International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

The Impact of Fouling on Heat Transfer, Pressure Drop, and the Effectiveness of Heat Exchangers

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ABSTRACT

A heat exchanger is a device used for effective heat transfer between two fluids (liquid or gas). Heat exchangers are utilized in various industries, including air conditioning, automotive, oil, gas, petrochemicals, and many others. Most heat exchangers in the industry are subject to fouling due to non-compliance with operational guidelines, incompatibility with chemical materials, or low-quality water in different regions. These deposits primarily form in the pipes or tubes of the exchangers and result in reduced heat transfer, consequently increasing production costs. To mitigate the effects of fouling, the performance of the exchanger must be continuously monitored and regularly cleaned. This process should be carried out at specified and appropriate intervals. Despite the significant costs that fouling imposes on facilities, very limited research has been conducted in this area. According to studies, 15% of the maintenance and operational costs of a facility can be attributed to boilers or heat exchangers, with half of these costs spent on descaling. Therefore, this research examines the fouling formation process, descaling methods, ways to prevent or reduce it, and the impact of fouling on heat transfer rates, mass transfer, and pressure drop.

Keywords: *Heat exchanger, fouling formation, descaling, industries, cost*

Introduction and Problem Statement

With the expansion of industries and the increasing need for optimizing thermal systems, heat exchangers have emerged as one of the most important industrial equipment. These devices play a crucial role in transferring thermal energy between two or more fluids without the need for direct mixing. The oil, gas, petrochemical, automotive, air conditioning, power generation, and many other industries utilize this equipment to optimize energy consumption and increase efficiency. However, the performance of heat exchangers is influenced by factors such as fouling, corrosion, pressure drop, and reduced heat transfer. Fouling is one of the major issues that reduces the efficiency of these devices and increases maintenance costs. Therefore, a precise understanding of the mechanisms of fouling formation and countermeasures is essential for improving the performance of heat exchangers and reducing operational costs. In recent decades, industrial development and increased energy consumption have highlighted the role of heat exchangers in optimizing energy use and reducing production costs. Despite technological advancements in the design and construction of heat exchangers, fouling remains one of the main challenges for these systems. Fouling in heat exchangers results from the accumulation of undesirable materials on heat transfer surfaces and can include mineral deposits, corrosion products, biological fouling, and organic layers. This phenomenon leads to a decrease in the heat transfer coefficient, an increase in pressure drop, a reduction in fluid flow rate, higher operational costs, and a decrease in the lifespan of exchangers. One study has shown that fouling can reduce the efficiency of heat exchangers by up to 30% and significantly increase maintenance and operational costs. Additionally, research has indicated that about 15% of maintenance costs in industrial facilities are related to heat exchangers, with half of these costs directly spent on descaling. Considering these challenges, this research aims to comprehensively examine the mechanisms of fouling formation, its effects on heat exchanger performance, various descaling methods, and preventive measures to provide solutions for increasing efficiency and reducing the operational costs of this equipment. Despite numerous studies conducted on fouling and the performance of heat exchangers, more precise models are still needed to predict fouling rates and optimize cleaning processes. This research explores innovative approaches such as analyzing the effects of different design methods and material properties on reducing fouling, examining new water treatment systems to reduce incoming impurities, utilizing modern technologies like electric and magnetic fields to reduce fouling formation, and modeling and numerical simulation of fouling in heat exchangers. This research is based on several main hypotheses:

1. Fouling in heat exchangers directly causes a reduction in thermal efficiency and an increase in pressure drop.
2. Different descaling methods (mechanical, chemical, electromagnetic) have varying effects on reducing deposits.
3. Selecting the appropriate material for heat transfer surfaces and optimizing the design of exchangers can reduce the rate of deposit formation.

4. Modeling and numerical simulation can be effective in predicting fouling rates and optimizing maintenance methods.

The results of this research can be applicable in various industrial and research fields, including increasing efficiency and reducing operational costs in the oil, gas, and petrochemical industries through optimizing descaling processes and preventing fouling. Improving the design of heat exchangers in power generation and automotive industries to extend the useful life of equipment. Providing new solutions to reduce maintenance costs and increase energy efficiency in thermal systems. This research addresses the problems caused by fouling in heat exchangers and presents innovative solutions to mitigate these challenges. The importance of this topic is evident in reducing maintenance costs, optimizing energy consumption, and enhancing the efficiency of industrial equipment. Given the direct impact of fouling on the performance of heat exchangers, the findings of this research can serve as a scientific and practical guide for various industries.

Types of Heat Exchangers

Today, heat exchangers play a vital and significant role in various industries around the world, such that the phenomenon of fouling in exchangers has destructive financial and technical impacts on industry owners. Heat exchangers are devices that facilitate the transfer of thermal energy between two or more fluids at different temperatures. They are used across a wide range of applications, including electricity generation, process industries, chemical, food, electronics, environmental engineering, waste heat recovery, manufacturing, air conditioning, and space applications. Heat exchangers are classified based on the following criteria. These devices are utilized in a wide array of industries, such as power plants, petrochemicals, air conditioning, and food processing. Heat exchangers can be categorized from various aspects: based on heat transfer method, heat transfer process, structure and physical shape, heat transfer mechanism, and arrangement of hot and cold flows.

1. Classification of Heat Exchangers Based on Heat Transfer and Recovery

• Heat Recovery Exchangers: These include exchangers where thermal energy is alternately transferred from hot fluid to cold fluid. Examples include:

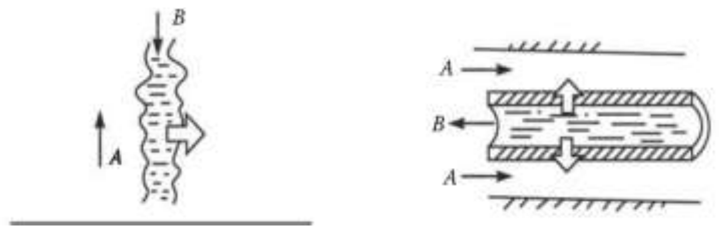
• Rotary heat exchangers (disk and cylindrical)

• Air preheaters in power plants

• Exchangers are used in steel furnaces and glass production.

• Heat Transfer Exchangers through Walls: In these exchangers, hot and cold fluids are separated by a wall, and heat is transferred from one fluid to another through conduction.

• Direct Contact Exchangers: In these types of exchangers, heat transfer occurs directly through contact between two fluids, such as cooling towers and tray condensers.



b) Direct Contact Heat Transfer — a) Wall Heat Transfer

Heat transfer through direct contact. — Heat transfer through walls.

Figure (1) Heat transfer in heat exchangers [8].

2. Classification Based on Transfer Process

• Indirect Contact Exchangers: These include tubular, plate, and finned surface exchangers where fluids do not mix.

• Direct Contact Exchangers: In these exchangers, fluids exchange heat while in direct contact with each other and are typically used for condensation and cooling towers.

3. Classification Based on Structure and Physical Shape

• Double Pipe Exchangers: These consist of an inner pipe located within a larger diameter pipe, with hot and cold flows running concentrically within them.

• Advantages: Simple design, suitable for high pressure.

• Disadvantages: Low efficiency, occupies a large space.

• Shell-and-Tube Exchangers: The most common type of heat exchangers in industries consisting of a series of tubes within a cylindrical shell. They come in various models, including fixed tubes, U-tubes, and floating tubes.

- Spiral Exchangers: In these exchangers, two metal plates are spirally twisted together with fluids passing between these plates.
  - Advantages: Resistant to clogging, suitable for viscous fluids.
  - Disadvantages: High construction costs.
- Plate Exchangers: These consist of thin metal plates that are corrugated and connected with gaskets or welds.
  - Advantages: High heat transfer efficiency, compact size.
  - Disadvantages: Suitable for low pressure and temperature.
  - Types: Gasketed plate exchangers, spiral exchangers, lamella exchangers.

Finned Surface Exchangers: These exchangers include fins on the main heat transfer surfaces designed to increase thermal efficiency on the gas side.

Types: Finned plate exchangers and finned tube exchangers.

4. Classification Based on Heat Transfer Mechanism

- Single-phase convection on both sides (e.g., in economizers and radiators).
- Single-phase convection on one side and two-phase convection on the other (e.g., in boilers and condensers).
- Two-phase convection on both sides (e.g., in steam generators of power plants).

5. Classification Based on Fluid Flow Arrangement

- Co-current Flow: In this type of exchangers, fluids flow in the same direction, resulting in a uniform temperature decrease.
- Counter-current Flow: Has higher thermal efficiency because there is a greater temperature difference between the fluids.
- Cross-flow: One of the fluids passes vertically through the flow path of the other fluid, such as in radiators and shell-and-tube exchangers with baffles.

Heat exchangers are classified based on various criteria, each having its advantages and disadvantages. The appropriate selection of heat exchanger type depends on factors such as fluid type, pressure, temperature, industrial application, and economic constraints. In industry, shell-and-tube exchangers are most commonly used due to their high efficiency and versatility; however, in cases where high efficiency and less space are required, plate exchangers are considered a better choice.

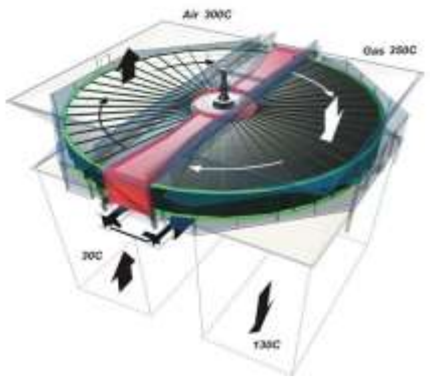


Figure (2) Vertical axis heat exchanger [1]

Figure (3) Two-tube heat exchanger [2]

Figure (4) Schematic of finned plate heat exchanger [4]

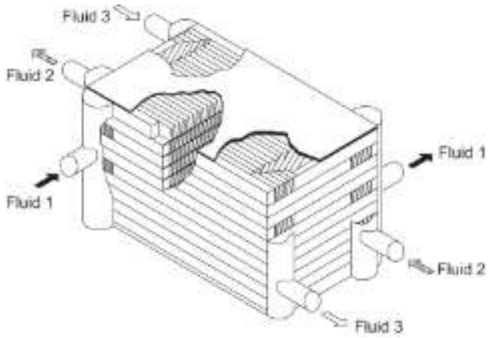


Figure (5) Finned tube heat exchanger [6]

Fouling Formation in Heat Exchangers

The formation of deposits from materials, undesirably on heat transfer surfaces during heating and cooling processes, occurs across all industries and most types of heat exchangers, with varying effects from degradation of heat transfer to flow resistance and pressure drop. The accumulation of deposits creates a type of insulation on heat transfer surfaces and reduces their efficiency. A particle or droplet settles in a fluid if its density is greater than that of the fluid in which it is suspended. Settling is a process by which solid materials are removed from water by sedimentation. However, various factors, including physical and environmental conditions such as particle shape and size, density and concentration, fluid viscosity, water temperature, particle load, soluble materials in water, environmental effects, and characteristics of the heat exchanger, can influence the settling process and the rate of fouling in heat exchangers.

Fouling in heat exchangers refers to the accumulation of undesirable materials on heat transfer surfaces. Various variables, such as water pH, product viscosity, surface roughness of components, and many others, play a role in the formation of fouling in heat exchangers. The chemical nature of the feed can be a significant factor that largely impacts the rate of fouling. In dairy factories, fats, sugars, and proteins contribute to fouling. In food and beverage applications, suspended particles can clump together and cause blockages; in pharmaceutical industries, cosmetic and pharmaceutical particles generated during processing can adhere and accumulate. These materials can include crystals, sand, gravel, polymers, mineral salts, corrosion products, and biological growths. The fouling process reduces the performance of heat exchangers and leads to increased pressure drops and decreased heat transfer rates. This issue can result in the degradation of heat exchangers through corrosion and blockage of fluid flow paths. Deposits can be categorized based on the type of formation process:

• Crystallization Fouling: This type of fouling includes the precipitation of soluble salts on the heat transfer surface, typically occurring due to increased temperature and reduced solubility. The salts involved in this process include calcium carbonate, calcium sulfate, and calcium chloride.

Factors affecting crystallization fouling include: increased temperature leading to solution saturation and precipitation of soluble salts; reduced fluid velocity facilitating particle settling; and increased concentration of dissolved minerals in water.

• Corrosion Fouling: Corrosion occurs when the metallic surface of the heat exchanger reacts chemically with a corrosive fluid, forming oxide layers or other corrosion products on the surface. This type of fouling is typically observed in two forms:

1. Corrosion caused by the liquid environment occurs due to the reaction of metal with compounds present in water.

2. Galvanic corrosion occurs when two metals with different electrochemical potentials come into contact with each other.

Deposit resulting from chemical reaction: This type of deposit forms due to chemical reactions between the process fluid and the surface of the heat exchanger. An example of this type of deposit is coke accumulation in petrochemical industries, which typically occurs at high temperatures. If not controlled, this type of deposit can lead to degradation and blockage of flow paths in the exchanger.

Biological deposit (biofilm): Biological deposits form as a thin, uneven, and adhesive layer on the surfaces of heat exchangers, resulting from the growth and accumulation of microorganisms. This type of deposit usually reaches its maximum growth at temperatures between 20 to 50 degrees Celsius and can also lead to sub-surface corrosion.

Deposit caused by freezing: When the fluid passing through the heat exchanger is cooled below its freezing point, ice forms and acts as a type of deposit on the heat transfer surface. This type of deposit occurs in cooling systems such as chillers and exchangers used in refrigeration processes.

Microbial deposits caused by bacteria, algae, and fungi

Microbial deposits from microorganisms (bacteria, algae, and fungi) and their by-products are another significant reason for fouling in heat exchangers. In contact with heat transfer surfaces, these organisms can attach and grow, consequently minimizing flow and heat transfer to an absolute minimum and sometimes completely blocking fluid passages. Such organisms may also trap sludge or other suspended solids, leading to deposit-induced corrosion.

Impact of Fouling on Heat Exchanger Performance

Fouling in heat exchangers has detrimental effects on their performance, including:

• Reduction in heat transfer coefficient: Deposits have a lower thermal conductivity than metals. Therefore, the formation of a deposit layer on the exchanger surface increases thermal resistance and reduces the heat transfer rate. In a numerical example, the overall heat transfer coefficient in a clean exchanger is 1232.6, but after deposit formation, it drops to 862, equivalent to a 43.2% reduction in efficiency.

• Increase in pressure drop: Deposits reduce the cross-sectional area of the fluid flow path, resulting in an increased pressure drop in the exchanger. This leads to higher energy consumption for pumps and reduced overall system efficiency.

• Increase in operational costs: According to research, 15% of the maintenance costs in industrial facilities are related to heat exchangers, half of which is spent on descaling. Consequently, optimizing design and reducing fouling can significantly impact operational cost reductions.

Methods for Preventing and Controlling Fouling in Heat Exchangers

The best method for reducing fouling is to prevent its occurrence in the first place by using a heat exchanger that is appropriately sized for the application and provides adequate velocity, surface area, and temperature distribution. While 100% prevention of fouling is not achievable, implementing the following measures can extend maintenance intervals: Appropriate selection and design of shell-and-tube heat exchangers can significantly reduce the amount of fouling on heat exchange surfaces. The formation of fouling affects both the overall heat transfer coefficient (U) and the pressure drop in the heat exchanger. As fouling forms, the free flow cross-section for fluid in the tube or shell decreases, leading to increased flow velocity at constant flow rates, which in turn increases pressure drop across the heat exchanger. To prevent fouling formation, several methods have been proposed:

• Optimal design of heat exchangers: Use of anti-corrosion and anti-fouling materials for constructing heat exchangers. Increasing fluid velocity to prevent particle settling. Employing designs with minimal dead zones that reduce the likelihood of deposit accumulation.

• Fluid quality modification: Use of water treatment systems to remove suspended particles and reduce water hardness. Adjusting pH and chemically controlling water to reduce the likelihood of crystallization fouling and corrosion.

• Use of electric and magnetic fields: Applying oscillating electric fields causes dissolved ions in water to crystallize within the fluid rather than depositing on surfaces, thereby reducing fouling rates. Fouling in heat exchangers poses a fundamental challenge across various industries, leading to decreased efficiency, increased operational costs, and reduced equipment lifespan. Various methods, including optimal design, fluid quality control, and the use of new technologies such as electric and magnetic fields, can be effective in reducing fouling. Optimizing maintenance processes and periodic cleaning of exchangers also play a crucial role in controlling this issue.

Importance of Descaling and Its Impact on Industries

Regular and effective descaling of heat exchangers has a significant impact on various industries. By reducing the fouling factor and increasing the heat transfer coefficient, the following benefits can be achieved:

• Reduced energy costs: With increased efficiency of exchangers, energy consumption decreases.

• Increased equipment lifespan: By preventing corrosion and damage to exchangers, their lifespan is extended.

• Lower maintenance costs: By avoiding sudden failures, maintenance costs are reduced.

• Improved overall system performance: With enhanced efficiency of exchangers, the overall performance of the system improves.

Problems Caused by Fouling in Heat Exchangers

Fouling in heat exchangers is a fundamental problem that leads to decreased thermal efficiency, increased pressure drop, and reduced heat and mass transfer. This phenomenon can cause equipment corrosion and ultimately lead to their failure. In many industries, including oil, gas, petrochemicals, food processing, marine industries, and HVAC units, fouling has become a serious challenge.

Effects of Fouling Formation in Heat Exchangers

• Increased pressure drop: One of the most significant negative impacts of fouling in heat exchangers is the increase in pressure drop in fluid flow paths. Pressure drop can occur due to:

• Changes in the internal surface roughness of the exchanger,

• Reduction in flow cross-section,

• Increased friction between the fluid and the walls of the exchanger.

Different models of pressure drop due to fouling include:

1. Model A - Reduction in flow passage: When layers of fouling reduce the internal diameter of tubes.

2. Model B - Rough fouling: The presence of rough deposits that increase flow turbulence and pressure drop.

3. Model C - Pipe blockage: When the accumulation of fouling completely obstructs the fluid passage.

• Reduced heat transfer: Deposits have low thermal conductivity; therefore, by creating an additional layer on the exchanger surface, thermal resistance increases and heat transfer rate decreases. In one study, it was found that the overall heat transfer coefficient in a clean state is 1232.6, while in a fouled state, it drops to 862, indicating a 43.2% reduction in efficiency.

• Increased operational and maintenance costs: According to research, about 15% of maintenance costs in industrial facilities are related to heat exchangers, half of which is spent on descaling. In countries like the United States, the damage caused by fouling in mechanical equipment is estimated at around $18 billion annually. Some costs associated with fouling include:

• Increased energy consumption to compensate for reduced heat transfer.

• Early replacement of equipment due to corrosion-induced wear and pipe blockage.

• High maintenance costs for periodic descaling.

Factors Contributing to Increased Fouling

• Type of fluid and impurities: Some water salts, such as calcium carbonate, magnesium sulfate, and silicate compounds, have a greater tendency to form deposits. Among these salts, calcium carbonate fouling is more common and predictable than calcium sulfate.

• Operating conditions of the exchanger: Certain conditions, such as temperature, fluid velocity, and flow turbulence, affect the rate of fouling formation:

• Increased temperature reduces the solubility of certain substances and accelerates fouling.

• Reduced fluid velocity: Increases the likelihood of suspended particles settling on exchanger surfaces.

Composition of exchanger materials

Some metals have greater resistance to fouling and corrosion. For example, stainless steel has lower fouling rates compared to cast iron. One way to prevent fouling formation is through the proper design of heat exchangers. Important measures in this regard include:

• Using anti-corrosion materials to reduce fouling formation.

• Designing optimal geometries to reduce areas prone to fouling.

• Increasing fluid velocity to prevent sedimentation of suspended particles.

• Using water treatment methods: The quality of the incoming fluid plays a crucial role in the extent of fouling. Some treatment solutions include:

• Chemical or mechanical washing to remove mineral salts.

• Using electronic and magnetic water softeners to reduce mineral deposits.

• Controlling operating conditions: Increasing fluid flow velocity to prevent sedimentation of deposits. Controlling temperature to avoid crystallization and reactive fouling. Reducing shear stress by alternating flow direction can help dislodge deposits. Fouling is one of the fundamental problems in heat exchangers that leads to reduced efficiency, increased pressure drop, higher operational costs, and corrosion. By optimizing design, appropriately treating the incoming fluid, controlling operating conditions, and using modern methods such as electromagnetic fields, the negative effects of fouling can be minimized. The optimal cleaning intervals are illustrated in the figure below. This chart is based on experimental results obtained from cleaning costs at different times and the outcomes of various processes.

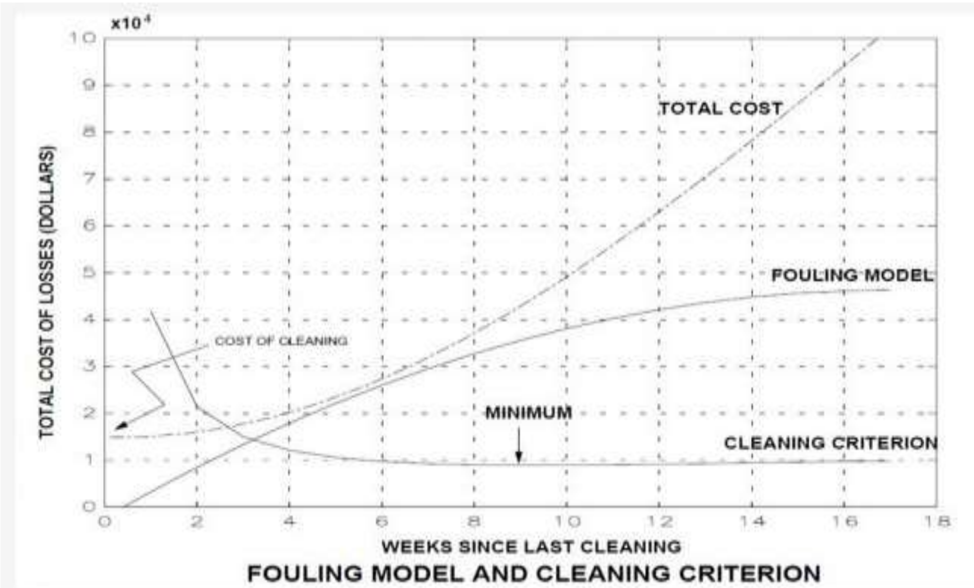


Figure (7): Chart of cleaning costs for heat exchangers and the impact of fouling over time [27].

Descaling in Heat Exchangers

Descaling in heat exchangers is a process aimed at removing the fouling layers formed due to fluid flow over heat transfer surfaces. These deposits result in reduced thermal efficiency, increased pressure drop, higher operational costs, and decreased equipment lifespan. Various methods for descaling heat exchangers exist, which are selected based on the type of fouling, operating conditions, and the level of contamination.

Methods for Reducing Fouling through Proper Design

One of the key methods for reducing the need for descaling is the optimal design of heat exchangers. Some design strategies include:

• Using heat exchangers with twisted tube designs that increase fluid turbulence and reduce the likelihood of fouling formation.

• Heat exchangers with baffles that prevent the creation of low-flow areas prone to fouling.

• Heat exchangers with helical baffles that help improve fluid flow and reduce fouling.

Methods for Reducing Fouling During Operation

These methods include actions taken during the operation of the heat exchanger to reduce fouling:

• Feed treatment or washing: Removing impurities from the fluid before it enters the heat exchanger to prevent fouling formation.

• Dilution or mixing of feed: Adjusting the composition of the incoming fluid to reduce fouling.

• Thermal shock: Sudden temperature increases to remove solid deposits from surfaces.

• Alternating changes in flow direction or velocity: Increasing turbulence to prevent sedimentation of fouling.

• Gas agitation: Injecting gas to reduce the likelihood of solid fouling formation.

Descaling Methods

Mechanical Methods: Mechanical descaling involves using physical tools to remove deposits from the surface of the heat exchanger:

1. Water jet: Using high-pressure water to clean the internal surfaces of the exchanger tubes.

2. Passing cleaning devices through the tubes: Using foam balls, metal brushes, and mechanical cleaning devices.

3. Using an electric field: Employing oscillating electric fields to break down deposit structures and prevent their formation.

4. Using turbulence-enhancing heat transfer devices: Equipment that increases fluid turbulence and reduces the likelihood of fouling.

5. Ultrasonic descaling: Using high-frequency sound waves to break down deposit structures and detach them from the exchanger surface.

Chemical Descaling Methods

For chemical cleaning of equipment, it is first necessary to identify the type of deposits. Depending on the type of fouling, various chemicals are used. In acid-cleaning methods, corrosion inhibitors are employed to mitigate adverse effects on metal surfaces. The acid used in these substances may be mineral, organic, or a mixture of both, depending on the nature of the deposits and system metallurgy. Table 1 lists the acids most commonly used in chemical cleaning. Each deposit should be removed based on its chemical nature and relevant physical properties. Most descaling solutions are based on organic and mineral acids. Among mineral acids, sulfuric acid plays a significant role, while citric acid and acetic acid are commonly used among organic acids.

Although chemical cleaning can be employed for descaling exchangers, efforts are always made to use minimal amounts of chemicals that are hazardous to the environment. The main issues with chemical cleaning methods are high costs and environmental impacts from waste materials. Additionally, this method does not completely separate deposits, and mechanical complementary methods are required for thorough cleaning. Furthermore, to enhance exchanger efficiency when facing fouling issues, experimental data should be collected for exchanger operation. The use of this method can also lead to damage to heat exchanger bodies, risks associated with handling chemicals, and high consumption of water and energy.

The most extensive solution for reducing fouling during the operation of heat exchangers is the use of chemical agents or inhibitors, which are specifically designed for heat exchangers with complex geometries where other cleaning methods may not be feasible.

Commercial anti-foulants are typically multifunctional, making them more adaptable and effective, as they can be designed to combat various substances that may be present in any given system. For example, in crude oil, raw materials such as oxygen, metals, salts, and asphaltenes can lead to different forms of fouling formation. Anti-foulants are designed to prevent the deposition on equipment surfaces but are generally not very successful in removing deposits that have already formed. Therefore, the addition of anti-foulants should begin immediately after the equipment has been cleaned. The method and amount of anti-foulant used depend heavily on the fouling mechanism and the expected severity of the deposits. Thus, information regarding the predominant fouling mechanism and the impact of operational variables such as dominant raw materials, temperature, and velocity is very important. Chemical methods for reducing fouling during operation can be useful; however, they may contain chemical agents that are potentially harmful to the environment, such as chlorine, hypochlorite, polyphosphates, and coagulants. The use of many of these chemicals should be reduced due to the implementation of environmental regulations and ultimately phased out completely. Furthermore, to prevent corrosion or degradation, the chemical compatibility of agents with the metallurgy of the equipment should also be examined.

Table (1): Classification of chemical inhibitors for various fouling mechanisms [57].

Inhibiting Agent	fouling agent	Deposition Mechanism
Ion Exchange	Ca^{2+}, Mg^{2+}	Crystallization, Sedimentation
pH Control	$CaCO_3$	
Scale Inhibitor (such as Ethylenediaminetetraacetic Acid [EDTA])	$CaSO_4$	

Surface Adsorption Agents (e.g., Polyphosphates)	Soft and Hard Scales	
Crystallization Inhibitors (e.g., Polycarboxylic Acid)	Soft and Hard Scales	
Surface-Active Agents or Dispersants	Fine Particulate Matter	Particulate
Antioxidants	Oxygen (Polymerization)	Chemical Reaction
Metal Neutralizers	Metals (Reaction Catalyst)	
Dispersants	Insoluble Hydrocarbon Particles	
Oxidizers (Chlorine, Biocide)	Micro- and Macro-organisms	Biofouling

When defects or a reduction in heat transfer occur in exchangers after taking them out of service, necessary chemical tests must be conducted on available samples of deposits according to process conditions to identify the type of deposits and whether they are due to process fluid or corrosion. Once the type of deposit is determined, the exchangers are cleaned using specific equipment. This equipment typically consists of several tanks with special corrosion-resistant coatings filled with suitable chemicals for the type of cleaning process and interconnected by pipes. To establish flow, pumps are provided that connect to the exchanger with flexible hoses and facilitate the circulation of cleaning agents. Various materials and solutions, such as alkalis, acids, corrosion inhibitors, wetting agents, and organic solvents, are used in industrial chemical cleaning. The selection of solvent type is based on the metal and alloy composition, solubility of the deposit, and economic cost. Some chemical solvents and their applications are mentioned below [65]:

• Boil-out solutions: Used to remove organic contaminants from exchangers and eliminate hard deposits, especially when deposits contain lubricating oils, grease, and paint for various reasons. Examples include sodium hydroxide and sodium bicarbonate solutions, a mixture of trisodium phosphate and disodium phosphate, and sodium metasilicate.

• Alkaline permanganate: Used for cleaning polymeric and asphaltic deposits. However, it should be noted that this solution has a corrosive effect on steel.

• Acid solutions: These solutions are the most suitable for dissolving mineral oxides and weak acid salts. A very important consideration when using acids is their high corrosiveness on metals, which minimizes their application in cleaning exchangers. In some cases, it is recommended to use weak organic acids that have lower hydrogen ion activity than mineral acids, such as acetic acid, oxalic acid, and citric acid.

• Alkaline solutions: Used for neutralizing residual acids resulting from chemical cleaning and aiding in passivating the cleaned metal surface. They should not be used when aluminum, lead, or zinc metals are involved.

• Ammonium bifluoride (NH4HF4): By adding this substance in small quantities to hydrochloric acid, silicate deposits caused by water such as akmite, analcite, and magnesium ortho-silicate hydrate can be removed from the tubes of the exchanger.

• Sodium Gluconate: This solution can simultaneously remove oil and rust, and it has been successfully tested in several cases. In most instances, washing with chemical solvents brings along hazardous waste, which poses significant risks for handling and disposal from the washing site and can also have detrimental environmental effects. Additionally, this method does not completely separate deposits, requiring complementary mechanical methods to finish cleaning and remove any remaining deposits.

Mechanical methods for reducing fouling, if applicable, may have advantages over chemical methods since chemical methods often involve substances that are difficult to use and control. The applicability of mechanical methods is usually determined by the type of fouled heat exchanger, the intensity and rate of fouling growth, operational conditions, and cleaning costs. The use of mechanical methods for reducing fouling in-line can lead to a significant reduction in downtime during maintenance, prevention of the use of chemical anti-foulants, and more optimal unit performance [66].

One of the major problems in the production and transportation of oil and gas is the formation of deposits in the production system. Various methods exist for preventing and treating this issue. The method used in the operations of the National Iranian Oil Company for removing deposits is primarily the injection of chemicals using a mobile tubing unit, which is only capable of removing deposits and cannot prevent their formation. Furthermore, the frequent need for chemical injections at approximately one-year intervals leads to increased costs and repeated production stoppages. Therefore, there is a need to explore and implement innovative methods that can prevent deposit formation [7].

Methods for Preventing Deposit Formation

In addition to descaling methods, actions can also be taken to reduce the likelihood of deposit formation in heat exchangers:

1. Use of self-cleaning and anti-fouling exchangers: Equipment that allows for automatic cleaning of surfaces.

2. Use of anti-fouling surfaces: Coatings made with nanoparticles that prevent sediment particles from adhering to the surface of the exchanger.

3. Use of electromagnetic anti-fouling technology: Creating a magnetic field that prevents sediment deposition.

4. Use of nanofibers: Employing coatings with a nanofiber structure to reduce fouling.

5. Improvement of water quality: Utilizing filters, softeners, and reverse osmosis systems to reduce dissolved salts in water.

Descaling is one of the most important processes for maintaining and optimizing the performance of heat exchangers. Various methods exist for removing deposits, including mechanical methods (such as water jetting and ultrasonic cleaning), chemical methods (such as acid cleaning), and fouling reduction methods (such as feed treatment and electromagnetic fields). The choice of an appropriate method depends on the type of deposit, operational conditions, and economic constraints.

Improvement of Water Quality

The most important method for preventing deposit formation is improving the quality of water used in the system. This method is carried out through various means such as sedimentation, filtration, degassing, oil removal, using underwater washing methods, and softening the water used. Physical methods for improving water quality in processing equipment and devices such as those in the oil, gas, and petrochemical industries are very important, which will be briefly explained for each. The first step in clarifying water is sedimentation. In this method, sedimentation tanks are used to reduce the concentration of sludge, silt, and suspended materials in water or to pass water slowly through large tanks to clarify it. This method is more suitable for turbid waters.

Generally, filtration should be performed after sedimentation to remove any remaining suspended particles. Industrial filters consist of layers of fine-grained sand that become coarser from top to bottom. Water enters from the top and exits from the bottom. Water can be filtered using its weight or under pressure; however, in industry, pressure filters are more commonly used. Typically, filter materials are sand made from silica with a purity degree of 98%. The grain size ranges from 0.35 to 1 millimeter. This small size facilitates the separation of all suspended materials at the filter surface; additionally, fine biological layers may form at the interface between water and sand. The bottoms of filters are usually made from plastic materials, and in each square meter, 60 to 90 plastic tubes (nozzles) are placed for the discharge of clarified water. Their ends are positioned inside the clarified water below the filter. The majority of corrosive gases dissolved in water, such as carbon dioxide and oxygen, can be removed through aeration. Open heaters are suitable for aerating water to produce low-pressure steam. However, if steam with a pressure higher than 27 bar is required, typically, spray-type aerators are used. Aeration occurs through two methods: physical and chemical. In the physical method, the removal of oxygen and carbon dioxide can be achieved by heating the water. This process reduces the concentration of oxygen and carbon dioxide in the liquid phase, causing the dissolved gases in the water to move from the liquid phase to the gas phase. Physical aeration is the most economical method of aeration. This process occurs at the boiling point of water and under the internal pressure of the aerator. Aerators can operate under pressure or in a vacuum. In the chemical aeration method, materials such as sodium sulfite or hydrazine are used to remove oxygen gas, producing compounds like sodium sulfate or nitrogen and water. Water softening refers to the reduction of calcium and magnesium ions, which is done through chemical precipitation and the use of ion exchange resins. Other methods to prevent scaling in thermal systems include acid injection, optimization with side flows, and using chemical inhibitors. Ion exchange methods are based on the reversible exchange of ions between a solution and a solid phase. The solid phase in water is insoluble and has groups in the form of acidic or basic bases. These bases are the main agents of ion exchange. Ion exchange resins have an organic origin and are composed of high molecular weight polymers. Ion exchangers include two groups: anionic and cationic [18].

Conclusion

Based on the collection of information obtained, it can be said that scaling and deposit formation in heat exchangers is not a one-dimensional or one-faceted issue; rather, it is a multidimensional and very important topic that, if neglected or given insufficient attention, can have a direct impact on all processes of design, operation, and maintenance. The correct selection of heat exchanger types will directly affect performance improvement, efficiency, increased heat transfer coefficient, and reduced pressure drop. The formation of deposits in heat exchangers leads to a decrease in heat transfer coefficient, an increase in pressure drop, and reduced performance, as well as increased costs for maintenance and production. Proper use of mechanical and chemical descaling methods, along with preventive measures against scaling in exchangers, will improve the performance of heat exchangers and reduce deposits within them. The proper design of heat exchangers, as well as the correct design of baffles, tubes, shells, and other components of heat exchangers, can be very effective in reducing and preventing scaling. Based on research findings, to prevent and reduce the effects of scaling on heat exchangers and their performance in various industries, the following points should be seriously considered. Since shell-and-tube exchangers are among the essential components of a process and their operating conditions significantly impact the economic status of a facility, special measures should be taken when selecting a suitable method for cleaning to enhance the efficiency and productivity of the exchangers. The chosen method from mechanical and chemical options should not only be effective but also cause minimal damage to the exchanger to reduce maintenance costs. Although chemical cleaning can be used for descaling exchangers, efforts should always be made to use minimal amounts of chemicals and hazardous substances. The main problem with chemical cleaning is the high cost and environmental effects of waste materials. Additionally, this method does not completely separate deposits, requiring complementary mechanical methods to complete the cleaning process. Furthermore, to increase the efficiency of exchangers when facing scaling issues, experimental data should be collected for exchanger operation so that, through analysis, the appropriate time for cleaning and the suitable method for it can be determined.

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