to 6 and higher the free ammonia present reacts with the small quantity of hydrogen sulphide in solution, making more ammonium sulphide salts. The rich hydrogen sulphide vapour above the water will continuously replace the consumed hydrogen sulphide. The overall sulphide concentration in the water increases making it difficult to raise the pH much further.

The sharp increase in corrosion rate in the 6.8 to 7.3 pH range is related to the concentration of the ammonium chloride and sulphide salts present. In large quantities these salts can become aggressive, especially the sulphide salts. If the pH is raised further the corrosion rate again falls off to a very low value. This is because the sulphide lattice has formed into a very strong hard film that cannot easily be broken.

The iron content in the deposits obtained from the heat exchangers may be an indication of fouling by corrosion. Although polymerisation may account for about 80% of the total

fouling associated with the “A” heat exchanger, in the Homs hydrotreating plant, fouling by corrosion is not negligible, with about 19% of the total fouling may be due to corrosion, as is clearly indicated by the iron content of the deposits obtained from this exchanger (Table 2).

Coking and Polymerisation are major causes of fouling in heat exchangers. Decomposition of organic products can lead to the formation of very viscous tar or solid coke particles at high temperatures and polymerisation involves the formation of undesirable organic sediments or polymers. The coke particles and polymers formed in the heat exchanger may grow to such a large size that they drop out of solution and deposit on the process equipment. Such deposits can be extremely tenacious and may require burning off the deposit to return the heat exchanger to satisfactory operation.

There are two major polymerisation mechanisms which can occur in the feed stream: free radical and non-free radical polymerisation.

Free radical polymerisation occurs when a free radical is formed and continues to react with other molecules. The free radicals continue to propagate in the feed stream producing longer chain polymers which will continue to be produced as long as free radicals are being formed. Free radical polymerisation is easily initiated in the presence of light and heat and its rate for polymer formation increases exponentially with temperature. A general rule is that for every 10°C increase in temperature the rate of polymer formation doubles. Free radical polymerisation readily takes place in heat exchanger tubes and storage tanks [6].

The formation of free radicals has been investigated extensively and it is known that numerous types of free radicals can be formed in a feed stream. These include alkyl radicals produced by the breaking of double or unsaturated bonds as well as other types of precursors such as nitrogen and sulphur radicals which are easily formed at the temperatures found in the heat exchanger train. Organic sulphur, nitrogen and oxygen compounds increase the potential for various polymerisation reactions, depending on the form in which they exist. Acidic compounds can promote free radical polymerisation by initiating free radicals through the formation of a positive ion or cation. Additional polymerisation precursors include carbonyls, mercaptans, and pyrrole nitrogen.

Oxygen may also react with hydrocarbons to form peroxide free radicals, a step that could occur in the storage tank. When the temperature is increased in the heat exchangers, the peroxides start fast polymerisation reactions leading to the formation of polymers which increase in chain length as more hydrocarbons are attached. The oxygen source is typically from air in non-blanketed storage tanks or oxygenated compounds in the feed stream, which become more reactive as the feed stream is heated [6, 11].

At lower temperatures, free radicals may be formed when a ligand is broken from a metal complex or salt. The unshared electrons resulting from this break react with an unsaturated hydrocarbon or oxygen to form a free radical [5]. There are numerous transition metals which, in very low concentrations, can act as a catalyst and initiate polymerisation reactions.

Some of these catalytically reactive metals are iron, copper, nickel, vanadium, chromium, calcium, and magnesium [6]

In non-free radical polymerisation, polymer formation results from the reaction of two different molecules under the right conditions. One of the reactive molecules may be a radical, or a compound from a free radical-initiated polymerisation step. Basic compounds can react with other compounds or with themselves to form polymers by several different polymerisation mechanisms. In condensation polymerisation, two large radicals or compounds react together to form an even larger compound, but in their reaction also generate a smaller compound, such as water. This new larger compound can continue to react with other reactive species in the feed stream to make higher molecular weight polymers. At some point, the polymer will either get so large in size that it is no longer able to stay entrained or soluble in the fluid stream and deposit, or all the different compounds that can react with it are consumed, and no further polymer is formed [6].

Various laboratory tests can provide an indication of a stream's polymerisation potential. These include laboratory simulations and analytical characterisation, to identify specific compounds in the feed which are known to contribute to polymerisation mechanisms. Such polymerisation precursors may include unsaturated hydrocarbons, acidic compounds, amines, carbonyls, mercaptans and pyrrole nitrogen.

The presence of unsaturated components in the feed stream contributes significantly to polymerisation reactions, particularly at high temperatures. The bromine number is a method of measuring the degree of unsaturation in a feed stream. The unsaturated bonds react with bromine, and the amount of bromine reacted is an indication of the degree of unsaturation [12].

The neutralisation, or acid, number measures the acidity of the fluid as it is titrated with a base. This number can be an indication of fouling tendency, where the more acidic the feed stream, the greater is its tendency to foul. This is most likely due to the fact that acidic compounds, as mentioned above, can promote free radical polymerisation.

The basic nitrogen test determines the amount of basic compounds in a sample, assumed to be mostly amines, by titrating with a mixture of organic acids. This method can, however, overestimate the basic nitrogen content.

A method of determining a sample's oxidative polymerisation potential is to run a potential gums test. This test is a method of determining a sample's oxidative polymerisation potential. In this test, the fluid is subjected to 100% oxygen for four hours, at 100°C, in a pressurised sample bomb. The measured gum content, as compared to an initial gum value, will indicate the impact of oxygen on the stream's polymerisation potential.

Detailed deposit analysis, as mentioned earlier, can also indicate the occurrence of polymerisation. It is apparent from examination of the deposit analysis results shown in Table 2 that most deposits are organic in nature, as the loss reported on heating the deposit

samples to 840°C was greater than 80% in both the "B" and "C" heat exchangers, where working temperatures are rather high. Since organic deposits result mainly from polymerisation reactions, the high organic content observed in the deposit analysis could be taken as an indication that the fouling in these two heat exchangers is due mainly to polymerisation, which could take place in the heat exchangers themselves or it could occur prior to the heat exchangers either during storage or in transport. Analysis for metals in the deposits indicates the presence of individual metals in the stream. Although, some of these metals are only found in very low concentrations, this may be sufficient for catalysing different polymerisation mechanisms [7].

2.3. Aggregation and flocculation

Some of the heavy organics, especially asphaltenes, will separate from the oil phase into large particles or aggregates. These aggregates may then remain in the oil by some peptising agents, like resins, which will be adsorbed on their surface and keep them afloat, but the stability of such steric colloids is a function of concentration of the peptising agent in the solution. When this concentration drops to a point at which its adsorbed amount is not high enough to cover the entire surface of heavy organic particles, these particles coalesce together, grow in size and flocculate. Flocculation of asphaltene in paraffinic crude oils is known to be irreversible. Due to their large size and their adsorption affinity to solid surfaces flocculated asphaltenes can cause irreversible deposition. Segments of the separated particles which contain S, N and/or H bonds could also start to flocculate and as a result produce the irreversible heavy organic deposits which may be insoluble in solvents.

Inorganic particles may also act as nuclei on which agglomeration of organic particles proceed until the particles become eventually large enough to drop out.

2.4. Transport and migration to the fouling sites

Starting with submicron particles, three transport mechanisms progressively predominate in turbulent flow as the particle size increases. After Gudmunsson [13], the corresponding regimes are designated simply as diffusion, inertia and impaction, respectively.

2.4.1. Diffusion

In the diffusion regime, suspended colloidal particles i.e., particles smaller than about 1 μm in at least one dimension, move with the fluid and are carried to the wall by the Brownian motion of the fluid molecules and through the viscous sublayer in the case of a turbulent flow. The submicron particles can then be treated like large molecules, so that the transport coefficient becomes equivalent to the conventional mass transfer coefficient, which can be obtained from the relevant empirical correlations or theoretical equations for forced convection mass transfer in the literature [14].

In the diffusion regime, the smaller the particle size, the greater is its propensity to be deposited. Thus, it is precisely the very fine submicron particles that are most difficult to remove by filtration or other means which have the greatest propensity to foul a surface.

2.4.2. *Inertia*

The transition from diffusional to inertial control of transport occurs at particle diameter in the order of 1–2 μm . In the inertia regime the particles are sufficiently large that turbulent eddies give some of them a transverse (Free flight) velocity which is not completely dissipated in the viscous sublayer. These particles then possess sufficient momentum to reach the wall. Some of the particles also experience a more gradual movement towards the wall by migration down the turbulence intensity gradient, i.e. by "turbophoresis" [15]. Much work has been done by a large number of investigators on predicting the results of this free flight excursion or inertial coasting in a turbulent field [16].

In the inertial regime a more desirable situation prevails. Here the larger particles, which are relatively easy to remove, are those which have the greater propensity to be deposited.

2.4.3. *Impaction*

In this regime, which starts at particle diameter $d_p \cong 10\text{--}20 \mu\text{m}$, the particle velocity towards the wall approaches the friction velocity and the particle stopping distance becomes of the same order as the pipe diameter. The response of such large particles to turbulent fluctuations becomes limited and the transport coefficient therefore levels off. As the particles get still larger they get even more sluggish in their response to turbulent eddies and the transport coefficient actually starts to fall gradually [14].

In the impaction regime, transport-controlled deposition would be virtually independent of particle size.

There is considerable experimental evidence to indicate that the effect of surface roughness is usually to enhance the transport of particles to the surface. The enhancement occurs because of the decrease of viscous sublayer thickness and corresponding increase in turbulence level above the roughness elements, because of the smaller stopping distance required for the particles to arrive at the outer asperities of the roughness elements, and because of the additional mechanism of particle interception by those elements along flow lines parallel to the macrosurface [15].

On the other hand, turbulent particle transport may be retarded as a result of deposition of very fine particles which tends to smooth initially rough surfaces. Transport-retardation is, however, far less common than transport-enhancement by surface roughness. The importance of clean and, where feasible also, polished surfaces for mitigating particle deposition under transport-controlled conditions is thus apparent [15].

2.5. Phase separation

Separation of solid particles from fluid stream and their eventual deposition onto heat exchanger surfaces may be a result of many physical processes including condensation from gas phase, gravitational settling, crystallisation and electro-kinetic effect.

Suspended particles such as sand, silt, clay, and non-oxides may become too large to remain entrained in the flowing fluid stream. If the particles are sufficiently large and/or heavy that gravity controls the deposition process, we then have what is known as sedimentation fouling, which can often be prevented with relative ease by pre-filtration or pre-sedimentation of the offending particles. Sedimentation fouling is strongly affected by fluid velocity, and suspended particles in the process fluids will deposit in low-velocity regions, particularly where the velocity changes quickly, as in heat exchanger water boxes and on the shell side [17]. Wall temperature, on the other hand, may have less effect in general on sedimentation fouling, although a hot wall may cause a deposit to "bake on" and become very hard to remove.

Dissolved inorganic salts in a polydisperse fluid may become supersaturated if any change in temperature, pressure, composition (such as solvent evaporation or degasification or addition of a miscible solvent) or other factors destabilises the fluid. The heavy and/or polar fractions may then separate from the fluid into steric colloids, micelles (= charged groups of molecules), another liquid phase or into a solid precipitate.

The dependence of salt solubility on temperature is often the driving force for precipitation fouling. This temperature dependence may be different for different salts, with salt solubility increasing or decreasing with increasing temperature so that different salts may foul the cooling or heating surfaces depending on their solubility temperature dependence. While for most salts the solubility gets higher with increasing temperatures, there are salts such as calcium sulphate which have retrograde solubility dependence and are therefore less soluble in warm streams. Such salts will crystallise on heat transfer surfaces if the streams encounter a surface at a temperature higher than the saturation temperature of these salts. The calcium sulphate scale is hard and adherent and usually requires vigorous mechanical or chemical treatment to remove it. Other typical scaling problems are calcium and magnesium carbonates and silica deposits.

Crystallisation normally begins at specially-active nucleation sites such as scratches and pits, whereas a scratch-free or a smooth surface can flush salt crystals. Subsequently particle deposit will start and continue to build up as long as the surface in contact with the fluid has a temperature above or below saturation. High fluid velocity, by increasing the attrition, can however reduce the rate of particle deposition and fouling.

The solubility of certain heavy hydrocarbons with high melting points such as paraffin wax and diamondoids depends strongly on temperature. If the temperature is decreased, the heavy hydrocarbons may precipitate in the form of solid crystals. Deposition of paraffin wax in cooled heat exchanger tubes showed an asymptotic behaviour due to decreasing heat flux

and increasing shear stress [18]. When various heavy organic compounds are present in a petroleum fluid, their interactive effects largely determine their collective deposition especially when one of the interacting heavy organic compounds is asphaltene.

Changes in the nature of oil fluids may lead to the precipitation of some heavy hydrocarbons, mainly asphaltenes, exceeding their solubility limits. Asphaltenes precipitation, which may be a major cause of crude unit fouling, is affected by many factors including variations of temperature, pressure, composition, flow regime, and wall and electrokinetic effect.

The deposition of heavy hydrocarbons is an example of what is known as solidification fouling, another example of which is the solidification of molten ash carried in a furnace exhaust gas onto a heat exchanger surface.

Precipitation fouling can also occur as a result of pressure changes, where the solubility of salts such as calcium sulphate decreases with decreasing pressure. Laboratory tests have further indicated that variations of pressure exerted on a petroleum fluid can cause the deposition of some of its heavy organic contents.

Motion of charged particles in a conduit may lead to the development of electrical potential differences along the conduit. This electrical potential difference could then cause a change in charges of the colloidal particles further down in the conduit, the ultimate result of which is their untimely deposition. The factors influencing this effect are the electrical and thermal characteristics of the conduit, flow regime, flowing oil properties, characteristics of the polar heavy organics and colloidal particles.

2.6. Particle deposition

Deposition and attachment of solid particles on heat exchanger surfaces is a function of several different operating variables which include particle size and concentration, bulk fluid density and bulk fluid velocity through the heat exchanger [4, 19]. Furthermore, the stickiness and attractive or repulsive forces between particles can significantly contribute to the deposition of particles [3]. Organic deposits may also be the result of heavy hydrocarbon particles bound to the metal surfaces by inorganic deposition. Attachment is also a function of the interfacial properties of the fouling material and the roughness and wettability of the surface where the fouling is going to occur. Whereas smooth and nonwetting surfaces may delay fouling, rough surfaces provide “nucleation sites” that encourage the laying down of the initial fouling deposits. Most initially smooth walls would tend to roughen as particle deposition occurred, so that roughness would then have to be taken into account. On the other hand, deposition of very fine particles onto initially rough surfaces can conceivably result in filling the roughness cavities, thereby smoothing the surface [15].

Recent studies have shown that particle size and concentration have great impact on every type of particle deposition. The average diameter of particles entrained in the fluid stream may vary widely, between a maximum of over 350 μm and a minimum of less than 90 μm (Table 4). Solid particles which foul heat exchangers range in size from submicron to several

hundred microns. Investigation revealed that shell and tube exchangers are generally plugged by particles above 20 microns. On the other hand, plate fin exchangers, having much narrower slots, can be plugged by particles as small as 2 microns [3]. The deposition mechanism for the smaller particles is Brownian diffusion while for the larger particles (10–100 μm) it is mainly gravitational settling. At areas of minimum flow velocities, the larger particles in the stream deposit first followed by the smaller particles and the fouling layer starts to build up as a consequence.

2.7. Deposit growth, aging and hardening

Following particle deposition, deposit growth and consolidation or alternatively auto-retardation and erosion, re-entrainment or removal may take place.

The rate of deposition growth and the accumulation of particles on heat exchanger surfaces is a function of the nature of the fouling material, the composition of the fluid stream and other variables such as temperature and flow rate.

With time, the surface deposit strength may increase and the deposit hardens through various processes collectively known as aging such as, for example, polymerisation, recrystallisation and dehydration. Some types of particles can bake on the surface and will become more difficult to remove over time. The toughness of the deposits may be further affected by the presence of asphaltenes, which are highly polar compounds, and which could act as glue and mortar in hardening the deposits. Biological deposits, on the other hand, may weaken with time due to contamination of organisms.

2.8. Auto-retardation and erosion or removal

The decline of particle deposition rate is commonly referred to as auto-retardation. This is a desirable but spontaneous process that is in the main not under the control of the designer or operator. Several mechanisms may account for auto-retardation and the progressive decrease in adherence of particles to the surface including the already referred to possibility of slowing down particle transport in cases where very fine particles fill the roughness cavities of a surface.

Depending on the strength of the deposit, erosion occurs immediately after the first deposit has been laid down. In saw-tooth fouling part of the deposit is detached after a critical residence time or once a critical deposit thickness has been reached. The fouling layer then builds up and breaks off again. Sometimes impurities such as sand or other suspended particles in fluid streams may have a scouring action, which will reduce or remove deposits [13].

3. Fouling mitigation, control and removal

In order to prevent or mitigate the impact of fouling problems, various steps can be taken during plant design and construction and also during plant operation and maintenance.

However, fouling mitigation and control is a very complex process and anticipating the likely extent of fouling problems to be encountered with different flow streams is a major difficulty faced alike by designers and operators of heat exchangers. In most cases, optimisation of the design and operational conditions is not possible or at least would not be realistic without a comprehensive modelling of the process backed up by practical observations. Modelling, however, is not an easy process, and the different models available in the literature are generally of limited value and application.

The use of multiple regression analysis (MRA), which is an extension of simple least squares regression analysis on a set of data, is an excellent means of modelling heat exchanger fouling. A dependent variable, such as the heat exchanger outlet temperature, is regressed against a set of independent variables, temperatures, pressures, and flows, which directly impact the dependent variable. Regression analysis results in a model equation of independent variables that combine to yield the dependent response. Variability in data and the interaction between independent variables is taken into account in the model equation which can be used to predict future performance. The impact of a change, such as antifoulant addition, can then be compared to the predicted response from the model to determine how effective the treatment programme is.

3.1. Plant design and construction

Fouling mitigation and control require scientific considerations in design and construction. In general, high turbulence, absence of stagnant areas, uniform fluid flow and smooth surfaces reduce fouling and the need for frequent cleaning. In addition, designers of heat exchangers must consider the effects of fouling upon heat exchanger performance during the desired operational lifetime of the heat exchangers. The factors that need to be considered in the designs include the extra surface required to ensure that the heat exchangers will meet process specifications up to shutdown for cleaning, the additional pressure drop expected due to fouling, and the choice of appropriate construction materials. The designers must also consider the mechanical arrangements that may be necessary for fouling inspection or fouling removal and cleaning.

Fouling resistances are different in different designs of heat exchangers. More than 35-40% of heat exchangers employed in global heat transfer processes are of the shell and tube type of heat exchangers. In process industries, more than 90% of heat exchangers used are of the shell and tube type [20]. This is primarily due to the robust construction geometry as well as ease of maintenance and upgrades possible with the shell and tube heat exchangers [1]. Well established procedures for their design and manufacture from a wide variety of materials, as well as availability of codes and standards for design and fabrication and many years of satisfactory service make them first choice in most process industries. However, fouling resistance in the shell and tube heat exchangers are usually much greater than in other types of heat exchangers (Table 5). In the shell side in particular lower fluid flow velocities and low-velocity or stagnant regions, for example in the vicinity of baffles, encourage the

accumulation of foulants. Furthermore, segmental baffles have the tendency for poor flow distribution if spacing or baffle cut ratio is not in the correct proportions. Fouling resistance in plate heat exchangers, on the other hand, can be much smaller. This may be due to the high degree of turbulence even at low velocities which keeps solids in suspension. Also, in plate exchangers there are no dead spaces where fluids can stagnate and solids deposit. Furthermore, heat transfer surfaces are generally smooth and plates are built with higher-quality materials with no corrosion products to which fouling may adhere. Finally, cleaning of plate heat exchangers is a very simple operation and the interval between cleanings is usually smaller [21]. Hence, the fouling factors required in plate heat exchangers are normally 20-25% of those used in shell and tube exchangers [22]. In certain applications, spiral plate exchangers may be chosen for fouling services, where the scrubbing action of the fluids on the curved surfaces minimises fouling. On the other hand, fouling is one of the major problems in compact heat exchangers, particularly with various fin geometries and fine flow passages that cannot be cleaned mechanically [23].

Type	Shell and tube	Plate	Spiral plate	Air cooled	Lamella	Plate fin	Coiled tube	Double pipe	Graphite	Scraped surface
Fouling risk	Very poor	Very good	Good	Poor	Fair	Poor	Fair	Fair	Fair	Very good
Fouling effect	Poor	Good	Good	Very poor	Poor	Very poor	Poor	Fair	Poor	Good

Table 5. Fouling risk and effects for different types of heat exchangers [24, 25]

Over the years, there has been much advance in the design and manufacture of shell and tube heat exchangers with resultant improvements in their fouling behaviour in operation. A striking example of a new design is the Helixchanger heat exchanger (Fig. 4) where the conventional segmental baffle plates are replaced by quadrant shaped baffles arranged at an angle to the tube axis creating a uniform velocity helical flow through the tube bundle. Near plug flow conditions are achieved in a Helixchanger heat exchanger with little back-flow and eddies, often responsible for fouling and corrosion. Low fouling characteristics are provided offering much longer exchanger run lengths between scheduled cleaning of tube bundles. Such run lengths are increased by 2 to 3 times those achieved using the conventionally baffled shell and tube heat exchangers. Heat exchanger performance is maintained at a higher level for longer periods of time with consequent savings in total life cycle costs of owning and operating Helixchanger heat exchanger banks [1].

If fouling is expected on the tube side, some engineers recommend using larger diameter tubes (a minimum of 25 mm OD) [26]. The use of corrugated tubes has been shown to be beneficial in minimising the effects of at least two of the common types of fouling mechanisms, *viz. deposition fouling* because of an enhanced level of turbulence generated at lower velocities, and *chemical fouling* because the enhanced heat transfer coefficients

produced by the corrugated tube result in tube wall temperatures closer to the bulk fluid temperature of the working fluids.

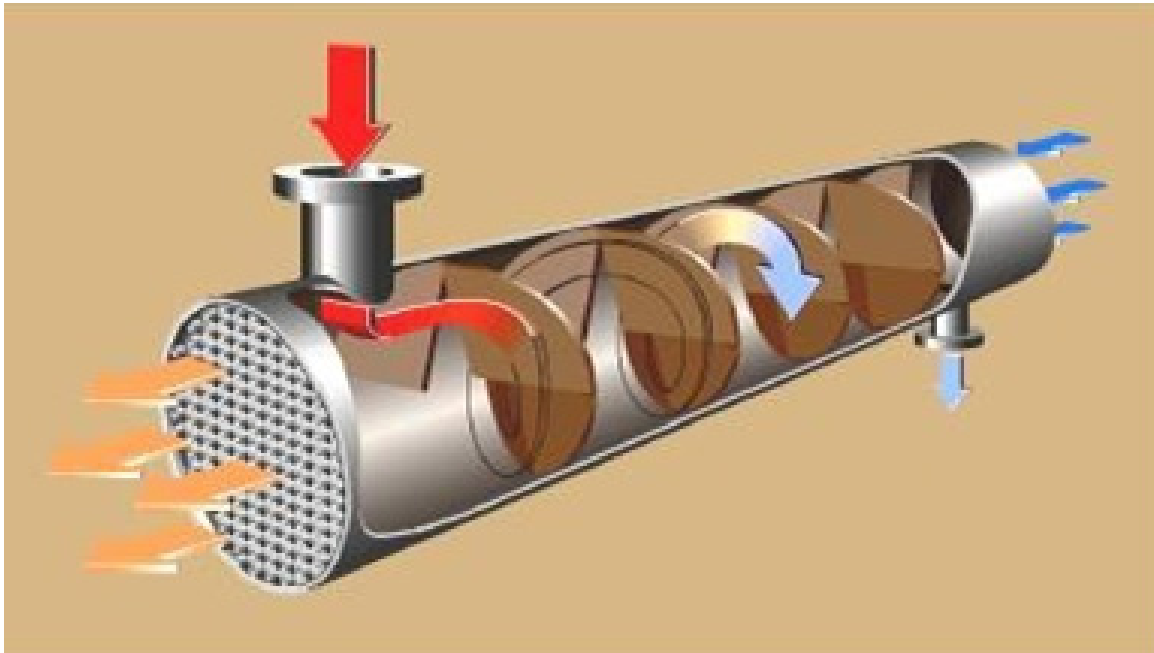


Figure 4. Helixchanger heat exchanger.

Mounting the heat exchanger vertically can minimise the effect of deposition fouling as gravity would tend to pull the particles out of the heat exchanger away from the heat transfer surface even at low velocity levels. Appropriate orientation of heat exchangers may also make cleaning easier [27]. In fluid allocation, it is usually preferred to allocate the most fouling fluid to the tube side as it is easier to clean the tube interiors than the exteriors and the probability of low-velocity or stagnant regions is less on the tube side. Placing the fouling fluid in the tube side tends also to minimise fouling by allowing better velocity control. The use of concurrent flow instead of counterflow is a strategy that may be resorted to sometimes in order to control solidification fouling [23].

Appropriate choice of construction materials for heat transfer surfaces may be necessary to alleviate fouling problems. For example, the use of low-fouling surfaces such as surfaces implanted with ions, very smooth surfaces or surfaces of low surface energy may be an option for some applications. Surface coatings and treatment, ultraviolet, acoustic, electric and radiation treatment, may further help to alleviate fouling problems. Surface treatment by plastics, vitreous enamel, glass, and some polymers can also minimise the accumulation of deposits [13]. Similarly, if biofouling is expected or encountered, the use of non-ferrous high copper alloys, which are poisonous to some organisms, can discourage the settling of these organisms on the heat transfer surfaces. Alloys containing copper in quantities greater than 70% are effective in preventing or minimising biological fouling, and generally 70% to 90% copper and 30% to 10% nickel are used for this purpose. Copper alloys are however prohibited in high-pressure steam power plant heat exchangers, since

the corrosion deposits of copper alloys are transported and deposited in high-pressure steam generators and subsequently block the turbine blades. Environmental protection also limits the use of copper in river, lake, and ocean waters, since copper is poisonous to aquatic life [23].

Corrosion-type fouling can also be minimised by the choice of a construction material which does not readily corrode or produce voluminous deposits of corrosion products. A wide range of corrosion resistant materials based on stainless steel is now available to the heat exchanger manufacturer. Noncorrosive but expensive materials such as titanium and nickel based alloys may be used sometimes to prevent corrosion. If one of the fluids is more corrosive, it may be convenient to send it through the tube side because the shell can then be built with a lower-quality and cheaper material.

The construction material selected must also be resistant to attack by the cleaning solutions in situations where chemical removal of the fouling deposit is planned. For fluid allocation, it is usually preferred to allocate the most fouling fluid to the tube side as it is easier to clean the tube interiors than the exteriors.

3.2. Plant operation and maintenance

In many cases, even the right design of a heat exchanger will not prevent fouling problems that may not be predictable at the design stage. For the control and mitigation of fouling it is generally necessary to take into account the different plant operational conditions such as temperature range, fluid flow rate and chemical composition, and, where possible, make such changes as are required by the severity and type of the fouling problems. For example, some types of fouling can be minimised by using high flow velocities, with due consideration of the possibility of metal erosion as it may be necessary to restrict the velocity to values consistent with satisfactory tube life.

Several techniques may be used for the control of fouling as part of plant maintenance. Some of these techniques are designed to prevent or mitigate fouling. These include avoidance of feed contact with air or oxygen by nitrogen blanketing, elimination or reduction of unsaturates, prior treatment of feed, the use of anti-foulants and application of mechanical on-line mitigation strategies. Cathodic protection and surface treatment such as passivation of stainless steel will minimise corrosion fouling [23].

Prior treatment of feed includes caustic scrubbing, desalting, filtration or sedimentation of feed. Caustic scrubbing removes sulphur compounds and desalting reduces trace metal contamination, both of which reduce polymerisation fouling [10]. Depending on system parameters, including fluid temperature, viscosity, pressure, solid concentration, particle size distribution, and fluid compatibility with the filter media, a filter can be designed to remove solid particles from the fluid. Filtration, however, can only remove the larger-sized particles leaving the smaller-sized particles in the feed stream. Filters used on the feed line require also regular maintenance. At the filter design stage, the

most important question to be answered is, whether the cost of filtration is higher than the fouling cost [3].

Antifoulants or chemical fouling inhibitors may be used to reduce fouling in many systems mainly by preventing reactions causing fouling, and minimising or interfering with the different steps of the fouling process such as crystallisation, agglomeration of small insoluble polymeric or coke-like particles, sticking or attachment of particles to tube walls and deposit consolidation [28]. Such antifoulants include antioxidation additives used to inhibit polymerisation reactions, metal coordinators which react with the trace elements and prevent them from functioning as fouling catalysts, corrosion inhibitors and dispersion agents. Other antifoulants may be used to control crystallisation such as distortion and dispersion agents, sequestering agents and threshold chemicals [28].

Various strategies and devices for the continuous mitigation and reduction of fouling have been proposed such as periodical reversal of flow direction for the removal of weakly adherent deposits, intermittent air injection and/or increasing wall shear stress by raising flow velocity or by increasing turbulence level. In order to enhance the removal of the fouling deposits, velocities in tubes should in general be above 2 m/s and about 1 m/s on the shell side [10]. In several patents, tubular heat exchangers equipped with fouling reduction devices mounted inside the exchanger tubes are described [29]. Such fouling reducers may comprise a mobile turbulence generating element that consists of a metallic winding in the form of a solenoid. The solenoid can be held in position by a hanging system in such a manner that the turbulence generating element can be driven in rotation by the liquid that circulates in the exchanger. The mobile components can be made of spring steel to make them unstretchable. Alternatively, an elastic solenoid may be used that extends over the entire length of the tubes and is agitated by the liquid that circulates in the exchanger [19]. In some heat-transfer applications, mechanical mitigation with dynamic scraped surface heat exchangers is an option. In self-cleaning fluidised-bed exchangers, a fluidised bed of particles is used to control fouling on the outside or inside of tubular exchangers. The self-cleaning exchanger consists of a large number of parallel vertical tubes, in which small solid particles are kept in a fluidised condition by the liquid velocities. The particles have a slightly abrasive effect on the tube walls, so that they remove the deposits [30].

Finally, different mechanical strategies for continuous on-stream cleaning of the interior surfaces of the tubes have been proposed including such strategies as circulation of cleaning balls such as sponge rubber or grit coated balls and pushing of brushes through tubes. In the sponge rubber ball cleaning system, the balls used for normal operation should have the right surface roughness to gently clean the tubes without scoring the tube surface. To remove heavy deposits, special abrasive balls that have a coating of carborundum are available [31]. In the Amertap System, slightly oversized sponge rubber balls are continuously recirculated through the tubes in order to remove the accumulation of scale or corrosion products. The M.A.N. System provides for on-stream cleaning by passage of brushes through the tubes.

Notwithstanding the various control and maintenance techniques which can minimise fouling problems and reduce their severity, fouling may still occur and fouling removal and process equipment cleaning may be necessary. A review of the patent activities related to fouling indicates in fact that most of the work deals with fouling removal and process equipment cleaning techniques. This could also mean that many process equipment manufacturers face problems after they appear rather than proactively prevent them from occurring [3].

There are several different techniques that can be employed for the removal of fouling. All such techniques require, however, costly system shutdown after a longer period of low efficiency heat transfer. The chief techniques normally utilised are either chemical or mechanical cleaning, but other procedures may sometimes be employed for some specific applications such as ultrasonic cleaning, which is a more recent procedure, and abrasive cleaning.

Mechanical cleaning is generally preferred over chemical cleaning because it can be a more environmentally-friendly alternative, whereas chemical cleaning causes environmental problems through the handling, application, storage and disposal of chemicals. However, mechanical cleaning may damage the equipment, particularly tubes, and it does not produce a chemically clean surface. Furthermore, chemical cleaning may be the only alternative if uniform or complete cleaning is required and for cleaning inaccessible areas. The shell side in particular can only be chemically cleaned. The tubes on the other hand can be mechanically cleaned provided that the tube pattern and pitch provide sufficient space and access to the inside of the bundle, and if mechanical cleaning is required for one of the fluids, the usual practice is to put that fluid in the tube side.

For the chemical removal of fouling material, weak acids and special solvents or detergents are normally used. Chlorination may be used for the removal of carbonate deposits. Mechanical techniques for the removal of fouling include scraping and air bumping. Air bumping is a technique that involves the creation of slugs of air, thereby creating localised turbulence as slugs pass through the equipment.

For tightly plugged tubes drilling, generally known as bulleting, may be employed and for lightly plugged tubes roding is employed. Particularly weakly adherent deposits may be mechanically removed by applying high velocity water jets or a mixture of sand and water. Jet cleaning can be used mostly on external surfaces where there is an easy accessibility for passing the high pressure jet [23].

In cases where biofouling occurs it may be removed by either chemical treatment or mechanical brushing processes. In chemical cleaning techniques biocides are employed such as chlorine, chlorine dioxide, bromine, ozone and surfactants. A more usual practice, however, is by continuous or intermittent "shock" chlorination which kills off the responsible organisms. Other cleaning techniques that can be effective in controlling biological fouling include thermal shock treatment by application of heat or deslugging with steam or hot water, and some less well-known techniques like ultraviolet radiation [23].

4. Rate of fouling

The rate of fouling is normally defined as the average deposit surface loading per unit of surface area in a unit of time. Deposit thickness (μm) and porosity (%) are also often used for description of the amount of fouling.

Depending on the fouling mechanism and conditions, the rate of fouling may be linear, falling, accelerating, asymptotic or saw-tooth as the case may be.

1. Linear fouling is the type of fouling where the fouling rate can be steady with time with increasing fouling resistance and deposit thickness. This is perhaps the most common type of fouling. It occurs in general where the temperature of the deposit in contact with the flowing fluid remains constant.

Ebert and Panchal [32] have presented a fouling model that expressed the average (linear) fouling rate under given conditions as a result of two competing terms, namely, a deposition term and a mitigation term.

Fouling Rate = (deposition term) - (anti-deposition term)

$$\frac{dR_f}{dt} = \alpha \text{Re}^\beta \text{Pr}^\delta \exp\left(\frac{-E}{RT_{\text{film}}}\right) - \gamma \tau_w \quad (1)$$

where α , β , γ and δ are parameters determined by regression, τ_w is the shear stress at the tube wall and T_{film} is the fluid film temperature (average of the local bulk fluid and local wall temperatures). The relationship in Eq. (1) points to the possibility of identifying combinations of temperature and velocity below which the fouling rates will be negligible. Ebert and Panchal [32] present this as the “threshold condition”. The model in Eq. (1) suggests that the heat exchanger geometry which affects the surface and film temperatures, velocities and shear stresses can be effectively applied to maintain the conditions below the “threshold conditions” in a given heat exchanger.

2. Falling fouling is the type of fouling where the fouling rate decreases with time, and the deposit thickness does not achieve a constant value, although the fouling rate never drops below a certain minimum value. Falling fouling in general is due to an increase of removal rate with time. Its progress can often be described by two numbers: the initial fouling rate and the fouling rate after a long period of time.
3. Accelerating fouling is the type of fouling where the fouling rate increases with time. It is the result of hard and adherent deposit where removal and aging can be ignored. It can develop when fouling increases the surface roughness, or when the deposit surface exhibits higher chemical propensity to fouling than the pure underlying metal.
4. Asymptotic fouling rate is where rate decreases with time until it becomes negligible after a period of time when the deposition rate becomes equal to the deposit removal rate and the deposit thickness remains constant. In general, this type of fouling occurs

where the tube surface temperature remains constant while the temperature of the flowing fluid drops as a result of increased resistance of fouling material to heat transfer. Asymptotic fouling may also be the result of soft or poorly adherent suspended solid deposits upon heat transfer surfaces in areas of fast flow where they do not adhere strongly to the surface with the result that the thicker the deposit becomes, the more likely it is to wash off in patches and thus attain some average asymptotic value over a period of time.

The asymptotic fouling resistance increases with increasing particle concentration and decreasing fluid bulk temperature, flow velocity, and particle diameter. The asymptotic fouling model was first described by Kern and Seaton [33]. In this model, the competing fouling mechanisms lead to an asymptotic fouling resistance beyond which no further increase in fouling occurs. The Tubular Heat Exchanger Manufacturers Association (TEMA) standards suggest fouling factors for several fluids based upon the asymptotic values. This approach, however, does not address all fouling phenomena as it does not, for example, address fouling at the “hot” end of a crude oil preheat train, since fouling there does not exhibit the asymptotic behaviour.

5. Saw-tooth fouling occurs where part of the deposit is detached after a critical residence time or once a critical deposit thickness has been reached. The fouling layer then builds up and breaks off again. This periodic variation could be due to pressure pulses, spalling, trapping of air inside the surface deposits during shutdowns or other reasons. It often corresponds to the moments of system shutdowns, startups or other transients in operation.

5. Prediction of fouling factor

The effect of fouling, as has been noted above, is to form an essentially solid deposit of low thermal conductivity upon the heat transfer surface, through which heat must be transferred by conduction. But since the thermal conductivity of the fouling layer and its thickness are not generally known, the only possible solution to the heat transfer problem is by the introduction of a fouling factor in order to take into account the additional resistance to heat transfer and make possible the calculation of the overall heat transfer coefficient. A fouling coefficient also is sometimes specified, which is the reciprocal value of the fouling factor.

In carrying out heat transfer calculations, caution needs to be exerted in selecting fouling factors, particularly where fouling resistances completely dominate the thermal design. The influence of uncertainties inherent in fouling factors is generally greater than that of uncertainties in other design parameters such as fluid properties, flow rates and temperatures [34]. A large fouling factor is sometimes adopted as a safety margin to cover uncertainties in fluid properties and even in process knowledge but the use of an excessively large fouling factor will result in an oversized heat exchanger with two or three times more area than is really necessary. Although there are many experience-based

tabulations available that provide typical fouling factors such as TEMA Table RGP-T-2.4 [35], acceptable evaluation of the effects of fouling needs to be judged and evaluated for each particular application. Such tabulations, however, can be used as a guide in the absence of more specific information.

A number of methods empirical or otherwise have been proposed over the years for the prediction of the rate of fouling in heat exchangers or for estimating a fouling factor to be used in heat transfer calculations. With the advent and development of digital computers with their ability to provide rapid means of performing calculations, new and accurate methods became possible. Matlab being a programming language widely used in all scientific fields and in engineering sciences in particular may be used in conjunction with the artificial neural network (ANN) approach to provide an accurate and reliable method for predicting the fouling rate and rate of heat transfer in heat exchangers. The development of high speed digital computers has provided a rapid means of performing the many calculations involved in the ANN method, and has had a stimulating effect on the current expansion of the ANN method which is progressing at an impressive rate.

In recent years, the ANN method has been applied in many disciplines of engineering and has produced promising results. The main feature of this method is its ability to learn and generalise the relationships in a data set and to provide quick and satisfactory estimations, which make it attractive for many different applications.

The artificial neural network method is a computational structure inspired by a biological neural system. An ANN consists of very simple and highly interconnected processors called neurons. The neurons are connected to each other by weighted links over which signals can pass. Each neuron receives multiple inputs from other neurons in proportion to their connection weights and generates a single output, which may be propagated to several other neurons [36]. The inputs (X) into a neuron are multiplied by their corresponding connection weights (W) and summed together, a threshold (θ), acting at a bias, is added also to the sum. This sum is transformed through a transfer function (f) to produce a single output (Y), which may be passed on to other neurons. The function of a neuron can be mathematically expressed as

$$Y = f(\sum wx - \theta) \quad (2)$$

Where the transfer function (f) of the neuron is the linear activation function, being in the present work given as:

$$f(x) = \text{purelin}(x) \quad (3)$$

for the output layer and the tansing function

$$f(x) = \text{tansig}(x) \quad (4)$$

for the hidden layers

Among the various existing kinds of ANNS, the back propagation (BP) learning algorithm has become the most popular in engineering applications [37]. The BP algorithm is designed to solve the problem of determining weight values for a multi-layer ANN with feed forward connections from the input layer to the hidden layers and then to the output layer. The algorithm is an iterative gradient algorithm, designed to minimise the mean square error between the predicted output and the desired output. Fig. 5 shows a scheme of a simple example for BP algorithm, and Fig. 6 is a flow chart for the back propagation (BP) learning algorithm.

Results of the application of the ANN approach show that it can be used to develop the best configuration in the training period. In general, this approach may however be time consuming; it is nonetheless feasible due to its ability to learn and generalise the complex data set with a wide range of experimental conditions. For exhaustive and fundamental treatment of the ANN technique, the reader is referred to any of the textbooks [38, 39].

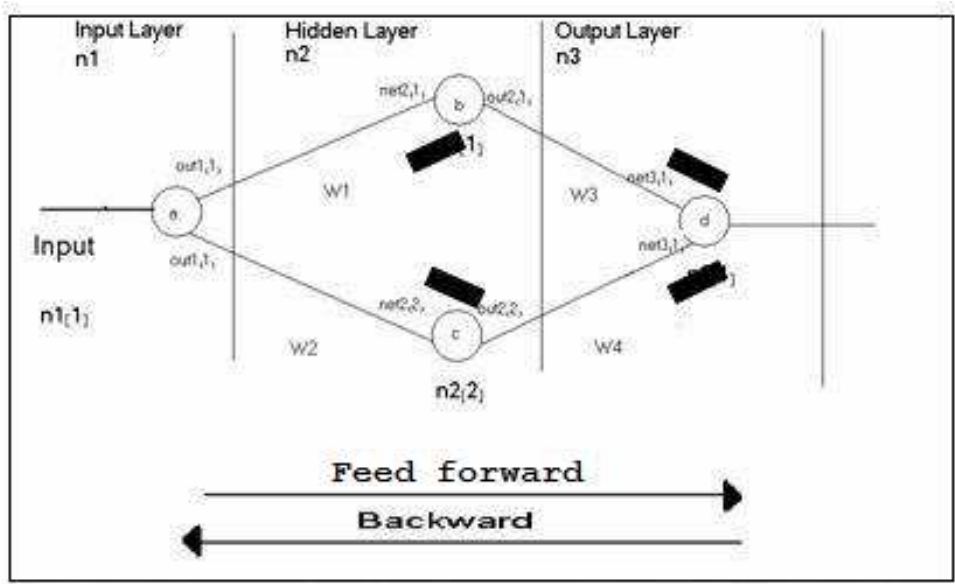


Figure 5. Scheme of a simple example of a BP algorithm.

Some of the recent applications for energy systems include modelling of appliances, light and space cooling energy consumption [40], solar radiation estimation [41], modelling gasoline consumption [42], modelling of heat pumps [43], performance prediction of solar domestic water heating systems [44], prediction of energy consumption of a passive solar building [45], prediction of temperature profiles in producing oil wells [46] and developing heating, ventilating and air conditioning systems for automobiles [47]. In addition, various applications of artificial neural networks in energy problems have been presented thematically [48–50].

In the field of heat exchangers, the Ann approach has been widely used, particularly in the design and control of heat exchangers [51, 52], and in the simulation of heat exchanger performance [14] and heat transfer analysis for different systems such as air–water spray cooling [53].

The ANN approach has also been used as an alternative and practical technique to evaluate the rate of heat exchange and heat transfer coefficient for tubular heat exchangers [34], fin tube heat exchangers [37], fluid—particle systems [54], heat rate predictions in humid air—water heat exchangers [55], and in other applications [22] including in particular the prediction of the rate of fouling and fouling factor in a shell-and-tube heat exchanger [56].

For predicting the rate of fouling and fouling factor in heat exchangers an ANN model can be developed and the available data set used for training the network and verifying its generalisation capability. The rates of heat transfer are then calculated and the input—output pairs presented to the network, and the weights adjusted to minimise the error between the network output and the actual value. Once training is complete, predictions from a new set of data may be done using the already trained network. The proposed algorithm is solved by a Matlab computer programme. After the rate of heat transfer is calculated, it can be used to estimate the fouling factor.

In order to test the applicability of the ANN model using the back propagation learning algorithm to predict the rate of heat transfer and fouling factor for heat exchangers, it was applied on a tube-shell heat exchanger used as a preheat device for the naphtha feed to the reactor in the naphtha hydrotreating unit at the Homs oil refinery.

Operation data of the heat exchanger are collected for this purpose [8]. A total of 73 readings tabulated in Table 6 are used for the ANN method. Empirical correlations for the rate of heat transfer (Q) is determined [57] as given below by Eq.5:

$$Q = m \text{ Cp } (t_{1d} - t_{2d}) \text{ kJ/hr} \quad (5)$$

$$Q = q_1 + q_2$$

$$q_1 = m \cdot 1 \times \text{Cp}_1 \times (t_{1d} - t_{2d}) \text{ (liquid)}$$

$$q_2 = m \cdot 2 \times \text{Cp}_2 \times (t_{1d} - t_{2d}) \text{ (gas)}$$

$$\text{Cp}_1 = 0.0045 \times t + 2.0687$$

$$\text{Cp}_2 = \text{Cp} \text{ (hydrogen)} + \text{Cp} \text{ (hydrocarbons)}$$

$$\text{Cp} \text{ (hydrogen)} = 4.19 (6.8 + 0.0006 \times t) \text{ y}$$

$$\text{Cp} \text{ (hydrocarbons)} = (0.00428 \times t + 1.5606) (1 - y)$$

$$y = 2.016 \times N / (100 \times M)$$

In developing an ANN model, the available data set is used for training the network and the same data are used to verify the generalisation capability of the network [58]. The input parameters were liquid naphtha feed quantity ($m \cdot 1$), gas reaction quantity ($m \cdot 2$), inlet temperature (t_{1d}), outlet temperature (t_{2d}), hydrogen purity (N), gas molecular weight (M), naphtha specific heat (Cp_1), gas specific heat (Cp_2) and the output parameter is heat transfer rate (Q).

The rates of heat transfer (Q) for the same data are calculated using Excel programme (actual values). Input—output pairs are presented to the network, and the weights are

adjusted to minimise the error between the network output and the actual value (this is done at the training step on a number of data ($n = 73$)). Once training is complete, predictions from a new set of data may be done using the already trained network. The proposed algorithm in this study was solved by a computer programme developed using the Matlab programming language, and all computations were performed with a personal computer. After the rate of heat transfer is calculated, it can be used to estimate the fouling factor.

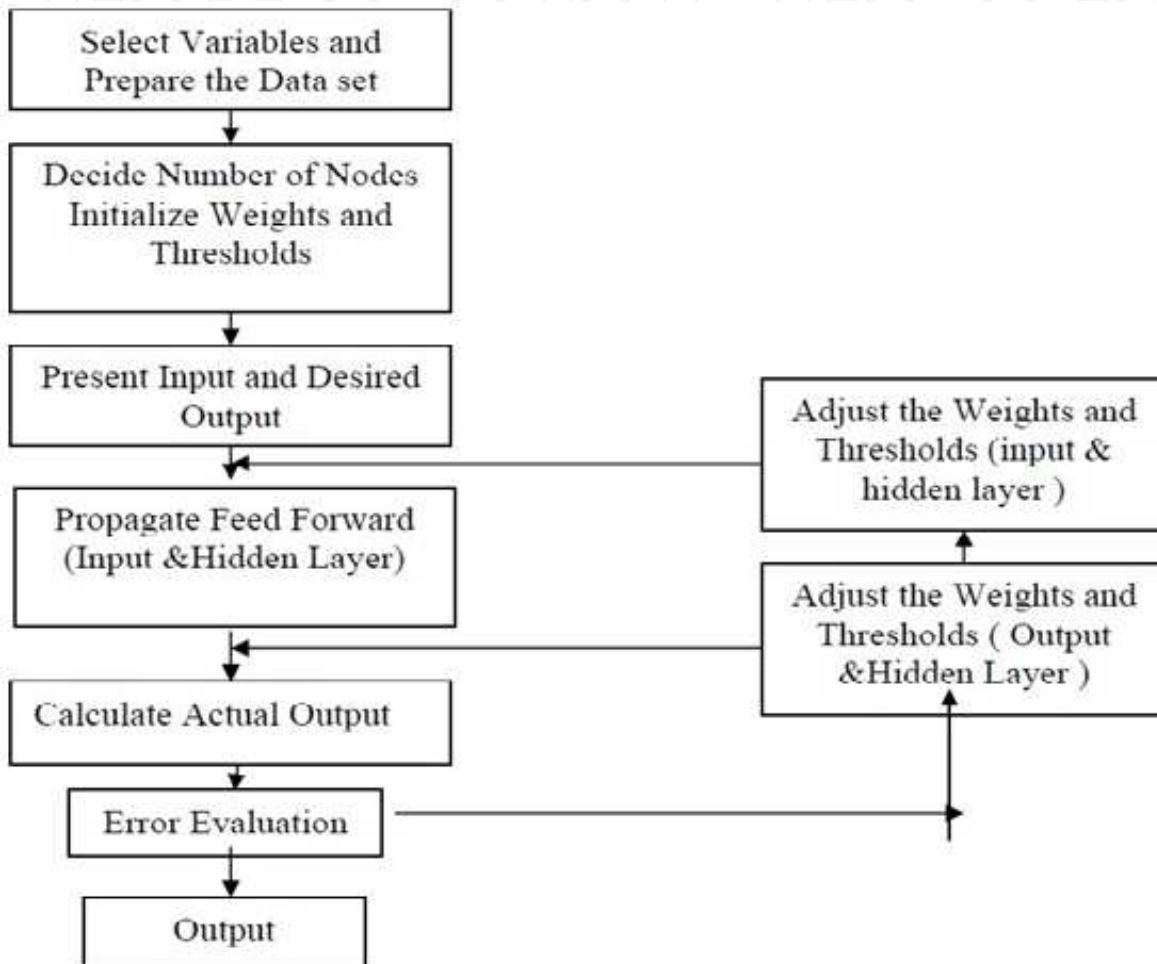


Figure 6. Flow chart for the back propagation (BP) learning algorithm.

The same steps used to calculate the rate of heat transfer by neural network (design, training) are used to calculate fouling factor for different data (Input-output pairs). The empirical correlations for the fouling factor are determined [57] as given below in Eq. 6:

$$f = U_c - U_d / U_c \times U_d \text{ m}^2\text{hr}^\circ\text{C}/\text{kJ} \quad (6)$$

$$U_c = h_o \times h_i / h_o + h_i$$

$$U_d = Q / A \times \text{LMTD}$$

$$h_o = J_h \times k / D_e \times \text{pr}^{0.33}$$

$$h_i = J_h \times k / D \times \text{pr}^{0.33}$$

$$\text{LMTD} = (T_1 - t_2) - (T_2 - t_1) / \ln(T_1 - t_2) / (T_2 - t_1)$$

$$G_s = \dot{m} / a_s \text{ where } a_s = ID \times C \times B / Pt$$

$$Res = G_s \times De / \mu \text{ (shell)}$$

$$Prs = C_p \times \mu / K \text{ (shell)}$$

$$G_t = \dot{m} / a_t \text{ where } a_t = N_t \times a_t' / z$$

$$Ret = D \times G_t / \mu \text{ (tube)}$$

$$Prt = C_p \times \mu / k \text{ (tube)}$$

A total of 73 values of input data tabulated in Table 7 are used for the ANN method, which were the rate of heat transfer (Q) obtained from the neural network, log mean temperature difference (LMTD), shell volumetric flow G_s , tube volumetric flow G_t , shell Reynolds Res and Prandtl Prs numbers, tube Reynolds Ret and Prandtl Prt numbers, and the output is the fouling factor (f).

The Fouling factor (f) for the same data is calculated using Excel programme (actual value). Input–output pairs are presented to the network, and the weights are adjusted to minimise the error between the network output and the actual value (this is done at the training step on a number of data ($n=73$)). Once training is complete, predictions from a new set of data may be done using the already trained network. The proposed algorithm in this study was solved by a computer programme developed using Matlab programming language; also all computations were performed with a personal computer.

The purpose of using the ANN model with the considered BP learning algorithm as a practical approach is to test the ability to predict the rate of heat transfer and fouling factor of heat exchanger. For the heat transfer function a network is designed with eight input parameters, namely liquid naphtha feed quantity (m_1), gas reaction quantity (m_2), inlet temperature (t_{1d}), outlet temperature (t_{2d}), hydrogen purity (N), gas molecular weight (M), naphtha specific heat (C_{p1}) and gas specific heat (C_{p2}), and one output parameter, the rate of heat exchange (Q). Model sensitivity was examined for different numbers of hidden layer nodes in the range of (1-5). There is no general rule for selecting the number of a hidden layer. The choice of hidden layer size is a specific problem and, to some extent, depends on the number and the quality of training patterns. The number of neurons in a neural network must be sufficient for correct modelling of the problem, and also, it should be low to ensure generalisation.

The number of neurons in a hidden layer drastically affects the outcome of the network training. If too few neurons are included, then the network may not be able to learn properly. On the other hand, if too many neurons were included, the network would encourage over fitting. Some researchers mentioned that the upper bound for the required number of neurons in the hidden layer should be greater than twice the number of input units. This rule does not guarantee generalisation of the network [59]. Every stage of an ANN problem requires a little trial and error to establish a suitable and stable network for the problem; so many networks are built by changing their parameters in order to reach a suitable result in these statements:

```
net_q=newff(minmax(input),[8,10,1],{'tansig','tansig','purelin'},'trainlm');
net_q.trainParam.show = 5;
```

```

net_q.trainParam.lr = 0.05;
net_q.trainParam.epochs = 1000;
net_q.trainParam.goal = 1e-13;
[net_q,tr]=train(net_q,input,q);

```

Q	C _{p2}	C _{p1}	M	N	t _{2d}	t _{1d}	m' ₂	m' ₁
7420754	5.62	2.43	5.9	88.1	113	50	30	1097
7897551	4.93	2.43	7.0	85.3	112	50	37	1173
10427147	4.50	2.42	7.9	82.2	111	48	53	1529
10937005	5.48	2.43	6.2	89.7	113	49	65	1548
6782209	4.47	2.43	7.9	81.6	112	50	69	945
9735495	4.71	2.42	7.3	82.5	111	48	46	1430
10815713	4.50	2.43	7.9	82.2	111	49	80	1564
10467559	5.07	2.42	6.7	85.4	111	47	41	1525
10544419	5.49	2.44	6.2	89.7	114	53	85	1512
9775821	6.32	2.453	5.1	90.2	116	55	75	1380
10508073	5.79	2.443	5.7	88.9	113	53	91	1491
9889096	5.87	2.454	5.6	88.9	115	56	94	1409
10594878	6.12	2.447	5.3	89.9	114	54	88	1507
10333419	6.19	2.436	5.2	89.5	112	51	85	1450
10032838	5.58	2.446	6.0	87.9	114	54	90	1449
9756511	6.05	2.452	5.4	89.6	114	56	83	1435
93056465	5.43	2.433	6.2	88	111	51	86	1342
10170994	5.29	2.433	6.5	88.6	112	50	79	1444
9552569	5.56	2.440	5.9	87	113	52	78	1368
10403199	6.52	2.427	4.9	90.9	110	49	86	1443
7971085	6.03	2.425	5.3	88.6	110	48	64	1105
10522022	5.17	2.418	6.5	85.7	109	46	73	1492
10463870	5.65	2.412	5.8	88.1	107	45	78	1486
10277598	5.18	2.407	6.5	86	106	44	88	1453
10288698	5.56	2.412	5.9	87	107	45	82	1452
9849226	5.36	2.408	6.2	86.5	107	44	77	1394
6762596	4.83	2.415	7.1	84.4	109	45	80	890
9817752	4.36	2.412	8.3	82.6	107	45	73	1488
9993798	5.10	2.400	6.6	85.5	105	42	81	1490
9955236	5.27	2.400	6.3	85.9	105	42	76	1492
9836656	5.38	2.423	6.2	86.9	109	48	82	1497
7035618	5.28	2.392	6.34	86.8	104	40	73	1060
10432795	5.26	2.381	6.2	84.7	102	37	81	1528
9787933	5.25	2.403	6.36	86.2	106	43	76	1471
9465628	5.27	2.415	6.3	85.7	108	46	82	1467

Table 6. Operation data for heat transfer.

f	Tube Pr	Tube Re	Gt	Shell Pr	Shell Re	Gs	LMTD	Q
0.0011	1.48	21626.83	602030	1.62	21123	757392	66.59	7420754
0.0011	1.47	23438.94	646368	1.62	22744	813172	67.64	7897551
0.0008	1.48	30387.8	845085	1.62	29534	1063172	67.38	10427147
0.0007	1.47	31538.99	361645	1.62	30543	1084005	67.95	10937005
0.0015	1.45	21187.03	541667	1.61	19793	681452	73.76	6782209
0.0010	1.46	29257.62	788462	1.62	27492	991935	72.36	9735495
0.0009	1.46	33515.82	878205	1.62	31264	1104839	73.89	10815713
0.0009	1.46	31068.49	836538	1.63	28929	1052419	73.99	10467559
0.0008	1.45	32702.56	853098	1.61	31140	1073253	70.74	10544419
0.0009	1.45	29913.23	777244	1.60	28687	977823	69.61	9775821
0.0008	1.46	32350.07	845085	1.61	30950	1063172	70.04	10508073
0.0010	1.44	32120.8	802885	1.60	30004	1010081	73.84	9889096
0.0008	1.45	32907.62	852030	1.60	31298	1071909	70.96	10594878
0.0010	1.44	32575.66	819979	1.61	29646	1031586	77.83	10333419
0.0010	1.44	32759.62	822115	1.60	30239	1034274	75.68	10032838
0.0010	1.44	32013.2	810897	1.60	29970	1020161	73.48	9756511
0.0011	1.45	29774.46	762821	1.61	27603	959677	75.02	93056465
0.0009	1.46	30972.04	813568	1.61	29213	1023522	72.19	10170994
0.0010	1.45	29631.19	772436	1.61	28037	971774	71.75	9552569
0.0009	1.45	31756.42	816774	1.62	29211	1027554	76.16	10403199
0.0013	1.45	24243.94	624466	1.62	22226	785618	76.65	7971085
0.0010	1.45	32383.05	836004	1.63	29227	1051747	79.01	10522022
0.0011	1.44	32829.65	835470	1.63	29028	1051075	82.29	10463870
0.0011	1.45	32212.47	823184	1.63	28628	1035618	81.54	10277598
0.0011	1.44	32131.64	819444	1.63	28575	1030914	81.41	10288698
0.0012	1.44	32125.61	785791	1.63	27224	988575	83.99	9849226
0.0018	1.43	21261.79	518162	1.62	18711	651882	83.17	6762596
0.0012	1.44	31827.77	817842	1.64	27804	1028898	84.03	9817752
0.0012	1.44	31967.45	817842	1.64	27325	1028898	87.40	9993798
0.0013	1.44	13937.11	816239	1.64	27185	1026882	88.28	9955236
0.0012	1.44	32069.81	821047	1.63	28309	1032930	82.41	9836656
0.0020	1.44	22709.1	577991	1.65	18965	727151	90.99	7035618
0.0013	1.44	32925.24	838141	1.66	27244	1054435	92.43	10432795
0.0013	1.44	31540.68	807158	1.64	27077	1015457	86.75	9787933
0.0013	1.43	31264.22	795406	1.64	26834	1000672	86.70	9465628
0.0012	1.44	31845.35	814637	1.63	27932	1024866	83.42	9780958
0.0012	1.44	31368.23	795940	1.63	27658	1001344	82.63	9517534
0.0013	1.43	32173.46	804487	1.63	27566	1012097	87.09	9509371
0.0014	1.44	29723.24	756410	1.64	25225	951613	88.49	9116431

f	Tube Pr	Tube Re	Gt	Shell Pr	Shell Re	Gs	LMTD	Q
0.0014	1.43	30476.46	760684	1.63	26214	956989	86,47	8893684
0.0015	1.42	33656.34	831197	1.65	27457	1045699	94.73	9748671
0.0014	1.43	33818.59	840812	1.64	28607	1057796	89.17	9601441
0.0013	1.43	32548.29	815171	1.62	28482	1025538	83.92	9280739
0.0014	1.43	34152.85	848825	1.65	28277	1067876	92.50	9834141

Table 7. Operation data for fouling factor.

After 211 training cycles the goal set was achieved, the level of error was satisfactory, and further cycles had no significant effect on error reduction. The network configuration with ten nodes in the hidden layer, a learning rate of 0.05 resulted in the fastest convergence and a low level of error during the training period. To be able to design a stable ANN, it would be more appropriate to conduct a parametric study by changing the number of neurons in the hidden layer in order to test the stability of the network. Fig. 7 shows the performance of the network with the numbers of neurons in the hidden layer (training step); in Fig. 8 the experimental values (actual value) of heat transfer rate (Q) are compared with the results predicted using the best ANN configuration.

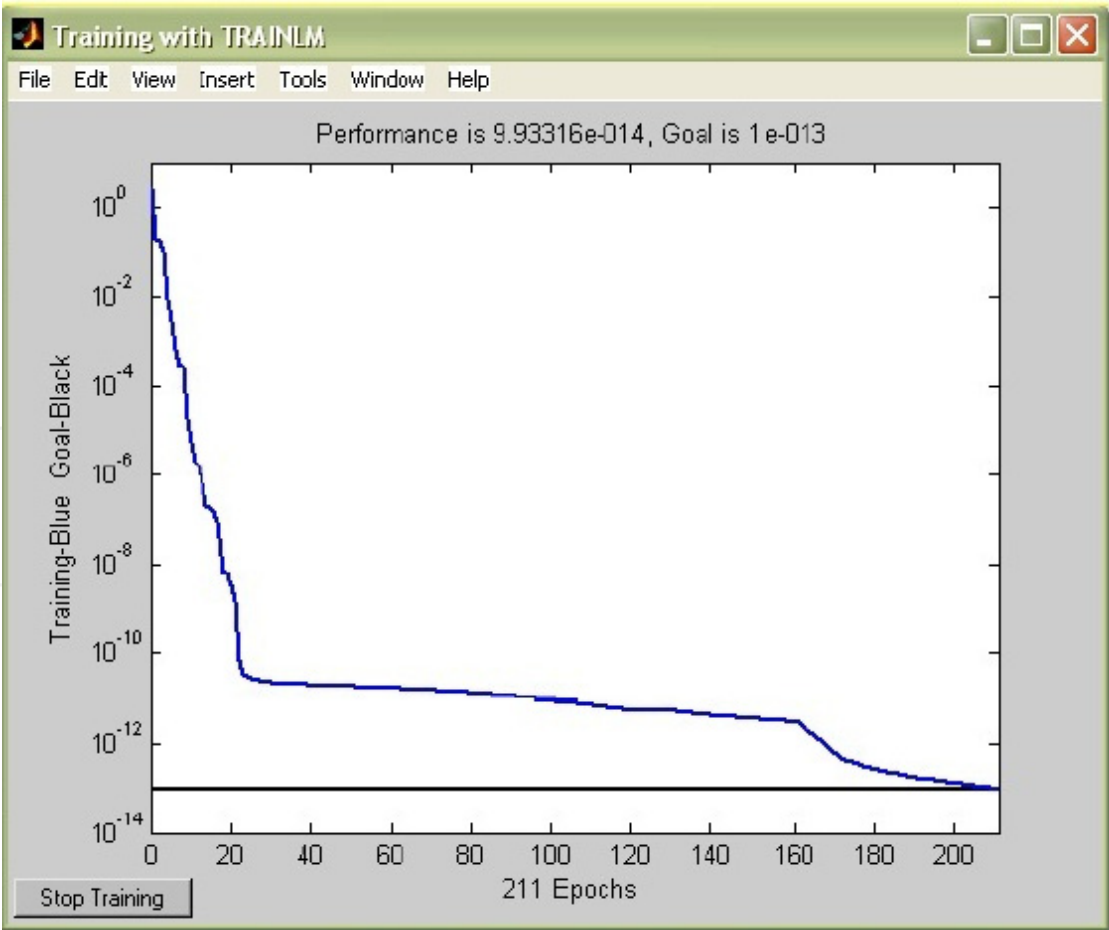


Figure 7. Training step (Heat transfer)

For fouling factor determination a network is designed with eight input parameters, the rate of heat transfer (Q) obtained from the neural network, log mean temperature difference LMTD, shell volumetric flow G_s , tube volumetric flow G_t , shell Reynolds number Re_s , shell Prandtl number Pr_s , tube Prandtl number Pr_t , tube Reynolds Number Re_t , and one output parameter, fouling factor (f), all physical properties are estimated at average values of the inlet and outlet temperatures for both sides of the heat exchanger. As before, every stage of an ANN problem requires a little trial and error to establish a suitable and stable network for the problem; so many networks are built by changing their parameters in order to reach a suitable result in these statements:

```
net_f=newff(minmax(input),[8,10,1],{'tansig','tansig','purelin'},'trainlm');
net_f.trainParam.show = 5;
net_f.trainParam.lr = 0.05;
net_f.trainParam.epochs = 1000;
net_f.trainParam.goal = 1e-13;
[net_f,tr]=train(net_f,input,f);
```

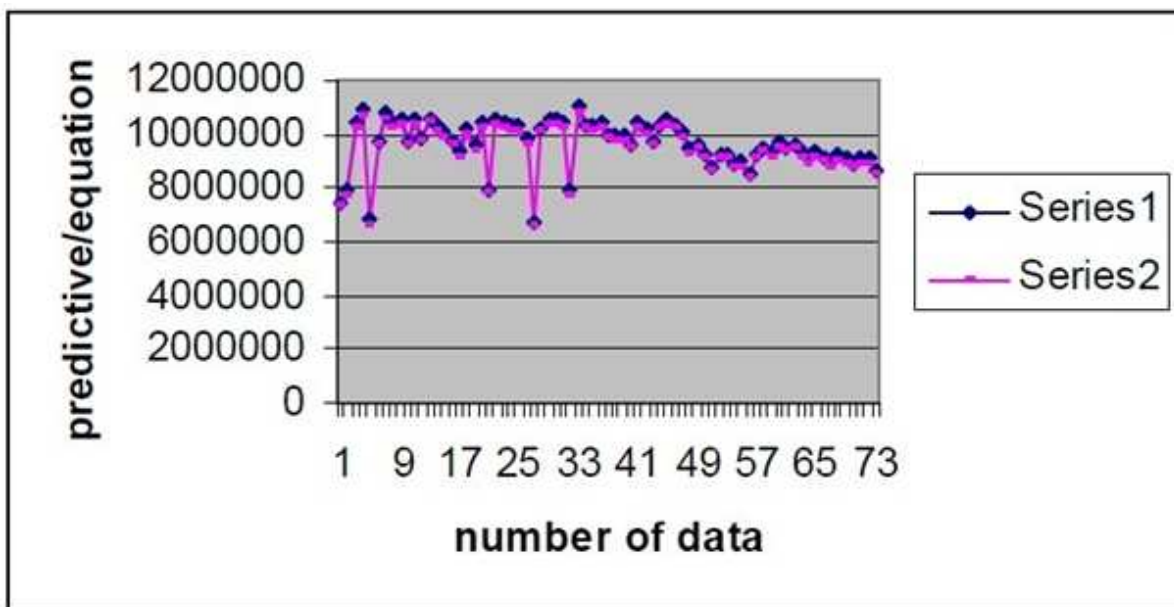


Figure 8. Comparison of experimental and predicted values of heat transfer rate (Q)

After 623 training cycles, the goal set was achieved, the level of error is satisfactory, and further cycles had no significant effect on error reduction. The network configuration with ten nodes in the hidden layer, a learning rate of 0.05 resulted in the fastest convergence and a low level of error during the training period. To be able to design a stable ANN, it would be more appropriate to conduct a parametric study by changing the number of neurons in the hidden layer in order to test the stability of the network. Fig. 9 shows the performance of the network with the numbers of neurons in the hidden layer (training step). In Fig. 10 the experimental values of fouling factor (f) are compared with the results predicted using the best ANN configuration.

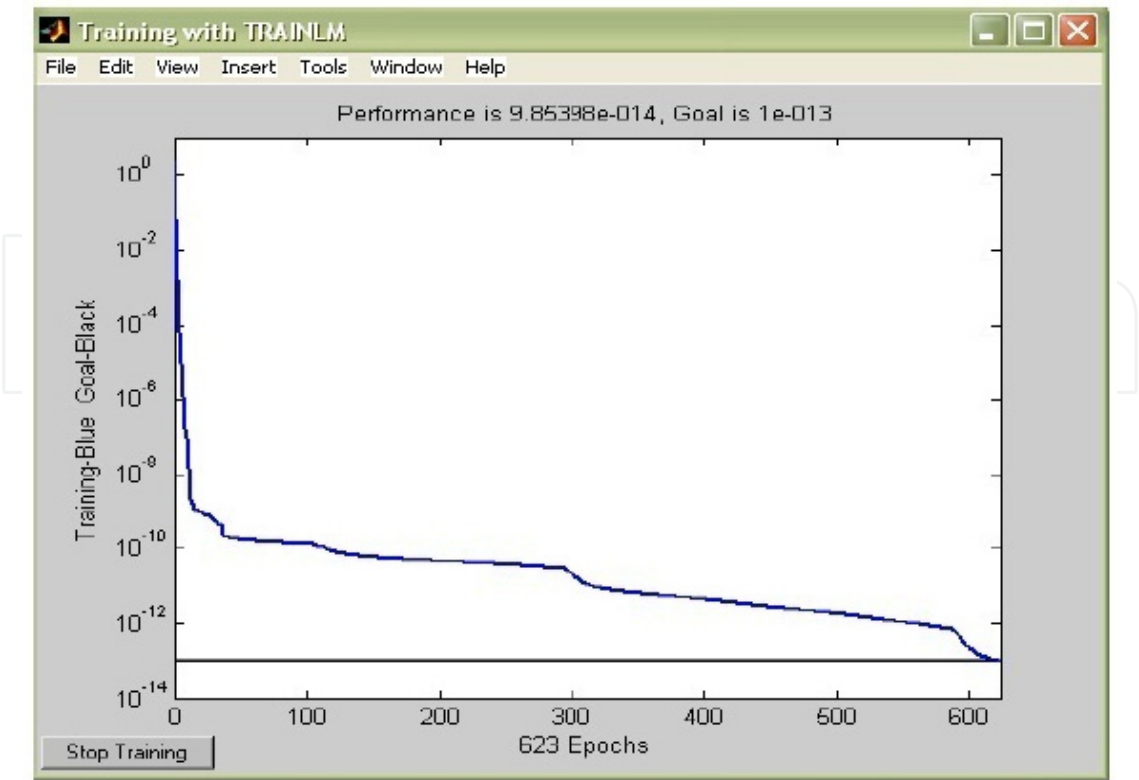


Figure 9. Training step (Fouling factor)

The results obtained and the comparisons made using both the ANN model and empirical correlations show conclusively that the proposed ANN approach could be used successfully to predict both the rate of heat transfer and fouling factor for heat exchangers. The accuracy and reliability of this approach for predicting the fouling factor can go a long way towards mitigating the detrimental effects of fouling in heat exchangers in particular and in other process equipment in which fouling may be of a major concern.

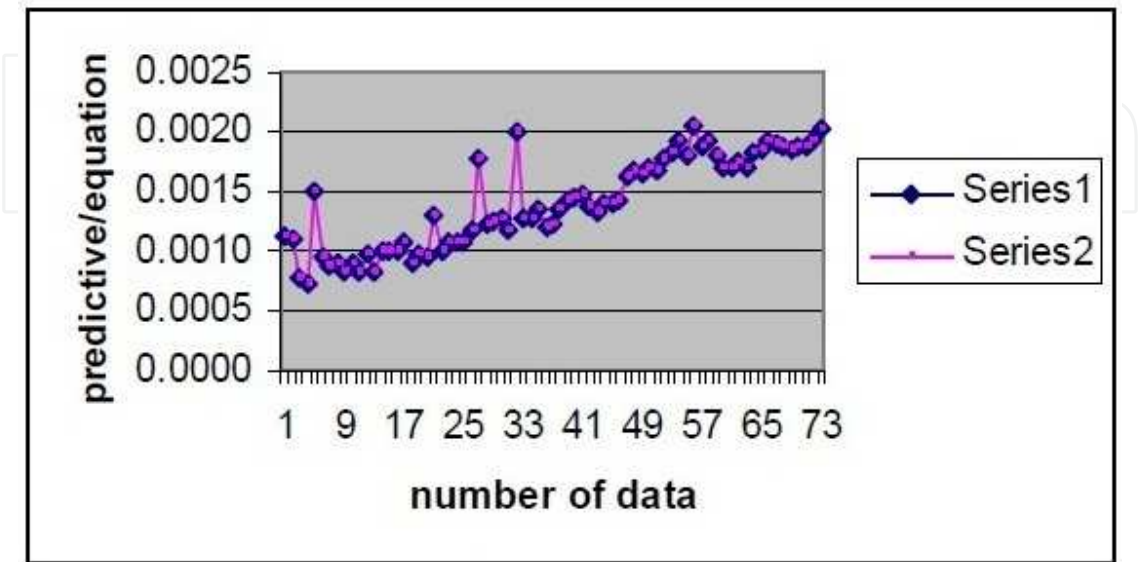


Figure 10. Comparison of experimental and predicted values of fouling factor (f)

Nomenclature

C_p	Specific heat, kJ/kg.°C
C_{p1}	Liquid specific heat, kJ/kg.°C
C_{p2}	Gas specific heat, kJ/kg.°C
D	Flow area per tube, m ²
D_e	Equivalent diameter, m
E	Activation energy, J/mol K
f	Fouling factor, hr.m ² .°C/kJ
G_s	Shell mass flow, kg/hr.m ²
G_t	Tube mass flow, kg/hr.m ²
h_i	Heat transfer coefficient inside tube, kJ/hr.m ² .°C
h_o	Heat transfer coefficient outside tube, kJ/hr.m ² .°C
k	Thermal conductivity, kJ/hr.m.°C
LMTD	Log mean temperature difference, °C
M	Gas molecular weight
m	Mass flow of gas and naphtha, kg/hr
m_1	Liquid mass flow, kg/hr
m_2	Gas mass flow, kg/hr
N	Hydrogen purity, %
n	Number of data
Pr	Prandtl number
Pr_s	Shell Prandtl number
Pr_t	Tube Prandtl number
Q	Total heat transfer, kJ/hr
q_1	Liquid heat transfer, kJ/hr
q_2	Gas heat transfer, kJ/hr
R	Gas constant, J/mol K
Re	Reynolds number
Re_s	Shell Reynolds number
Re_t	Tube Reynolds number
R_f	Fouling resistance, m ² K/kW
T_{1d}	Tube inlet temperature, °C
T_{2d}	Tube outlet temperature, °C
T_{film}	Fluid film temperature, K
t	Time, s
t_{1d}	Shell inlet temperature, °C
t_{2d}	Shell outlet temperature, °C
U_c	Clean overall coefficient, kJ/hr.m ² .°C
U_d	Dirt overall coefficient, kJ/hr.m ² .°C
W	Weight
x	Input
y	Output
θ	Threshold

μ	Viscosity, kg/m. hr
τ_w	Shear stress at the tube wall

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