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Improving Efficiency and Safety for Heat Exchangers and Water Piping by innovative Solutions

Agostino G. Bruzzone[1] *, Emanuele Magi[2], Antonio Giovannetti[1] and Bharath Gadupuri[1]

[1] Simulation Team, via Magliotto, 17100, Savona, Italy
[2] DCCI, Simulation Team, via Trento 34, 16145, Genova, Italy
[3] University of Genova, , via Opera Pia 15, 16145, Genova, Italy

*Corresponding author. Email address: agostino.bruzzone@simulationteam.com

Abstract

The purpose of the following Research Project is to improve the efficiency and safety of heat exchangers and pipes inside industrial plants thanks to the removal of limescale and biofilm. The automatic system is designed to keep pipes clean by dosing a mixture of inert gases of food purity. This solution is intended to be used to solubilize and avoid the formation of limestone deposits and concretions, as well as biofilm, inside pipes and accessories of hydraulic circuits with particular attention to the Industrial Plant

Keywords: Threating Water; Limescale ; Biofilm; Concretion in heat Exchangers and pipes, Modeling Cleaning Processes

1. Introduction

Limestone incrustations and biofouling in the fresh or sea water piping systems, represent a crucial issue in Industrial Plants because of the reduction of the flow rate efficiency. The accumulation of these incrustations reduces the useful section and consequently the water flow gradually decreases up to the limit and in the worst case to stop completely (Andristos et al., 1997, Muryanto et al., 2014). Furthermore, since the thermal conductivity of limescale deposits is much lower than the thermal conductivity of metals, the fouling not only seriously affects the heat transfer efficiency of the heat exchanger, but also easily leads to system malfunctions (Knudsen, 1981).

In addition, the incrustations generate efficiency problems in the pipes and in heat exchangers, creating "hot spots", for instance in boilers operations (De Baat Doelman, 2001, Liang et al., 2011). The high maintenance costs of the machinery and the decrease in productivity, due to the increase of time in which production and/ or service cannot be carried out regularly, lead to the continues search for new systems capable of preventing or reducing fouling.

For these reasons it is essential to find a method that is able to definitively eliminate the limestone in order to return the components to their initial state and functionality. This would obviously lead on one hand to the reduction of both maintenance costs and MTBF (mean time between failures), and on the other hand it would increase the productivity and therefore the profit of the Industrial Plant.

To reach this goal, in this study it is proposed an innovative anti-corrosion method that uses a mixture of food-grade, inert gas to be injected into the water. This system aims to solubilize the limestone that is found in the suspended water and the limestone already formed in the pipes and in the heat exchangers. Furthermore, this method also seems to represent a defensive tool against Legionella Phneumophila.

The modern techniques of Modeling and Simulation allow us to think that this research can lay create the foundations to a database for future research linked to creating simulation models to help these systems to reduce MTBF and MTTR and support their management and their service. This is obviously an interesting point for future developments that will allow the creation of Digital twins of these systems capable of being scalable and applicable in different contexts and on different platforms (Boxall & Saul, 2005; Bruzzone et al., 2012 & 2017). This approach can be very promising to create aids both for the training of operators and for both remote and predictive maintenance by integrating with the appropriate Extended reality and Artificial Intelligence supports (Bruzzone et al., 2013).

2. State of the Art

Limestone can be defined as a solid deposit of salts dissolved in water. A parameter that expresses the content of some of these salts is hardness, defined as the total content of Calcium ($Ca2+$) and Magnesium ($Mg2+$) ions. The unit of measurement most used for the water hardness corresponds to a content of calcium and magnesium salts equivalent to 1g of calcium carbonates ($CaCO3$) every 100 liters of water. The total hardness of the water is the sum of the temporary hardness and the permanent hardness. The first one is caused by calcium bicarbonates $Ca(HCO3)2$ and magnesium bicarbonates $Mg(HCO3)2$, which can be eliminated by heating the water. In this process there is a loss of carbon dioxide which gives rise to the formation of slightly soluble carbonates which precipitate in the solution. This occurs, for instance, when hard water flows through heat transfer equipment: bicarbonate ions precipitate forming mineral deposits (limestone) on the heat transfer surface in a process called “fouling”:

$$Ca^{2+} + 2HCO_3^- \rightleftarrows CaCO_{3(s)} + H_2O + CO_2 + H_2O + CO_2$$

Fouling can be defined in the simplest way as that unwanted deposit or sedimentation on heat exchange surfaces that can reduce the effectiveness of the equipment. Some of the typical deposits that appear on the surfaces of heat exchangers are made up of mineral substances such as calcium carbonate ($CaCO3$), calcium sulfate ($CaSO4$) and calcium silicate ($CaSiO2$).

These deposits create a layer that has been shown to resist the heat transfer rate in heat exchangers mainly due to the very low thermal conductivity (2.9 Wm-1K-1) of the mineral salts. There are some significant parameters that need to be considered (Andristos & Kabarelas, 2003):

• speed: low flow speeds favor the growth of encrustations.

• fluid temperature: the chemical fouling reaction is influenced by this factor since it usually determines the activation energy threshold for a chemical reaction

• surface temperature of contact with the heat exchanger: this temperature regulates the solidification speed of the encrustations on the surface.

• pH: determines the alkalinity or acidity suitable for the formation of certain minerals

• surface of the material: some surfaces are prone to favor biological fouling and some increase the deposition of minerals.

• surface roughness: the rough surface provides a larger total surface which facilitates the formation of encrustations.

• heat exchanger configuration: the type of heat exchanger is one of the problems affecting the scale rate.

Another important aspect to consider is biofouling, which refers to biological deposits on any surface. Biofilms are made up of both microbes and their extracellular products, usually polysaccharides. The effect of the biofilm is to protect microbes from hostile environments and to act as a trap for the acquisition of nutrients (Yin et al., 2019; Characklis, 1990; Mattila-Sandholm & Wirtanen, 2009). In addition to causing problems of cleanliness and hygiene, biofilm can cause energy losses and form blockages, even total, in condenser tubes, cooling fill materials, water circuits and heat exchange tubes. The biofilms form a gel layer that isolates the surface of the heat exchanger from the liquid phase. The gel allows only the diffusive transport of heat. Therefore, heat transfer by convective transport is inhibited. In addition, the frictional resistance is increased, which increases energy consumption. Biofouling problems do not arise from microorganisms that have suddenly invaded the system, but are much more likely to be caused by an increase in the concentration of nutrients or the absence of inhibitory factors (Flemming, 2002).

The hard waters treatments can be divided into two types: physical and chemical-physical treatments (external) and chemical conditioning (internal).

Among the most used physical and chemical-physical treatments are filtration and softening. In filtration, hard water is passed through a membrane. However, this treatment remains very coarse and not very useful for the purposes of real prevention and elimination of limestone deposits.

Softeners are devices that allow to soften the water using ion exchange resins. Resins are artificially produced organic substances that have a "mobile" functional group, that is in chemical equilibrium between the resin itself and the ions dissolved in the water. When water containing calcium and magnesium passes through a resin in the sodium form, these are retained in place of the sodium present, which is released to the water. Obviously, the resin loses its functionality with each use and must therefore be regenerated through the passage of water containing a high concentration of sodium ions through the resin. Softening therefore represents a process that must be constantly kept under control.

Another recently used physical treatment is the magnetic decalcifier. This physical treatment consists in the passage of hard water through a powerful magnetic field, so that the calcium carbonate and all the other ions dissolved in the water are electrically saturated.

The use of chemical additives to reduce water hardness represents a field of research that is still expanding today, with the important requirement of eco-compatibility that these products must strictly meet. In fact, when selecting an anti-fouling method it is important to consider the nature of the microorganisms, the thermohydraulic conditions of the process, the costs of the treatment, safety, environmental impacts (Eguìa et al., 2008).

There are references of experiments conducted in the use of mixtures that use CO2 to reduce limescale deposits both on heat exchangers and on membrane desalination plants where these are deposited and it is therefore necessary to try to solubilize them to clean the membranes (Krauter et al ., 1998; Hart et al., 2011; Peng et al. 2016; Shahid 2017 & 2018). In these cases, studies related to which pH value to maintain to inhibit the formation of limestone deposits may be of interest.

The variety of methods for water treatment and their continuous research suggests that it is not yet possible to find a completely effective solution to the problem of limestone and biofilm inside pipes and heat exchangers. for this reason an innovative method is proposed in this paper which aims at the total elimination of the problem.

3. Case Study

The method reported in this study is based on the use of a mixture of inert gases of food purity capable of solubilizing and avoiding the formation of incrustations and calcareous concretions and biofilms inside pipes and heat exchangers. Furthermore, this method in liquids binds dissolved free oxygen which causes oxidation and fermentation of the bacterial load. In particular it seems to represent a useful defense tool against Legionella. In fact, due to the biofilm layer present in the pipes, the effect of the disinfectants is canceled. The action of this treatment against Legionella is therefore indirect, since it eliminates the biofilm allowing the disinfectant to intervene on the bacterium.

In order to study the efficacy of this innovative treatment a circuit has been designed and it is represented in Fig.1

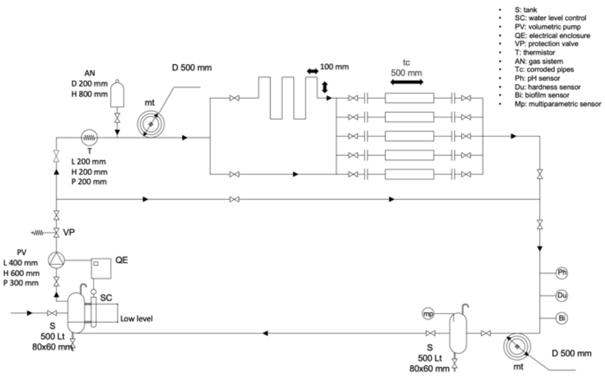

Figure 1.

In this circuit, the pump pushes the water through the first part of the pipe which circulates the gas mixture in the water. A skein of tubes allows the gas to be absorbed before passing the mixture inside test tubes that derive from already encrusted pipes. The mixture containing scale and biofilm residues is analyzed using biofilm, pH and temperature sensors. The water is thus discharged into the tanks where there are parametric probes that study the characteristics of the water.

In our Case Study, the goal is to parameterize the action of the descaling agent on a Naval Unit of 200 crew members with a per capita consumption of 200 liters of water per day, for a total of 40 cubic meters. Therefore these measures will be scaled in order to study the action of this innovative method within a circuit.

The action of any descaling agent, whether chemical or physical, obviously depends on the type of motion inside the duct. With a turbulent motion, the descaling action will be more effective but at the same time it is not always possible to maintain high fluid flow rates in all the pipes. For this reason, in the study the action of this system will be examined through two different types of regime, laminar and turbulent.

In laminar motion, the various layers of a fluid move in a translational motion, sliding on top of each other without forming vortices. On the contrary, in turbulent motion the fluid particles exhibit a chaotic motion. The calculation of the type of motion is done by means of the Reynolds formula below:

$$Re = \frac{wD\rho}{\mu}$$

Re = Reynolds number [-]

w = fluid speed [m / s]

μ = dynamic viscosity [Pa * s or N * s / m2 or Poise)

ρ = density [kg / m3]

D = diameter ["o m]

It is therefore sufficient to modulate the speed to obtain different regimes and consequently study the action of our system on calcareous concretions and on the biofilm as the fluid motion varies. If Re <2100 the motion is certainly laminar, if Re <2500 and Re> 2100 the regime is said to be metastable, if Re <3500 and Re> 2500 the motion is in transition regime while if Re> 4300 the regime is turbulent. Through this formula it is therefore possible to calculate the critical speed (the limiting speed of passage from one regime to another).

During the experimental analysis we will therefore vary the parameters of speed, flow rate, etc. to optimize the efficiency of our gas mixture.

This innovative system is a mixture of inert gases of food quality that injected into the water, aims to solubilize the limestone that is found in the same in suspension and the limestone already formed on the walls of the water network and in the heat exchangers. Furthermore, this gas mixture in liquids binds dissolved free oxygen which causes oxidation and fermentation of the bacterial load. In particular it seems to represent a useful defense tool against Legionella. In fact, due to the biofilm layer present in the pipes, the effect of the disinfectants is canceled. The action against Legionella is therefore indirect, since it eliminates the biofilm allowing the disinfectant to intervene on the bacterium. The modern techniques of Modeling and Simulation allow us to think that this research can lay the foundations, through its experimentation, to create the database necessary for future research linked to creating simulation models to help these systems and support for the management and their service. In fact, the experimental campaign that will be conducted could prepare the knowledge necessary to create models based on modern Modeling and Simulation techniques to study these phenomena in relation to the plants and evaluate both their efficiency and environmental impacts, with particular attention to the context. operational under consideration and in the marine environment. This is obviously an interesting potential for future developments that will allow the creation of Digital Twins of these systems capable of being scalable and applicable in different contexts and on different platforms (Boxall & Saul, 2005; Bruzzone et al., 2012 & 2017).

On the one hand, this approach can be very promising to create aids for both operator training and remote and predictive maintenance by integrating with the appropriate Extended Reality and Artificial Intelligence supports (Bruzzone et al., 2013)

From this point of view, the study in question envisages the application of Design of Experiments, Sensitivity Analysis and Metamodeling techniques to extract useful information and approximate models from the experimental data (Montgomery 201). This activity may, in the future, be used, together with other analysis and control systems, to create the dynamic component of the aforementioned Digital Twins. In this way it will be possible to create a series of new aids both for the design phase of the engineering, and for the installation and commissioning of the plants, but above all for the operational use and the service (Bruzzone et al., 2018; Dawood 2020)

4. Conclusions

This study introduces an innovative method against the formation of limestone and biofilm, as well as a remedy for the appearance of bacterial populations such as Legionella. The mixture of inert gases of food purity used is being tested and its concentrations will be tested to evaluate its effectiveness and optimize its parameters. Limescale deposits represent a big problem for pipes and heat exchangers, reducing their effectiveness and raising the costs of any system due to a higher energy requirement. For this reason it is important to find a definitive and low cost remedy against this problem. In this study, many parameters of treated and untreated water will be analyzed to understand the real action of this innovative system. This treatment also represents an important resource for creating, through the analysis of its effectiveness on already encrusted pipes, a database that can be used in the future to generate predictive and simulation models.

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