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Mitigating the Risks of Energetic Facilities by Cleaning Internal Surfaces

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The article deals with the mitigation of risks of energetic facilities caused by contamination of internal surfaces. To ensure reliability of facility, the internal surface must be cleaned and process of cleaning must be safe, which means that risk of process must be acceptable. For process risk determination, the checklist is used. The experiment shows chemical cleaning of the exchanger. In spite of ensuring the cleaning process safety, for achievement of acceptable risk of exchanger, which required by valid standard, the cleaning process must be carried out twice.

Keywords: Energetic facility, risk, process safety, reliability, cleaning, checklist.

1. Introduction

An important asset of any State is energy infrastructure, which consists of energy facilities of various types and their interconnection. In order for energy facilities such as boilers, turbines, engines, generators, heating and cooling systems and many others to ensure the safe operation of critical energy infrastructure, a specific maintenance must be carried out to mitigate specific risks. In this article, we focus on the problems of heating and cooling systems.

In the energy sector of heating and mainly cooling systems, dirt and deposits on the inner surface of the equipment are a problem, because they impede heat transfer. This results in a reduction in the efficiency of the systems in question, an increase in energy and pressure losses, a reduction in the possibility of regulation and an overall decrease in the efficiency of these systems. In the article, we focus on mitigating the internal risks, such as corrosion, erosion, fouling and mechanical damage to monitored energy equipment. We will monitor the issue of clogging in detail. Clogging can be divided into several types, and these are:

- crystallization and precipitation clotting,
- particle silting – sedimentation and alluvial particles,
- corrosion clogging,
- silting due to chemical reaction,
- biological clogging,
- frost silting,
- or a combination of previous types of clogging.

The safety, reliability, durability and sustainability of the working parameters of industrial and energy equipment of entire demanding systems, therefore, depend on the quality of maintenance of the internal surfaces of the monitored facility. Maintenance is carried out by cleaning the internal surfaces, which are divided into mechanical and chemical. When applying online methods (dry cleaning and sound cleaning), there is no need to shut down the facility. For off-line methods (manual mechanical cleaning, light blasting, high-pressure water cleaning, projectile cleaning and other special cleaning methods) the facility must be taken out of service.

The maintenance by cleaning the internal surfaces of these facilities is generally difficult, but can be done with the necessary information and appropriate methods. The design of industrial and energy equipment is always made of a number of different materials (steel, cast iron, brass, copper, plastics), and therefore, it is necessary to determine such cleaning methods and cleaning agents that none of the individual materials of the facility will damage. Therefore, for each material, a suitable method must be chosen.

Therefore, to select a suitable method of cleaning energy facility, especially heating systems, which will not damage the material of the energy facility, we conduct experiments in a special laboratory. During the experiments, we monitor both the condition of the material and the flow, heat transfer and heating time. The aim of the experiments is to determine not only the appropriate method of cleaning, but also the cleaning interval depending on local conditions so that the operation corresponds to the requirements placed on it.

We use a checklist to determine the risks of monitored energy facilities and data from relevant standards for risk assessment. Experiments have shown that in some cases it is necessary to carry out cleaning repeatedly in order to achieve the required level of heating time. Therefore, proposals for maintenance programs have been established on a case-by-case basis to guarantee the safe operation of the facility in question under the given conditions.

2. Summary of Knowledge on Risks of Power Equipment

Risk associated with technical equipment is understood as the degree of loss, damage and harm to technical equipment, operating personnel, entire technical facility or public assets in the vicinity (property, public welfare, environment and critical infrastructures). Therefore, it is necessary to implement measures to minimize losses, damages and injuries to the monitored items (Prochazkova 2011). This means preventing the technical equipment conditions that lead to damage. One of the tools, it is, for example, maintenance (Procházková 2015).

The main sources of technical risks of power equipment are corrosion, erosion, fouling and mechanical damage. Originator of fouling can be divided into several types, and these are: crystallization and clogging, particle silting – sedimentation and alluvial particles, corrosive clogging, silting due to chemical reaction, biological clogging, freezing fouling, or a combination of previous types of fouling (Kazi 2012 and Kuchar et al. 2019).

Corrosion is a self-perpetuating irreversible process of gradual disruption and degradation of material by chemical and physics-chemical environmental influences (Kreibich 1996). The corrosion system then consists of the material, the medium and their interactions. Corrosion in power facilities is caused by 4 main factors, according to (AB 2020a): temperature; vibration; flow velocity; and change in flow direction. The first of the places where corrosion occurs earlier than elsewhere is the part of the pipe that passes through the bulkhead in the shell (AB 2020). This is due to the fact that when the tube vibrates, it can rub against the partition through the surface. When hot water flows, the areas most affected by corrosion are the places where the temperature is highest. Therefore, if we heat the water, the most affected places will be at the outlet, and if we cool it, then at the entrance.

Erosion is a process of wear in which surface damage is caused by repeated action of high localized stress (Cousens 1984). Erosion in power facilities leads to serious operational and economic problems. According to (Wojnar 2013), the wear of equipment pipes depends on many factors: velocity of flowing particles; particle diameter – the erosion rate increases until the particle diameter reaches the range of 50-100 μm. If the particles are larger, the rate of erosion is no longer affected by the particle diameter; particle shape – the erosion rate by non-spherical particles with sharp edges is noticeably higher for metal surfaces; particle hardness; and particle impact angle – maximum wear of pulling materials occurs at an impact angle between 20°-40°, whereas for brittle materials at a vertical impact.

According to (Kazi 2012, Kubin 2013), it is possible to meet with several types of clogging, namely:

- Crystallization and fouling – they occur when the process conditions inside the heat exchanger differ from those at the inlet. A current on the wall with a temperature higher than the corresponding saturation temperature of dissolved salts allows the formation of crystals on the surface.
- Particle silting – sedimentation and alluvial particles occur on the heat-exchanging surface by the accumulation of solid particles suspended in the stream, heavy particles settle on the horizontal surface due to gravity and fine particles settle on heat-exchanging surfaces.
- Fouling due to chemical reaction – pollution occurs when depositions are formed as a result of a chemical reaction that leads to the formation of a solid phase on or near the surface.
- Biological fouling – clogging by bacteria, algae, fungi occur due to untreated operating media.
- Fouling caused by frost – ice is on internal exchanger surfaces.
- Combination of previous types of fouling.

Clogging of power equipment (Fig. 1) impairs heat transfer, increases surface roughness, thereby impairing fluid flow and increasing the risk of corrosion, which leads to shortening the life of equipment. Sediment growth also increases operating costs.

Fig. 1. Clogged heat exchanger tube (PC 2013); white to beige color denote deposits.

Greater energy consumption of heat exchangers caused by deposits is also responsible for 1-2.5% of global CO_2 emissions (Malayer et al. 2016). According to (Zubair et al. 2000), fouling of heat exchangers can also lead to uneven heat heating, especially in equipment with high heat flow, such as steam generators. This can eventually cause a mechanical failure of the heat exchanger. The worst consequences of mechanical failure tend to be in refineries or thermal power plants.

Fouling of energy equipment is according to (Kazi 2012 and Thulukkanam 2013) dependent on many parameters: properties of fluids and their susceptibility to the formation of deposits; high temperature; hydrodynamic effects of convection; pipe material; purity of liquids; roughness of the pipe surface; excreted solids; placement of more clogging liquid; type of heat exchanger; geometry and orientation of the heat exchanger; overall design of the equipment; and seasonal temperature changes.

According to (Kazi 2012 and Thulukkanam 2013) the properties of liquids and their susceptibility to the formation of deposits are the most important parameters influencing the fouling of power equipment. By changing the parameters of the process, it is possible to change the conditions so that deposits form less. At higher temperatures, there is a greater formation of deposits This is mainly due to faster chemical reactions, crystal formation and increased corrosion rate. However, some of the liquids used behave in the opposite way at low temperatures, promoting crystal formation. For these cases, it is better to use the optimum temperature to overcome these problems. For water prone to limescale, the temperature should not exceed 60 °C. The rate of formation of biological deposits is highly dependent on temperature. At higher temperatures, chemical and enzymatic reactions occur faster and thus the rate of cell growth increases. However, if the temperature rises to an even higher level, some heat-sensitive cells may die. The hydrodynamic effects of convection, such as its velocity and shear friction on the surface, also affect fouling. The higher the flow velocity, the higher the heat output and the lower the fouling of the heat exchanger. Constant media flow also reduces clogging. Deposits will be deposited mainly in places where the flow velocity changes. Thus, when maintaining relatively uniform flow velocities, the formation of deposits is reduced.

The choice of material also affects clogging. For example, carbon steel is the most susceptible to corrosion, but at the same time it is also the cheapest. Copper in water has shown the ability to kill some harmful organisms, but its use is limited to the following (Thulukkanam 2013):

- Copper alloys are completely prohibited in high-pressure steam heat exchangers in thermal power plants, as their resulting corrosion products are deposited in steam generators and subsequently block turbine blades.
- Environmental protection limits the use of copper in the waters of rivers, lakes and oceans because it is poisonous to aquatic life.

According to (Thulukkanam 2013): non-corrosive materials such as titanium and nickel prevent corrosion, but are expensive and cannot kill harmful organisms.; and glass, graphite or Teflon pipes often reduce clogging and simplify cleaning. Therefore, a surface treatment of materials (by plastics, enamel, glass or polymers) is important for reducing the formation of deposits. The purity of liquids is never foolproof, and the ingress of even a small impurity in the liquid can initiate the formation of deposits either as the first layer of contamination or as catalysts for clogging processes. For example, pollution of refinery hydrocarbon streams is caused by the ingress of oxygen or trace elements such as vanadium or molybdenum. It also happens that impurity particles act as a seeding for crystal formation. Conversely, impurities such as sand in cooling water can sometimes have a positive effect and reduce the amount of impurities or remove them altogether.

The type of heat exchanger also influences fouling according to (Thulukkanam 2013). The most susceptible types of heat exchangers to fouling are tubular exchangers. In the case of a plate heat exchanger, fouling is 10-25% lower than in the case of a tubular heat exchanger, mainly due to high turbulence, the absence of standing areas and the smooth surface of the individual plates. A spiral heat exchanger also experiences high turbulence and there are no standing spots, so it will also clog more slowly than a tubular heat exchanger. The geometry of the heat exchanger mainly affects the uniformity of flows and the resulting clogging. Their orientation can then greatly facilitate their cleaning. The overall design of the device can greatly affect the degree of clogging of the exchanger. For example, by using filtration. Seasonal changes in temperature should be considered when water is used as coolant, mainly due to winter conditions when the ambient temperature can be below 0 °C. Because of this, it is necessary to increase the temperature, which, in turn, contributes to clogging.

Mechanical damage inside the heat exchanger is manifested by clogging or leakage during operation (Klein, Zunkel, Eberle 2014). However, steam or liquid gets out of the exchanger when cracks and cracks occur. Leaks cause the two media to mix and thus cause undesirable effects such as pollution, which can cause the electrical conductivity of hot water. When blockage, in turn, an increase in pressure can be observed. Failure can cause fluid leakage from both the pipe and the shell (Pasha, Zaini, Mohd 2017). According to the cited work, there is also a potential danger of explosion, fire or leakage of toxic substances. In addition, they can have consequences such as significant loss of production, injury, death, or damage to the entire facility.

According to the data in (Klein, Zunkel, Eberle. 2014), damage to the exchanger usually results in long and expensive system shutdown due to subsequent damage analysis, repairs or replacements. Operating companies try to minimize these losses, but in the event of a hot or poisonous vapor leak, employees, bystanders, or even the environment can be injured. In the tubular exchanger if a smaller number of pipes are damaged, it is possible to blind them. However, if an inadmissible number of pipes had to be blinded, the exchanger would be inefficient and should be completely replaced, or the conditions of subsequent operation should be considered (PE 2017).

3. Methods of Cleaning the Devices

Methods of cleaning internal surfaces are divided into several ways according to (Ibrahim 2012, Kazi 2012, Kononenko 2014). They can be divided into two basic cleaning methods, and these methods are:

- mechanical cleaning,
- dry cleaning.

It is also possible to find a division of cleaning methods into methods: "online" and "off-line". On-line methods are methods where there is no need to "shut down" the equipment. Thus, unlike off-line methods, on-line methods can be used on the fly of the device. Off-line methods include manual mechanical cleaning, light blasting, high-pressure water cleaning, projectile cleaning and other special cleaning methods. On the contrary, online methods include sound cleaning and dry cleaning of surfaces.

The main methods of mechanical cleaning are divided into: mechanical blasting and light blasting; cleaning with a cleaning projectile; and high pressure cleaning. According to (Kreibich 1996), kinetic energy is assigned to particles (means) or abrasive of low mass by compressed air. With the help of a nozzle, the mixture is directed at a suitable angle. A suitable medium for blasting is, for example, corundum (Al_2O_3.). Brown corundum is used for steel blasting. White corundum is used for blasting non-ferrous metals and stainless steels. White corundum contains a lower content of additives in corundum such as iron, sulfur and chromium atoms. Corundum grains are more tenacious. They split less and become dull. This self-cleaning effect ensures a longer service life and less dustiness of the abrasive. From other means for light blasting, it is possible to give sodium bicarbonate (baking soda), dry ice, which are environmentally friendly abrasives.

One of the options for mechanical cleaning is according to (Abd-Hady, Malaveri, Jalarirad 2014, PTC 2017) the use of a cleaning projectile or cleaning with high pressure. Special projectiles of various shapes and materials are used. Kinetic energy is supplied to these projectiles, which then pass through the exchanger tubes. Projectiles are used metal, plastic, nylon or stainless. Each type of projectile is designed for different contamination, for example, a nylon bullet is intended only for cleaning and light dirt, while a metal projectile is designed for extreme contamination. Projectile cleaning is limited by a medium temperature of around 120 °C due to the stability of the projectile material.

The main advantages of projectile cleaning include environmental friendliness and safety of the method (use of low pressures) and the disadvantage is the need to disassemble the heat exchanger system, the residual layer of unremoved impurities and laboriousness (Abd-Hady, malaveri, Jalalirad 2014, PTC 2017). Pressure cleaning is based on pumping water under high pressure (up to 3000 bar) using special pumps (Woma 2019). This is a very effective method of removing deposits. During cleaning, the inner tubes of the exchanger are usually removed from the outer shell and sent to the cleaning station.

However, when moving the exchanger is not appropriate, special equipment is_used that can handle cleaning even at the place where the exchanger is located (Rossiter, Jones 2015). This equipment must be portable and large so that it can be used even in a limited space.

Chemical (dry) cleaning is divided into two methods, namely reaction cleaning and decontaminating. In both cases, a combination of chemical reactions, flow and temperature is used. The success of cleaning depends on the right combination of all three aspects of cleaning. This is also the reason why planning dry cleaning takes much more time than planning pressure cleaning (Rossiter, Jones 2015). When dry-cleaning power equipment composed of several types of material, care must be taken to ensure that the chemical does not damage any component. Poor qualification and ignorance of persons can result in damage to the entire cleaned system (Kuchar, Kreibich 2019). Dry cleaning is divided into: reactionary; and decontamination.

According to (Rossiter, Jones 2015), the reaction cleaning method is used to remove inorganic deposits such as calcium, carbonates, phosphates and sulphates. The main reason for using reaction cleaning is to increase the energy efficiency of water coolers and boilers in particular. Depending on the type of sediment and material of the power plant, a weak or strong acid is allowed to flow through the circuit to remove deposits while having as little impact as possible on the base material. It is important to be careful not to expose the pipes to acid for an unnecessarily long time, otherwise there is a risk of degradation of the base material. After cleaning, passivation usually comes into play. Passivation is also dependent on the type of base material, for example, carbon steel is passivated with sodium nitrite and stainless steel with soda ash.

According to (Rossiter , Jones 2015), decontamination cleaning is also used in the removal of hydrocarbon deposits. Various methods are used, from pH adjustment to surfactant packages focused on specific types of hydrocarbons. Flow and temperature are regulated in different ways according to the type of chemical used. The required flow rate can be achieved by circulation, filling and soaking, or even by application in the gas phase. The temperature is often controlled by direct steam injection, or by using an additional heat exchanger.

The advantages of dry cleaning over pressure cleaning are according to (Rossiter, Jones. 2015): *price* – carried out without costly and time-consuming disassembly and installation of equipment, thereby reducing labor and system downtime; *efficiency* – significantly improves the cleanliness of the system, deposits are often completely removed, increasing the efficiency of heat flow and transfer; *thoroughness* – complete removal of deposits prevents the appearance of new deposits and prolongs the operating time of the equipment; *speed* – noticeably faster than most methods, especially on more complex systems; *range* – allows cleaning in otherwise inaccessible places; and *operation uninterrupted* – some methods can be performed without shutting down the device.

The disadvantages of dry cleaning compared to pressure cleaning are (Rossiter , Jones 2015) are: *length of preparation* – greater planning requirements; *waste* – waste must be neutralized or disposed of by appropriate means; and *unexpected effects* – in the case of reaction cleaning, all deposits are removed, including those that may have helped, for example, in places where pipes are thinned by corrosion.

According to (Kieser et al. 2011, Kubín 2013), the sound cleaning method uses sound waves to create turbulence in the flowing medium. These turbulences cause loosening of the deposited layers or prevent settling. Audible (frequency approx. 75 Hz) or infrasound (approx. 10 to 35 Hz) waves are used. Infrasound waves induce higher turbulence, which leads to higher cleaning effects, but increases the risk of structural damage to the exchanger. Sound cleaning is a direct method with an optimal interval of a few minutes between cleaning cycles. Cleaning can take place by immersion in the bath, when the cleaned equipment needs to be melted, or when using special sound instruments, when cleaning can take place directly during the operation of the cleaned equipment. The application of this method is more in the prevention of fouling than in the removal of already applied layers, the best is a combination with another cleaning method.

4. Data on Experiment

Described experiment shows chemical cleaning of the exchanger. On a plate brazed exchanger from the heating industry, the flow and heating time of the secondary side to a temperature of 30 °C were measured before and after each of the two chemical cleaning (Kuchar et al. 2017, Kuchar et al. 2018). The exchanger parameters are in Table 1.

Table 1. Design parameters of the exchanger.

Parameter (unit)	Value
Operating temperature (°C)	175/-160
Operating pressure (bar)	32
Material (-)	AISI 304
Power for heating (kW)	500
Power for heating water (kW)	380

A circulation pump with a flow rate of 1.68 m3/h was used to ensure circulation, and an aqueous cleaning concentrate with an acidic pH was used as a cleaning agent. The cleaning time was 4.5 hours with all the preparation.

5. Method for Ensuring the Quality of Experiment Results

To ensure high quality experiment results, i.e. safe process of cleaning, and also correct recommendations for practice, we follow conditions at which the experiment is done, i.e. from safety reasons we manage risk of cleaning process . For risk rate determination we use check list method. According to rules given in (Prochazkova 2011) we compile the special check list in Table 2 and for its evaluation we use scale given in Table 3 (Prochazkova 2011) .

Table 2. Checklist for cleaning process; Y-yes, N-no.

Question	Y	N
Is the device checked before cleaning?		
Is a chemical analysis of impurities carried out before cleaning?		
Is the correct cleaning method used?		
Is there any pre-cleaning of the device?		
Are any cleaning parameters monitored during cleaning?		
Is there a flush after cleaning? (from detergent)?		
Is the surface passivated after cleaning?		
Is the device flushed after passivation?		
Are other parameters monitored besides the cleaning parameters?		
Is the device been inspected after cleaning and passivation?		
Is a suitable cleaning agent been used?		
Total		

Table 3. Value scale for determining the level of risk in measurement; the risk level ***r = n/N***, where ***n*** is the number of answers NO and ***N*** is the total number of questions.

Risk rate	Values *r in* %
Extremely high – 5	More than 95 %
Very high – 4	70 - 95 %
High – 3	45 - 70 %
Medium – 2	25 – 45 %
Low – 1	5 – 25 %
Negligible – 0	Low than 5 %

6. Experiment Results, Their Evaluation and Proposal of Countermeasures

The measurement results are shown in Table 4. After the first cleaning, the secondary side heating time was reduced by 18.75% compared to the uncleaned exchanger. After the second cleaning, the time was reduced by another 12.5%, i.e. by a total of 31.25% compared to the uncleaned exchanger. It follows that even according to the heating time of the secondary side, there was a significant improvement (Vlcek 2020).

Table 4. Measured values during heat exchanger cleaning (Kuchar et al. 2017, Kuchar et al. 2018)

Condition	Flow [m^3/h]	Secondary side heating time to 30 °C [min]
Uncleaned exchanger	0.3	16
After the 1st cleaning	0.8	13
After the 2nd cleaning	1.1	11

Based on data in Table 4, it is clear that:

- Before cleaning, the risk was very high in comparison with standard values, i.e. the failure of the technical equipment was almost certain.
- After the first cleaning, the risk level decreased, but not enough in comparison with valid standard. Risk level remained at the range of high and medium levels, and therefore, the cleaning of the second was carried out.
- After the second treatment, the risk level was further reduced to medium, which fulfils demands of standard.

From this it follows recommendation for practice (Vlcek 2020) - it is necessary to carry out a regular inspection of the exchanger in order that problems may be revealed in time and the level of risk would not rise to very high. Regular cleaning of the exchanger would also prevent the risk from rapidly increasing and prevent the risk level from rising. The heat exchanger operator should also notice the increased pressure at this range of clogging. Another measure that would slow down the rate of fouling and delay the increase in the risk level to a very high level is the use of filtration or water treatment. Both can reduce the amount of clogging and corrosion accelerating substances, thereby slowing down the clogging of the heat exchanger. The proposed measures are therefore as follows: observe regular inspections of heat exchangers; observe regular cleaning intervals of the heat exchanger; the use of filtration, or some kind of water treatment; and training of heat exchanger operators so that they can analyze data and prevent an increase in the level of risk in time.

7. Conclusion

The described experiment results show that mitigation of risk in real practice is not easy task. In spite of it is ensured that process of cleaning is done safely, i.e. with high quality, its results are not acceptable after first cleaning in comparison of valid standards in energetic practice. To reach acceptable exchanger condition, which is required by standards, the cleaning process must be carried out twice.

We conclude for practice that it is necessary according to (Prochazkova et al 2019) to:

- introduce risk-based inspections,
- ensure cleaning process safety,
- to carry out maintenance works according to risk level; sometimes works must be repeated..

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