A Review on Crude Oil Fouling and Mitigation Methods in Pre-heat Trains of Iranian Oil Refineries

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ABSTRACT

Crude oil fouling of the equipment surfaces is a troublesome issue which leads to operating difficulties, economic penalties, increased environmental impacts, health and safety hazards in petroleum industry. With a rough estimation, a minimum cost of equal to 4 million barrels of oil/year is required to be invested to offset the costs of crude oil fouling in Pre-heat Trains of Iranian oil refineries. Considering the price of each oil barrel equal to 50$, crude oil fouling cost is predicted to be 200 million$/year. Additionally, burning extra fuel leads to the emission of a great portion of CO2, which is associated with strikingly negative environmental and economic impacts. Hence, crude oil fouling mitigation methods such as controlling the operating conditions, utilizing additives, and surface modification techniques have received a great deal of attention. Surface modification in terms of modification of its geometry and texture and/or surface energy can help mitigate fouling to a large extent.

1. Introduction

Fouling is among the foremost industrial problems which may lead to a lot of issues in upstream sector (e.g. reservoirs and production wells), as well as downstream sector (e.g. transport lines and refineries). In refineries, fouling starts with sludge formation in crude storage tanks. This heavy crude sludge build-up can be equal to several feets (i.e. approximately 100,000 barrels), and more, of debris, depending on the cleaning cycles. Fouling continues in the following sections such as desalter, pre-heat trains, furnace and distillation columns. The deposit material can be organic or hydrocarbons (such as Asphaltene and wax), inorganic, corrosion products, particulates, microorganisms, etc. The importance of crude oil fouling in heat exchangers, reactors, and catalysts in petroleum industry has attracted increasing attention to this phenomenon. On the other hand, studies have revealed that the API of petroleum reserves will decrease from 32.75 to 32.2 and their sulphur content will increase from 1.1 to 1.35 in a time interval between 1995 and 2020. Considering the aforementioned information, the probability of crude oil fouling increases as crude oil will become heavier in the upcoming years.

Fouling on equipment surfaces can result in damages to the equipments and process. For instance, in distillation units of refineries, removal of sludge from crude storage tanks is associated with the significant use of manpower and equipment, huge downtime, disposal of produced waste, environmental and safety concerns, and exceptionally high utility consumption. In addition, Pre-Heat Trains (PHTs), which are employed to reduce the energy consumption by pre-heating the crude oil feed using hot distillation products (Figure 1), are highly prone to crude oil fouling. A schematic of fouling in shell and tube sections of these heat exchangers is presented in Figure 2. Fouling in PHTs leads to 1) operational difficulties due to reduced thermal efficiency and increased pressure drop along the heat exchanger, 2) economic penalties as a result of initial investment, operational cost, and reduced production, 3) environmental issues as a consequence of emission of greenhouse gases and the removal of pollutants, as well as 4) health and safety concerns [1]. Overall, the costs imposed by fouling in PHTs on the petroleum industry is equal to 0.25% of the Grass Domestic Product (GDP) of the industrial countries [2, 3], which consists of overdesign, treatment of process fluid, maintenance, shut down, and cleaning [2].

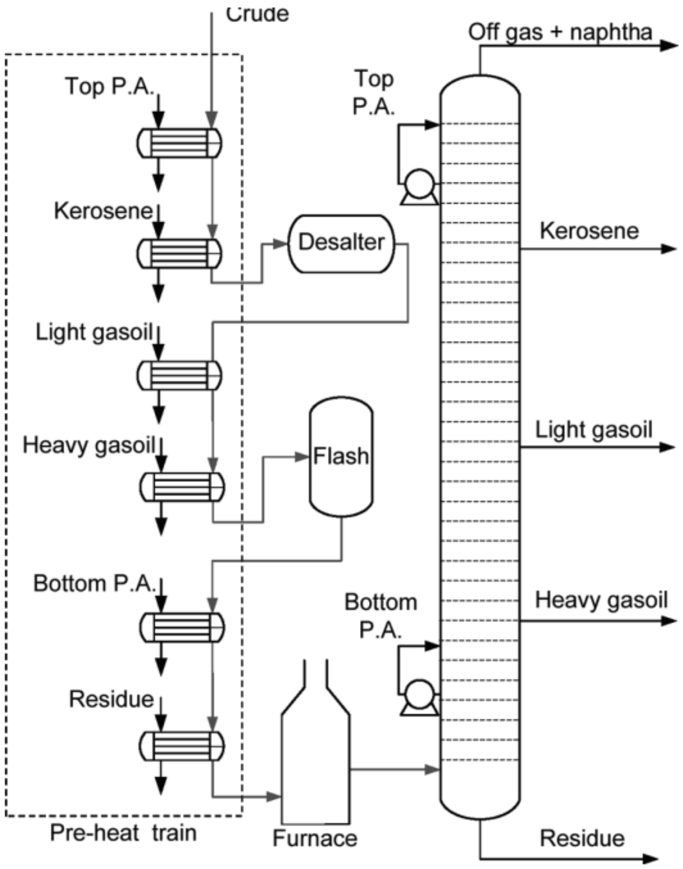
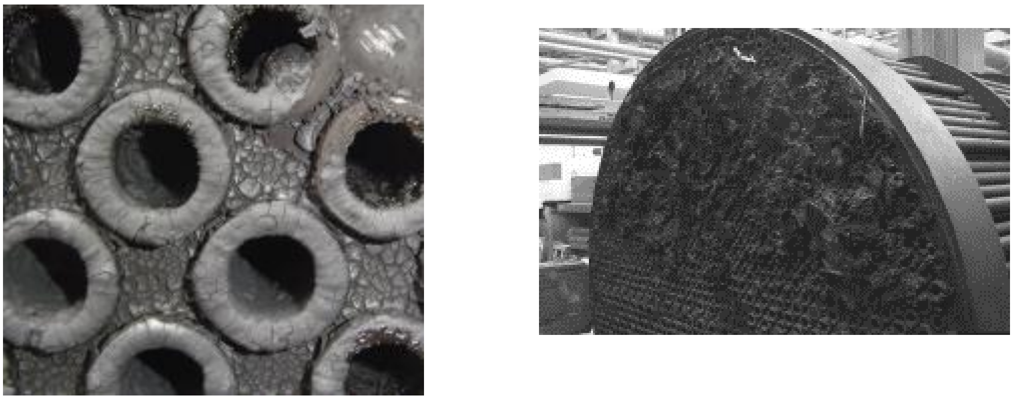


Figure 1. Schematic of a typical Crude Distillation Unit (CDU) including PHTs [4]

In addition to the fouling in PHTs, wax fouling on inner walls of heat exchangers (coolers) [6] or in transports lines [7, 8] results in an increase in pressure drop, reduction of pipe effective diameter and pipeline capacity, operational difficulties, as well as process shut down (Figure 3).

Fouling is defined as the adhesion of each undesired and unwanted material on the surface under the influence of wettability, surface forces, etc. [10]. To date, various methods have been utilized in order for fouling mitigation or cleaning of the fouled surfaces. Some of these methods include changing the operating conditions and using additives in order to inhibit fouling, and using high pressure water jets or chemical solvents for cleaning the equipment surfaces. However, due to the limitations in employing some of these methods in petroleum industry, recently, there has been growing attention to the surface modification methods.



(a)

(b)

Figure 2. Crude oil fouling in Shell and Tube PHTs. a) Tube-side, b) Shell side [5]

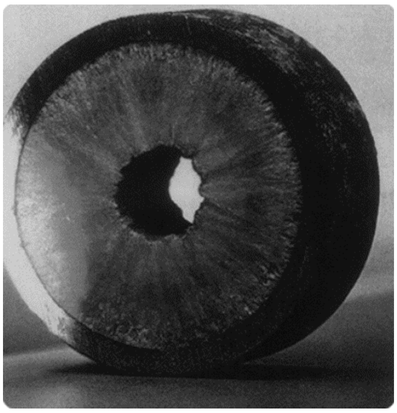


Figure 3. A scheme of wax fouling in pipeline [9]

Since to the extent Iran is an oil-rich country and the petroleum industry plays a decisive role in the growth of its economy, there is an inevitable need for cost reduction in this industry and especially in the refining sector. One of the candidate issues for the reduction of costs in petroleum industry is crude oil fouling. On the other hand, in spite of the fact that crude oil fouling in PHTs of Iranian oil refineries has been associated with huge expenses, this issue has not been investigated thoroughly. Also, an assessment and/or estimation of the fouling costs and consequences in PHTs of Iranian oil refineries have not been presented in the literature. In addition, the attempts to confront the fouling problem in Iran have been restricted to traditional methods. For example, in some circumstances, the fouled equipment is removed and replaced by new equipment, which imposes a great cost on the refineries. Hence, the aim of this study was to investigate crude oil fouling phenomenon, present an estimation of its costs involving operational, economic, and environmental costs in PHTs of Iranian oil refineries, introduce fouling mitigation methods, and describe the potential of modern mitigation techniques such as surface modification. Therefore, in the following section, first of all, fouling and the influential parameters on this phenomenon are described. Second, fouling costs in Iranian oil refineries are illustrated. Third, fouling mitigation methods are introduced, and finally, some of the world's most recent and most significant studies on the mitigation of crude oil fouling are explained.

2. Crude oil fouling and the effective parameters

Fouling is a dynamic process, which consists of the following 5 steps according to the matrix proposed by Epstein [11]:

1. Initiation: a delay period before any significant fouling is recorded [12].
2. Transport: transport of fouling precursor from bulk of fluid to the surface [13].
3. Attachment: attachment of the key component to the surface [14, 15].
4. Removal: removal of the deposit under the influence of various forces acting on the surface [16, 17].
5. Aging: growth of deposit layer including structural or chemical changes [18, 19].

Some of the aforementioned steps might occur in parallel. For example, in crude oil fouling, the mass transfer, attachment, and removal occur in parallel. In another classification, these three stages are classified as two steps: deposition and removal (Figure 4).

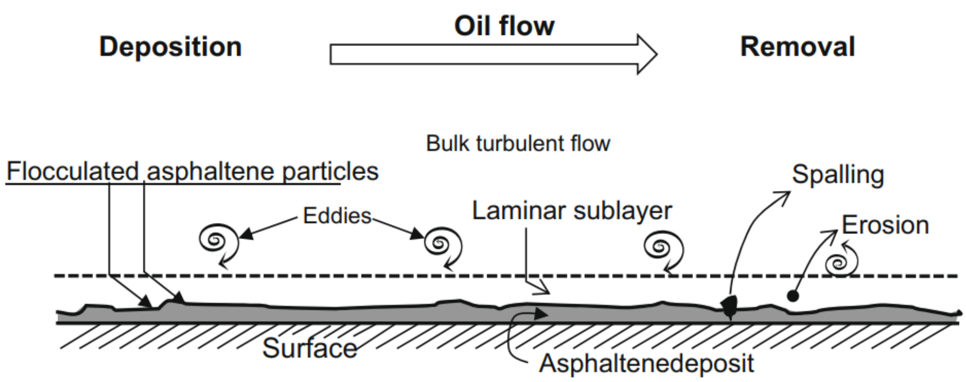


Figure 4. A schematic of Asphaltene deposition and removal steps [20]

The experimental studies on fouling have revealed that the most effective parameters on fouling are as follow:

1. Surface and Bulk temperatures [21, 22].
2. Velocity and surface tension [23, 24].

3. crude oil feed composition and inorganic pollutants [25].
4. Surface characteristics including surface energy and geometry [19, 26–28].

Flow velocity in PHTs is in the range of 0.5-5 m/s. Pressure is varied from 1-15 bar. Temperature exeeds 200°C and crude oil composition is different for various sources of crude oil [29]. Due to the fact that crude oil fouling is mainly influenced by mass transfer to the surface, attachment to the surface, and removal, in order to understand the impact of the mentioned parameters on this phenomenon, it is required to investigate the effect of each of these parameters on each of the fouling steps, separately. For instance, some experimental studies and observations in the industrial units have shown that mass transfer is marginally increased by increasing the surface temperature [20, 30]. On the other hand, the attachment step is largely influenced by surface temperature; however, it has a little dependence on the bulk temperature. In addition to the impact of temperature on the afore-mentioned steps, increased temperature also influences the surface corrosion rate and chemical reaction and reduces the induction time. Also, the effect of surface temperature on the aging cannot be ignored, in a way that the deposit layer might become hardened by increasing the temperature so that its removal can become more difficult.

Velocity influences the mass transfer directly and a linear relationship can be observed between them; while the attachment step has an inverse relationship with velocity and decreases by increasing velocity due to the reduction in the probability of attachment of the particles to the surface. Furthermore, the removal rate of the deposit increases with an increase in the velocity and surface tension. The reduction in fouling rate caused by increasing velocity, which is observed in industrial units, is mainly due to fact that crude oil fouling is controlled by adhesion and/or reaction [20, 30].

The composition of crude oil feed and the presence of inorganic pollutants, have a large effect on crude oil fouling. For instance, Asphaltene is one of the main sources of crude oil fouling in refineries. The solubility and concentration of Asphaltene in the fluid are considered as the influential factors in the amount and rate of the deposit formation. Observations have revealed that even crude oils with a low percentage of Asphaltene form deposits at the hot ends of the PHTs. The solubilized and bonded oxygen in crude oil, sulphurous compounds such as Sulfides, Disulfides, and Thiols, which are capable of forming free radicals; metals and metallic compounds present in crude oil; and also Nitrogen in the form of Pyridine and Pyrrole are other factors which can influence crude oil fouling [30].

Besides the mentioned factors, surface is another factor which affects the crude oil fouling through surface energy and geometry. Within the last decade, a lot of studies have been conducted that investigated the influence of surface on fouling. While some of these studies have shown that the deposit forms on high-energy surfaces, others have reported the reverse. However, some of them have also stated that there is no relationship between the surface energy/wettability and fouling [31]. As a consequence, in order to reach a consensus, studies on the impact of surface and surface modification techniques such as using various coatings have been going on. The influence of surface and different coatings are discussed thoroughly in the following sections.

3. Crude oil fouling costs in Iranian oil refineries

As it was mentioned in the previous sections, crude oil fouling on equipment surfaces imposes high operational and economic costs on the petroleum industry. Iran holds the world's 4th largest proved crude oil reserves with 9 active oil refineries. Thus, crude oil fouling in upstream and downstream leads to high costs, and mitigation of this type of fouling on surfaces through a deep understanding of this phenomenon can reduce the imposed expenses to a large extent. Refineries have a bold and decisive role in petroleum industry by separation and treatment of crude oil and production of products such as liquefied gas, fuels, kerosene, solvents, engine oil, etc. In refineries, fouling occurs mainly on surfaces of heat exchangers, pipelines and storage equipment.

According to the statistics released in 2017, Iran has a refining capacity of more than 1.8 million barrels of oil/day and it is expected that this value will increase to 3 million barrels/day after the completion and exploitation of new refineries at the end of 2020. According to the statistics released by the National Iranian Oil Refining & Distribution Company (NIORDC), the refining capacity will experience a 70% growth by exploitation of the following refineries: Setare Khalij Fars with a capacity of 360,000 barrels/day, Siraf with a capacity of 480,000 barrels/day, Anahita with a capacity of 150,000 barrels/day, Bahman Geno with a capacity of 300,000 barrels/day. Along with increasing the refining capacity, crude oil fouling will definitely become more important in the future. In order to better understand the fouling costs in Iranian oil refineries, the classification of these costs and consequences will be discussed in the following sections.

Table 1. The capacity of 9 Iranian oil refineries [32]

Refinery	Theoretical Capacity (Thousand barrels/day)	Practical Capacity (Thousand barrels/day)
Abadan	390	366
Isfahan	375	372.6
Bandar Abbas	320	322.9
Shahid Tongouyan Tehran	250	246
Imam Khomeyni Arak	250	252.9
Tabriz	110	108
Shiraz	58	55.3
Lavan	50	57.1
Kermanshah	22	20.8
Total	1825	1801.6

3.1. Operational difficulties

The operational cost due to crude oil fouling in refineries' equipment, especially PHTs, is classified into two categories: reduction of thermal and hydraulic efficiency. Because of a two-order decrease in the conductivity of the formed deposit compared with the metallic substrate, energy transfer and recovered energy are reduced [5]. Hence, a 10-30% extra energy must be consumed in order to compensate for this occurrence [33, 34]. On the other hand, increasing the heat load of the furnace is limited and cannot solve the problem of reduced thermal efficiency. As a result, decreasing the throughput is inevitable. Additionally, crude oil fouling causes the reduction in heat transfer area or total plugging of pipes and increases the pressure drop. In these extreme circumstances, process shut down is necessary. The proper time for process shut down is determined using different standards. Reaching a heat transfer coefficient equal to 30% of the clean value [35], a thermal efficiency of 80-85% of the initial value, or a specific value of fouling resistance are some criteria for starting the process shut down and cleaning [5].

3.2. Economic costs

The economic costs associated with fouling cannot be estimated easily as it depends on various factors, the most important of which are oil price, geographical location, and cost of the environmental policies. The economic cost consists of the following [5]:

1. Increasing the pumping power: This cost is due to the consumption of higher electric power. However, it is much lower than the costs related to decreased thermal efficiency.
2. Burning extra fuel: It is carried out to offset the reduced thermal efficiency. For a refinery with the capacity of 100,000 barrels/day, for 1 degree reduction in Coil Inlet Temperature (CIT), an approximate value of 400,000$/year is charged to burn the extra fuel. Considering the aforementioned information, with a rough estimation, an approximate value of 7.5 million $/year is required to compensate for the crude oil fouling of PHTs in Iranian oil refineries.
3. Reduction of throughput: Regarding the limitations in increasing the heat load of the furnace and pumping power to offset the reduction of thermal and hydraulic efficiency, throughput reduction must be carried out to compensate for these issues, which is associated with the highest value of operational cost. Considering a cost of 9.7 million $/year for PHTs in a 100,000 barrels/day refinery due to throughput reduction, for Iranian oil refineries, this can be estimated to be approximately 180 million $/year.
4. Anti-fouling additives: The cost of using additives might be offset with a large degree of reduction in fouling and cleaning. However, the degree of success of this method depends on various factors. Considering a cost of 400,000 $/year for buying additives for PHTs in a 100,000 barrels/day refinery, for Iranian oil refineries it is estimated to be 7.5 million $/year, which is equal to the cost of burning extra fuel.
5. Cleaning: In some cases such as high cost of burning extra fuel and increasing pumping power, the occurrence of plugging in system, or high economic cost of throughput reduction, the best solution is to shut down the process and clean the surface utilizing high pressure water jets or chemical solvents. This cost is placed in the category of maintenance cost. An estimation based on the cleaning cost of PHTs in a 100,000 barrels/day refinery, reveals that for Iranian oil refineries it is equal to 1 million $/year.

6. Capital cost: The most significant cost of this category is overdesign to offset the reduction of thermal efficiency. The cost of overdesign of heat exchangers is estimated to be 1.4 million$/year. The cost of injection equipment is also placed in this category.

Overall, each refinery has a total number of 10-60 PHTs and the required energy for each refinery is 6-7% of the entering crude oil to the refinery, the major amount of which is consumed in PHTs. As mentioned earlier, the cost of fouling is approximately 10% of the required energy for the refineries. With a rough estimation, the cost to compensate for fouling in PHTs in 9 Iranian oil refineries is approximately equal to 4 million barrels of oil/year, which is estimated to be 200 million$/year considering the price of 50$/barrel of crude oil. If sum of the economic costs is calculated, by considering the increased pumping power, a similar figure is obtained.

3.3. Environmental impacts

The trend of greenhouse gas emission from 2000 to 2010 reveals that the emission of these gases has an annual growth rate equal to 6%, which is high compared with the global trend. According to the statistics released in 2015 by Carbon Management in Research & Technology Directorate of National Iranian Gas Company (NIGC), in order to reach an economic growth rate of 3.5%/year, the amount of greenhouse gas emission in the energy sector will experience an increment from 500 million tons/year in 2005 to 2.2 billion tons/year in 2025. One of the global rules legislated for the inhibition of uncontrolled emission of CO_2 gas into atmosphere is Cap-and-Trade. According to this rule, after the cap has been determined, allowances for portions of the total limit are allocated. If companies produce a higher level of total emissions than their permits allow, they must pay taxes; but they can also sell off any unused allowance to other producers, which is called trade.

Burning extra fuel with the aim of offsetting the impact of fouling in PHTs in Iranian oil refineries is one of the major sources of CO_2 emission through human sources. Thus, one of the solutions to reduce greenhouse gas emission to the atmosphere is to mitigate crude oil fouling in refineries. In addition to CO_2, the removal of carbonaceous materials, sulphur, nitrogen, and metals through cleaning process is another source of environmental pollution in crude oil fouling. As mentioned earlier, increased percentage of sulphur in crude oils from 1995 to 2020 also can lead to an increase in the emission of its compounds into the atmosphere.

3.4. Safety

Safety concerns have always been the utmost priority and one of the biggest challenges in all of the industrial processes. However, their importance is more perceptible in petroleum industry due to dealing with hydrocarbons, poisonous and flammable materials, as well as high operating pressures and temperatures. For crude oil fouling, heeding the safety is necessary during the process shut down, opening, dismantling, transportation, cleaning, and reassembling of the equipment. For instance, flammable atmospheres and pyrophoric material are typically present in the PHTs. Hence, opening these equipments is associated with the danger of being exposed to these types of dangerous materials. Electric shock is another danger that is probable in the stage of dismantling the tube bundles of PHTs, which is generally carried out using a crane. Cleaning the fouled equipment with high-pressure water jets (1000-3000 bars) or chemical solvents can result in the emission of poisonous materials to the atmosphere. Also, high pressure pumps cause strident noise, which is intolerable and harmful for human. Finally, reassembling of the equipment is associated with the noise of transportation vehicles and burning of the fossil fuels for their operation [5].

4. Prevention of crude oil fouling

4.1. Mitigation methods

As fouling results in numerous operational and economic problems in petroleum industry, mitigation of this phenomenon is of the priorities in industrial processes. One of the methods which has been always employed to offset the reduction of hydraulic and thermal efficiency and prolong the operating time of the heat exchangers is overdesign of the heat exchangers based on some standards such as The Tubular Heat Exchanger Manufacturers Association (TEMA). The basis of this standard is to calculate the clean heat transfer coefficient by setting the fouling resistance equal to zero and overdesigning the heat exchanger 15-50% larger depending on the circumstances [36].

In addition to considering fouling in the initial design of the heat exchangers, preventing this problem is carried out through mitigation (before and after the installation) and cleaning or removal. Three factors influence the fouling process: 1) operating fluid, 2) operating conditions, and 3) surface properties. Thus, in order to mitigate this problem, it is required to investigate the changes in all of these three factors. For example, controlling the operating conditions [37] and utilizing additives [38, 39] can be carried out after the installation and during the process. In some cases, changing the operating conditions (e.g. temperature and velocity) or the operating fluid through using additives or chemical inhibitors are either impossible or might change the quality of the finished product. Additives are also harmful for the environment [40]. Due to the mentioned limitations in changing the operating fluid and operating conditions and in order to modify the surface energy and geometry, surface modification techniques have received a great attention.

The fouling process, its mitigation and cleaning can be investigated through colloids and surface chemistry. As the material of surface substrate and deposit are different, the formation of deposits first takes place by adhesion. After the deposition of the first layer, the following layers are deposited by cohesion between similar particles or adhesion between other particles with the deposited particles. Adhesion occurs only if the fluid flow including particles is not capable of overcoming the attraction forces. Thus, upon studying the colloids and surface chemistry in fouling, mitigation and cleaning becomes significant [14].

Attending to the surface properties, especially surface energy, has been developed from mid- 90s. Since that time researchers have found relationships between fouling and surface properties. From the perspective of surface science, fouling of the metallic surfaces is due to the interactions between surface and deposit. Hence, all of the surface modification techniques act as turbulence promoter and/or reducer of the adhesion between surface and deposit [41]. Surface modification can help to eliminate using harmful chemicals, reduce cleaning time, and decrease the emission of greenhouse gases due to burning of the carbonaceous deposits. Surface modification methods are categorized into two groups of modification of surface energy and modification of surface geometry (texture and roughness) (Figure 5). Modification of surface energy using embedded or external coatings or by changing the surface substrate, or modification of its roughness/texture can also lead to fouling reduction. Recently, modern methods such as plasma have been employed for this purpose [42, 43]. Plasma, or ionized gas, is identified as one of the four states of matter. Plasma irradiation is one of the techniques that can help improve surface wettability and can act as a surface modification technique with the purpose of minimizing the adhesion of deposits to the surface as well as enhancement of the surface cleaning. The ions such as OH^- can adsorb on the surface and change the wettability of the surface, which can help mitigate fouling. Additionally, the excited, accelerated, and reactive ions can result in cleaning of the surface [44, 45].

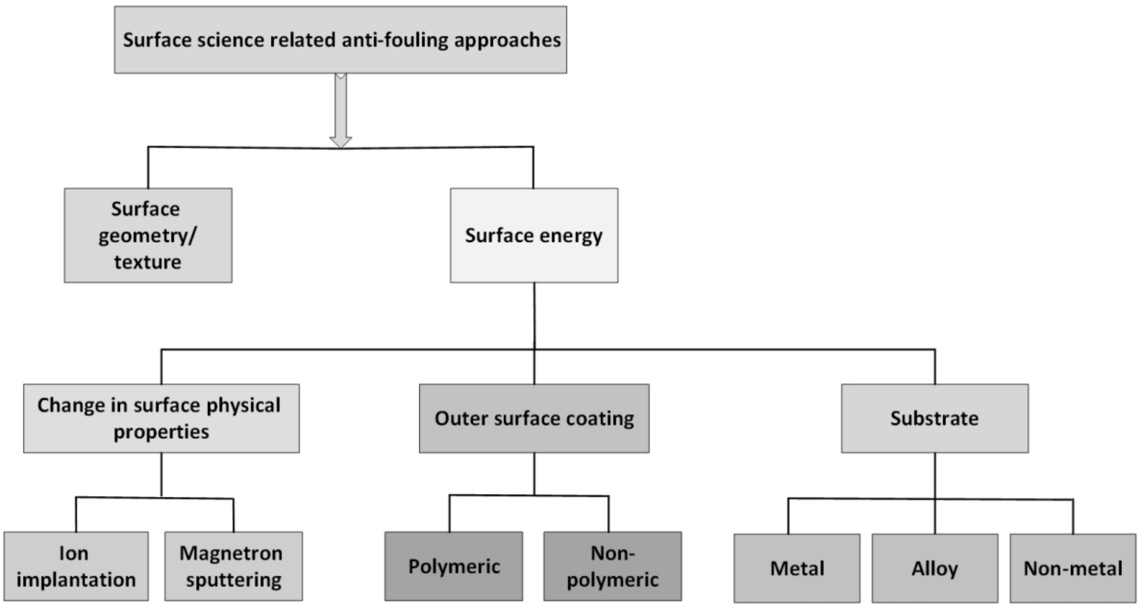


Figure 5. Surface modification methods with anti-fouling properties

4.2. Cleaning of the surface

After the deposit formation occurs, three mechanisms based on fluid dynamics, colloid chemistry, and reaction can be used for its cleaning. One of the cleaning methods is passing the high velocity, high pressure water jet over the surface, which can remove the deposit by applying surface tension on it. The other method is employing solvents, detergents, alkaline, and enzymes to reduce the adhesion [14]. Plasma, supercritical CO_2 [46–50], and ultrasound have also been utilized for cleaning purposes.

5. Recent studies on the mitigation of crude oil fouling

In recent years, numerous studies have been carried out on crude oil fouling phenomenon due to the high costs imposed by it. Researches done by Alfa Laval in Switzerland, Danish Technological Institute in Denmark, and Chevron Energy Technology in USA are some of the major studies in this regard. The key activities of these companies have been allocated to produce coatings with anti-fouling properties to reduce adhesion as well as investigation of the role of different coatings in crude oil fouling mitigation.

Coatings with anti-fouling properties must have some characteristics other than reducing the adhesion between deposit and surface. Some of these properties can be named as follow [51, 52]:

1. The coating must have low thickness and a desired thermal conductivity. Otherwise, even if it helps to mitigate fouling, it leads to the thermal efficiency as well as yield of the system to reduce.
2. The coating must have a good adhesion to the surface substrate and a high resistance to flow and surface tensions (i.e. it should not become detached from the surface).
3. The coating must have flexibility and durability during extreme changes in system pressure in order not to be cracked in these circumstances.
4. The coating must have a high chemical and thermal resistance and must be resistant to wear and corrosion.

Because of the complicate nature of coatings and fouling mechanism, not many real cases of using the coatings in industrial units have been reported. In 2012, Bischoff and Holberg synthesized a glass ceramic hybrid organic-inorganic coating based on Dipodal diurea silane and Methyltriethoxysilane (MTES) using sol-gel method [53]. Then, Bischoff et al. tested the synthesized coating with high thermal conductivity, flexibility, and wear resistance (with a thickness of 5 microns) on titanium plate heat exchangers in an offshore unit exposed to organic (wax) and inorganic (limestone) fouling. They observed that the heat exchangers with coated plates were in operation for 1000 days compared with 180 days in normal conditions without applying the coatings [51]. Also, Bischoff et al. tested different coatings on carbon steel shell and tube heat exchangers with the purpose of finding the optimum coating for the fouling mitigation. The selected coating must be compatible with the high pressure and temperature conditions in these heat exchangers [54].

Santos et al. tested a hybrid organic-inorganic coating based on Polydimethylsiloxane (PDMS) on titanium plate heat exchangers and reported a 65% reduction in the amount of fouling after 8 months being in operation. They also observed that adhesion of deposits to the surface has been reduced and the surface can be cleaned easily with high pressure water jet. Additionally, the coated plates of heat exchangers were in continuous operation for 2 years [52].

6. Conclusion

Crude oil fouling has caused a great deal of problems and costs in the petroleum industry. This type of fouling occurs in different sections of petroleum industry including crude oil storage tanks, desalters, and PHTs of the refineries. However, due to the higher intensity of fouling in PHTs, in this study, the operational, economic, environmental, and safety costs, as well as the consequences of crude oil fouling in PHTs of Iranian oil refineries were investigated. It was estimated that approximately 200 million $/year is consumed to offset the crude oil fouling in PHTs of the oil refineries. Due to the great importance of crude oil fouling in oil-rich countries like Iran, the complex nature of the process, its huge cost, and the fact that in most cases the only ways to confront this problem has been the replacement of the equipment or its cleaning, it is required to organize active research groups and carry out thorough investigations on this topic. We hope that the operational, economic, environmental, and safety consequences of crude oil fouling will be reduced to a large extent in the future through development of surface modification technologies and coatings.

Nomenclature

API	American Petroleum Institute
CIT	Coil Inlet Temperature
GDP	Grass Domestic Product
MTES	Methyltriethoxysilane
NIGC	National Iranian Gas Company
NIORDC	National Iranian Oil Refining & Distribution Company
PDMS	Polydimethylsiloxane
PHT	Pre-Heat Trains
TEMA	Tubular Heat Exchanger Manufacturers Association

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مروری بر تشکیل رسوب نفت خام و روش‌های پیشگیری از آن در مبدل‌های حرارتی پیش‌گرمکن پالایشگاه‌های نفت ایران

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چکیده

تشکیل رسوب نفت خام روی سطوح تجهیزات از جمله مشکلاتی است که همواره در صنعت نفت منجر به هزینه‌های هنگفت عملیاتی، اقتصادی، زیست محیطی و ایمنی می‌شود. در پالایشگاه‌های ایران با یک تخمین سرانگشتی، حداقل سرمایه‌ای معادل قیمت ۴ میلیون بشکه نفت خام در سال برای مقابله با تأثیرات تشکیل رسوب نفت خام در مبدل‌های حرارتی هزینه می‌شود که با احتساب قیمت هر بشکه نفت خام ۵۰ دلار خسارتی حدود ۲۰۰ میلیون دلار در سال به همراه دارد. همچنین سوزاندن سوخت اضافی مقدار زیادی کربن‌دی‌اکسید تولید می‌کند که سهم بالایی از آلودگی هوا داشته و هزینه‌ی اقتصادی زیادی را به بار خواهد داشت. از این رو، بکارگیری روش‌های پیشگیری از تشکیل رسوب از جمله تغییر شرایط عملیاتی و مواد افزودنی و بهبود سطح مورد توجه قرار گرفته است. بهبود سطح به صورت تغییر هندسه و بافت سطح یا تغییر انرژی آن می‌تواند به پیشگیری از تشکیل رسوب کمک کند.