RESEARCH REPORT

Asset management research project

The research on water jetting
for maintenance of Heat Exchangers

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1. Introduction

In all sectors of the economy, whether in the governmental or private sector, one of the most crucial factors for success is the ability to maintain one's assets most efficiently and effectively. Finding the best approach for the maintenance of an asset means that it will create the best value possible, that can be transformed into a profit, like production rate or revenue. If the maintenance strategy will fail it can create certain risks or limitations in the operation of an asset that consequently can shorten the lifespan of an asset, or even make it worthless.

The "DOW" company, or "the client", is one of the world's leading suppliers of chemicals, plastics, synthetic fibers, and agricultural products. This company is international and has more than 33 billion US dollars in net worth. Besides having a lot of industrial assets around the globe to take care of this company also participates in environmental care programs, such as climate protection action plans, the circular economy, and the development of "safer" materials. The company's effort was recognized by international agencies and governmental institutions several times, for example, "DOW" became a 2008 Energy Star Partner of the Year for excellence in energy management and reduction in greenhouse gas emissions.

However, in the modern world with its climatical and environmental challenges, it is not merely an achievement to develop environmentally friendly strategies, it is a matter of utmost importance for the future of nature and humanity. Therefore "DOW" keeps setting new ambitious goals and roadmaps, like the 2025 sustainability goals of the company.

Therefore, the company is in constant search of sustainable and environmental development. However, to achieve it, the breakdown of all the processes is needed to find a way to optimize the operations of "DOW". Only by improving every link of the production and operational chain, it is possible to achieve development for a whole system.

1.1. Background material

1.1.1. HEX cleaning methods

Figure 1. A close-up view of a tube heat exchanger tube bundle. Moskvitin, A. (n.d.). Shutterstock.com.

Among many assets of the client, there is a particular one that can be found in many production chains – shell and tube heat exchange. The heat exchanger, or HEX, is the most commonly used pressure vessel in the process industry (Patil et al., 2017), particularly in oil refineries and many chemical productions. This system is used to transfer the heat between the source and the working fluid, both for heating and cooling operations. The most common application is cooling the undesirable heat generated by industrial activities.

During the operation of HEX, the surfaces of a heat exchanger's inner and outer parts develop layers of solid material called fouling material. HEX systems are subjected to many fouling materials of different natures due to the vast number of applications of heat exchangers. This material can contain but is not limited to waxes, cokes, dust, bacteria, minerals, etc. The fouling materials change the properties of the system, decrease the area of the tubes, reduce the efficiency of heat exchange, and therefore create risks for operation.

There are numerous methods to clean shell and tube heat exchangers from fouling materials. The client developed the decision tool, that describes the procedure of overall selection and work process for the maintenance of the company's assets, including factors of choosing a fitting cleaning method for the right equipment, general determining of the type of fouling, factors to consider in equipment design, etc.

Among other guidelines, some tables compare different cleaning methods. The information provided is based on two factors:

- whether the cleaning method is effective against specific fouling materials *(table 1);*
- whether the cleaning method can be applied to all parts subjected to fouling contamination in different designs of HEX *(table 2)*.

Cleaning methods		Mechanical																	Thermal			Chemical		
	Organic of nature	Tube Darting & Scraping	3D- Nozzle	Rotating Hose Devices	Water Jetting (UHP)	Pigging	Ultrasonic Baths (Chemical Cleaning)	Abrasive Blasting	Drilling (Rodding)	Hydrokinetic Cleaning	Manway Canons	Remotely Operated Vehicles	CO2 Blasting	Flushing	Brushing	Air Lancing	Sodium Bi-Carbonate Blasting	Vacuum, Blowing, Suction Techniques	Liquid Nitrogen Jetting	Laser Cleaning	Pyrolysis	Acidizing	Degreasing	Decontamination
Asphaltine	+		+	+	+		+	+	+			+					+		+	+	+		+	+
Cokes	+			+	+	+		+	+			+					+		+	+	+			
Coolingwater Products		+	+	+	+	+	+	+	+			+							+	+		+		
Corrosion			+	+	+	+	+	+	+			+					+		+	+		+		
Dust		+	+	+	+	+	+		+			+	+	+	+		+	+	+	+				
Oil	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+		+	+	+		+	+
Paraffin	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+		+	+	+		+	+
PolyEthylene	+		+	+	+				+	+		+								+	+			
Organic Scale	+		+	+	+		+	+	+			+					+		+	+		+		
Anorganic Scale	-																							
Waxes	+	+	+	+	+	+	+		+	+	+	+	+	+	+		+	+	+	+	+		+	+

Table 1. Cleaning methods effectiveness for fouling materials. (DOW)

According to the information provided by the client, many cleaning methods were observed and evaluated, including mechanical, thermal, and chemical cleaning methods.

Several cleaning methods show the versatility in application against all fouling materials represented in this table. These cleaning methods are Water Jetting (UHP – Ultra high pressure), Rotating hose devices, Drilling (Rodding), Remotely operated vehicles, and Laser cleaning.

While the degree of efficiency of each cleaning method for a particular fouling material is not clear from the data provided by the client, it is still possible to indicate whether or not a particular cleaning method can remove certain materials from the surface. However, since the fouling material is rarely of the singular type, and is usually developed in several layers of different materials formations attached, the versatility gives the knowledge that it is not needed to apply different methods for a cleaning activity, and it is possible to use a different setup of one cleaning method to get rid of all the layers present in the system.

Another factor affecting the versatility of cleaning methods is the ability of a cleaning method effectively reach every part of the equipment that is subjected to fouling.

Cleaning methods	Mechanical																	Thermal			Chemical		
	Tube Darting & Scraping	3D - Nozzle	Rotating Hose Devices	Water Jetting (UHP)	Pigging	Ultrasonic Baths (Chemical Cleaning)	Abrasive Blasting	Drilling (Rodding)	Hydrokinetic Cleaning	Manway Canons	Remotely Operated Vehicles	CO2 Blasting	Flushing	Brushing	Air Lancing	Sodium Bi-Carbonate Blasting	Vacuum, Blowing	Liquid Nitrogen Jetting	Laser Cleaning	Pyrolysis	Acidizing	Degreasing	Decontamination
Shell and Tube																							
- Bundle (inside tubes)	+			+		+		+	+				+	+				+		+	+	+	+
- Bundle (external)				+		+	+					+	+			+		+		+	+	+	+
- Shell		+	+	+			+					+	+			+		+	+	+	+	+	+
- Heads & Channels				+			+					+	+			+		+	+	+	+	+	+
Shell and Tube (Not towable)																							
- Bundle (inside tubes)	+			+		+		+	+				+	+				+		+	+	+	+
- Bundle (External) + Shell						+							+							+	+	+	+
- Heads & Channels				+			+					+	+			+		+	+	+	+	+	+
Shell and Tube U-Bundle																							
- Bundle (inside tubes)	+			+		+			+				+	+				+		+	+	+	+
- Bundle (external)				+		+	+					+	+			+		+		+	+	+	+
- Shell		+	+	+			+					+	+			+		+	+	+	+	+	+
- Heads & Channels				+			+					+	+			+		+	+	+	+	+	+
Fin Fan / Aircoolers																							
- Tubes (inside)	+			+				+	+					+							+	+	+
- Fined tubes external				+									+			+						+	
- Collector				+			+					+	+			+		+	+		+	+	+
- Collector Plate				+		+	+					+	+			+		+	+	+	+	+	+
Compablock/Plate Exchanger																							
- Plates				+		+	+					+	+			+		+	+	+	+	+	+
- Housing				+		+	+					+	+			+		+	+				
Compablock/Plate Exchanger (Welded)																							
- Plates + Housing				+		+							+							+	+	+	+

Table 2. Cleaning methods effectiveness for equipment parts of different Shell and Tube designs. (DOW)

As the result, from the information provided the water jetting technique can be identified as the effective method that is suitable to be used as the primary cleaning method due to its versatility and reach. However, the degree of effectiveness against certain fouling material types, optimization of the water jetting setup for different fouling events as well as optimization of the cleaning process itself are important matters for research. Also, it is important to note that in reality the primary cleaning method may be supported by some other secondary maintenance activities (e.g. brushing) to compensate for the drawbacks of the primary cleaning method.

1.1.2. Water jetting

Figure 2. Cleaning with a high-pressure water jet. hydroblast.co.uk (n.d.)

Water jetting, or hydro blasting is a technology that is broadly used in many fields besides cleaning. For example, one of the most common applications in the industrial sector and mining is using water jetting as a cutting technique, cutting softer materials with straight water jets, and cutting the hardest metals with abrasive water jets. This example is a good representation of the forces that can be achieved with jetting technology. Another common application is the surface treatment process, where water jetting is used alone or as a part of a bigger machining process. It is used to perform surface hardening, de-coating, cleaning, and other manufacturing and maintenance activities. (Jurisevic et al., 2005)

The range of designs of waterjets that found useful application starts with 10 bar and flow rates of less than one liter per minute (lpm). The most extreme waterjet designs that are used in mining have flow rates of over 1000 lpm, while the military uses of waterjets have an impact pressure above 600,000 bars. (Summers D., 1995) Every year there are new designs of water jets come to the market, its' ever-growing technology development optimizes its works and pushes its extremes even further. During the last decades, this development led to the usage of water jets in new, unexpected ways.

Regardless of the application, water jetting machining processes have a similar three-step process: firstly, energy in the fluid is created by a drastic increase in its pressure. Secondly, a high-speed jet is generated at the output orifice. And finally, the kinetic energy of this jet creates an impact at the surface or working area, acting on it with a required force. (Jurisevic et al., 2005)

1.2. Problem statement

1.2.1. Maintenance

There are many consequences connected to fouling appearance in heat exchangers, related to increased capital investments, additional operating costs, loss of production, the costs of remedial action, etc. (Awad M., 2011) Fouling leads to thermal inefficiencies and occurrences of pressure drops that lead to energy losses. Therefore, the plant's production rate decreases due to losses of efficiency and due to the time that the plant is not in operation during the maintenance activities, while the cleaning of the plants as well as preventive measures like antifoulants are affecting the budget. Some designs of HEX, especially relatively large heat exchanger systems, are subjected to large budget losses due to the complexity and higher expenses of the maintenance activities for them. (Epstein N., 1983)

While many cleaning methods can be used for fouling removal still the optimization in terms of sustainability, time, resources, and energy efficiency of these cleaning techniques and maintenance strategies for HEX are the subjects of ongoing research. In the water jetting industry, many companies rely primarily on the guidelines drawn from the practical experiences of a particular company, while the results of these approaches are validated by visual confirmation of the effectiveness of the method. Therefore, optimization of the cleaning strategy commonly comes from the practical domain and lacks a theoretical foundation behind it. Besides, there is limited literature on this topic since private companies are keeping their developments and guidelines as a commercial secret.

The client, the "DOW" company, hires a cleaning company to perform maintenance of the client's assets, particularly water jetting cleaning of shell and tube heat exchangers. However, at the moment the client has doubts about the cleaning company's performance regarding the optimization of the cleaning methods that the cleaning company uses for maintenance. The client's goal is to avoid the abovementioned issues.

Many factors can affect the efficiency of water jetting cleaning, including nuances to particular designs of HEX, water jet setups, different approaches in operation, fouling material cases, etc. Therefore "DOW" hired the HZ University Asset management research group to validate and optimize the maintenance strategy. It is impossible to create a universal solution, there are hundreds of fouling materials and all of them have different properties that are interacting with many coating and construction materials. The setups of water jets are adjustable, and there are many ways to regulate the process of cleaning for an operator of a water jet.

The goal of "DOW" is to develop sustainable cost-efficient strategies. Particularly for water jetting several operation-related factors affect the sustainability and budget of the cleaning process. Besides the equipment, rent, labor, and water costs, there is one major factor that may be optimized – the amount of fuel used by the motor to generate energy that supplies the pump. The fouling materials can be cleaned by a range of pressures, however, if the process can be optimized to avoid excessive energy usage it will greatly affect the footprint and costs of the maintenance strategy.

1.2.2. Modelling and lab-test setup

"DOW" company together with its partner "Hexxcell" company developed a simulation model for internal cleaning of shell and tube heat exchanger's tube bundles shown in chapter 2.2.9. This model provides some tools for the minimization of total costs based on the optimization of needed target pressure for cleaning fouling material. However, it has some assumptions and approximations that do not take into account the mechanical and other important properties of the fouling material that are necessary to compare the model to the reality of the particular fouling scenario. Instead, the model suggests two fouling classes – hard and soft fouling, depending on the time between the maintenance events and consequent "hardening" of the fouling material Hexxcell and DOW suggest different factors for the determination of required pressure for cleaning the material.

The values that are described in this model can be provided by the client, and it is also possible to calculate the amount of energy applied from a water jetting system for a particular water jet setup. However, the information regarding how much energy is needed for a particular fouling material is lacking.

Therefore, one of the main problems is the fact that it is clear that to calculate the energy needed for each fouling layer that needs to be removed it is needed to overcome forces that bind fouling to the surface as well as forces that bind layers of fouling materials together, however, it is not clear how to express these values. The "DOW" company intends to perform lab tests, in collaboration with the research of the asset management group, to determine the lacking data and further develop the maintenance strategy.

1.3. Goals and objectives

The desk research, modeling for the cleaning of the fouling material and linking the model to the water jetting is the main focus of this research. This research is a part of the Asset Management project and will focus on the tasks and information required for the research group. Other members of the research group are focusing on their areas of research to provide complementary and comprehensive results.

The goals and objectives are expressed as the research questions. While the main research question is the main objective of this research, the sub-questions are used to frame the path to an answer to the main question, either by obtaining fundamental knowledge related to the topic or by narrowing the field of research to a particular topic.

1.3.1. The main research question

How to achieve effectiveness in the water jet cleaning used for maintenance of HEX systems that are subjected to different types of fouling materials?

1.3.2. The sub-questions

- What is a heat exchanger (HEX) and what kind of function does it perform?
- How does fouling affect the performance of HEX?
- What is water jetting and how is it used for cleaning?
- What properties of the setup and operation of the water jetting system can be adjusted to achieve cleaning effectiveness?
- What are the fouling materials' properties that affect the cleaning process of HEX tubes?
- How the material properties can be linked to the water jetting to determine and optimize removal rate?
- How the potential experimental design setup can be designed for the water jet cleaning of fouling?

2. Theoretical framework

2.1. HEX systems

2.1.1. Shell and tube heat exchanger components

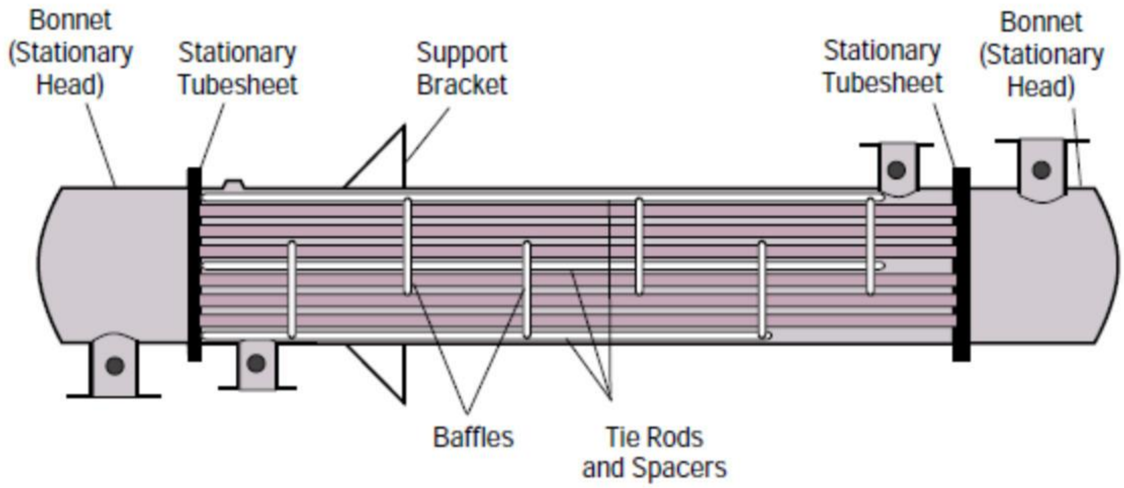

Figure 3. Fixed tube sheet exchanger. (Mukherjee R., 1998)

Shell and tube heat exchangers work on the principle of heat transferring between the hotter and colder fluids. Since the colder fluid heats in the exchanger tubes, the hot fluid transfers its energy to the colder fluid due to the law of thermodynamics. The inner tubes, also known as tube bundles, are located inside the vessel which is called an outer shell. Both shell and tube flows have separate inlets and outlets. Shell and tubes are made of thermally conductive metals, like steel or aluminum alloys, to achieve effectiveness in heat exchange between the tube-side flow and shell-side flow without mixing them. By changing the tube bundle setup the surface that is exposed to the heat exchange between the inner flow and outer flow can be regulated.

Shell and tube heat exchangers are preferred due to their excellency in heat transfer as well as their advantages in construction, operation, and maintenance in comparison to other designs of heat exchangers. (Patil et al., 2017) There are several types of designs of shell and tube heat exchangers, however, all of them have similar components *(Figures 3 and 4)*:

- shell and shell cover – designed to be corrosion-resistant and withstand extreme temperatures;
- tubes – are connected in tube bundles to provide the compactness of the HEX system as well as increase the transfer surface between hot and cold liquid;
- channel and channel cover;
- tube sheet or tubeplate – support for the tube bundle;
- baffles – the primary functions are to increase heat transfer and reduce fouling by directing a flow of fluids inside a system;
- nozzles – distribute fluids through a HEX system.

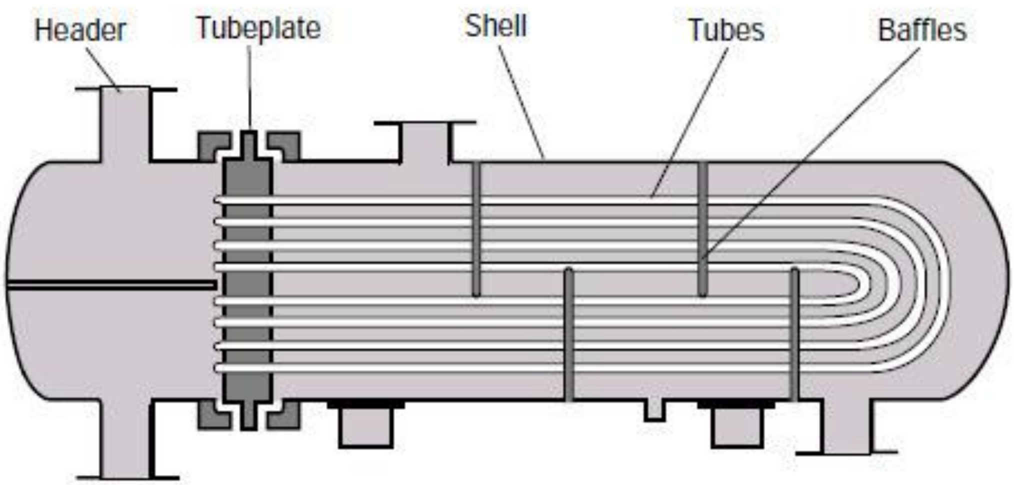

Figure 4. U-tube exchanger. (Mukherjee, 1998)

One of the major design criteria for shell and tube heat exchangers is the fouling resistance parameter that is determined for both shell-side and tube-side streams. (Mukherjee, 1998) Fouling layer depositions have low thermal conductivity and they reduce the cross-sectional area that leads to an increase in pressure drop in the system. (Awad M., 2011)

2.1.2. Cleaning of the shell side

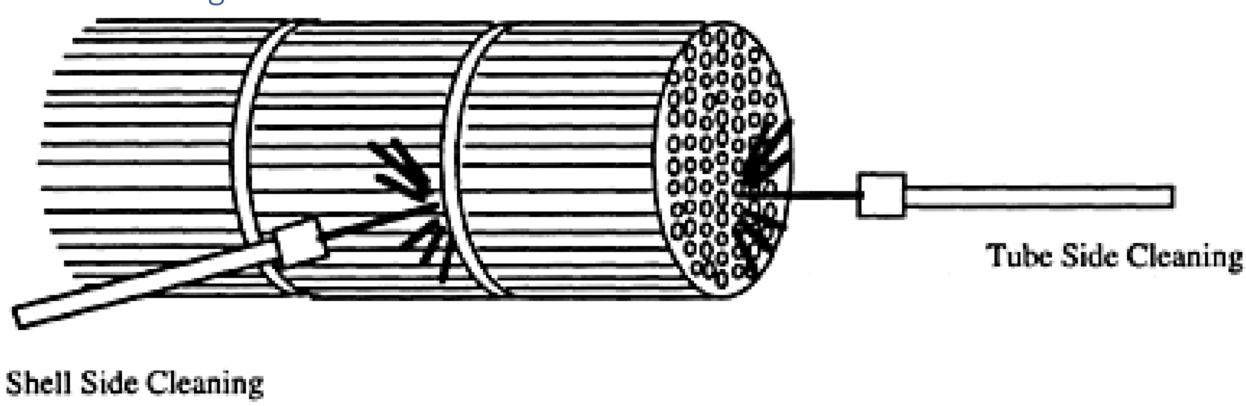

Figure 5. Tube and Shell side cleaning. (Summers D., 1995)

Cleaning of the shell side of heat exchangers is considered more difficult because HEX consists of many small diameter tubes. The shell side of the tubes is located on the outer layer, and depending on the number of tubes surrounding them, also called “forest”, it can be difficult to clean fouling material. (Summers D., 1995)

Generally, there are two main challenges of water jet application in cleaning – the reachability of the water flow, and ensuring the free unhindered flow of the washed fouling material along the water. In many shapes that have corners or certain “deepening” in the surface the appearance of fouling pockets is unavoidable. When the fouling pocket appears the fouling material that was washed away from the reachable parts for the water jet will be accumulated there until the pocket will be full. This decreases the heat transfer ability of the HEX system and leads to the need of choosing an alternative cleaning method.

However, unlike other cleaning techniques, the water sent by water jets into the tube bundle can reach the furthest openings between tubes and clean the material. The Tube and Shell design of Heat exchangers are very well fitted to be cleaned with water jets (Summers D., 1995). The flexible line or hose can penetrate deep inside the largest tube bundles, and there are modern automated and manual techniques to monitor the cleaning process as well as direct a line toward the desirable place.

2.1.3. Cleaning of the tube side

There are several factors affecting the cleaning effectiveness of the tube side of HEX:

- number of tubes;
- range of inlet diameters;
- geometry of the bundle.

Depending on these parameters adjusting the cleaning setup might be needed. In the past, the cleaning of the tube side was done by using a lance made of steel or a hose that was penetrating every tube manually. Nowadays, depending on the size of a heat exchanger and the number of tubes, cleaning can be done remotely by using frames with multiple lances that can penetrate several tubes simultaneously decreasing the time needed for maintenance activity.

Monitoring before, during, and after the cleaning process is essential in tube-side cleaning. Nowadays, the cleaning of the inner tubes is easier even in bundles with complex geometry due to the accessibility of inspection cameras and remotely controlled supply lines.

2.2. Water jets

2.2.1. Basic principles

Figure 6. Automated heat exchanger tubes cleaner. (n.d.) Ax-system.com

Water jetting, also known as hydro blasting, is a technique that is used to perform a vast range of work activities on the working surface.

There are several basic principles of the water jetting or hydro blasting process. Firstly, the regulated volumes of liquid from the tank are pushed into the high-pressure feed line, or lance, by a pump. Then, when the water travels to the end of a feed line it reaches a nozzle with one or multiple holes or orifices. Redirection of the flow into several smaller holes and a large decrease in the diameter leads to a further increase of water pressure before the launching of the stream. Since the volume of water that reaches the nozzle is constant the water at the orifices accelerates creating a water jet or hydro blast. The work is performed by applying the energy created by the pump that pushes the high-pressurized stream of liquid that is directed on the working surface and converts pressure drop in a system into kinetic energy. (Summers D., 1995)

Two main losses in the system can be identified: the loss in the line friction against the walls of the tube in the delivery line and the loss in places where the shape and size of the line changes, like in the nozzle or control valve, these changes in shape and size of the passages cause the occurrence of turbulence. (Summers D., 1995)

The energy of the jet, as a result of its velocity, when reaches the working surface is transferred to impact pressure, which can be used to calculate the effective amount of desired work done knowing the properties of the fouling material. There are two major factors behind this transition – the volume of water that reaches the object and jet velocity. These variables can be controlled by these factors:

- amount of water sent in a water jetting system;
- pressure output by a pump;
- number, size, and shape of orifices;
- the diameter of the delivery line;
- velocity of water in the lance.

Water jetting requires Ultra-high pressure, or UHP, to remove fouling materials. Modern UHP pumps are used due to their high power and pressure output, and their higher efficiency. Besides, usually, water jetting pumps have only a discharge function and do not have a suction section.

There are numerous designs of water jetting systems, however, all of them are working on these basic principles. The device diagram of the common handheld waterjet gun system is shown *(Figure 7).*

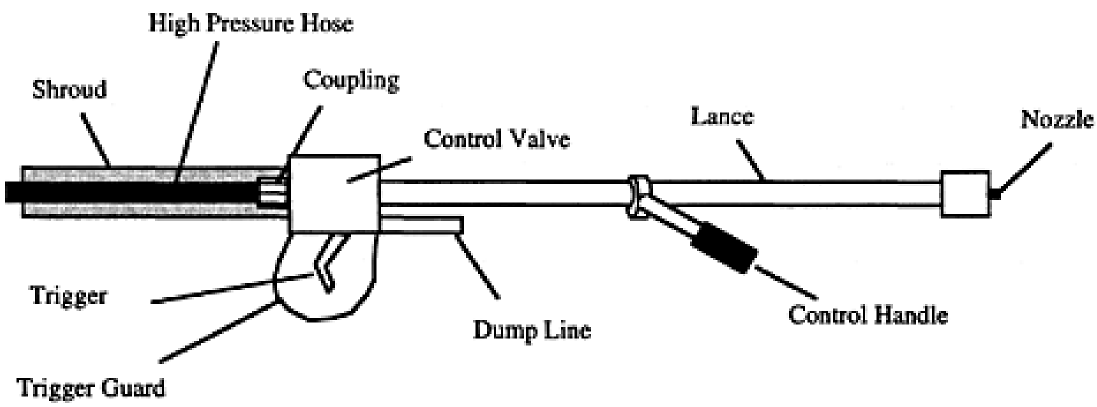

Figure 7. Device diagram of handheld water jet gun (Summers D., 1995)

- high-pressure hose to deliver water from the tank to the control valve;
- control valve that controls the volumes of water coming from a tank to the outlet;
- trigger or control lever is used to operate the control valve in manual handheld systems;
- dump line that directs the water at no pressure into the open air or back to the tank;
- control the handle to let the operator direct the water jet and control the standoff distance and angle of the water jet. It also helps to withstand the force that the jet applies to the operator;
- a nozzle, also called a tip, has different designs to set up desired properties of the water jet.

Apart from the design, the water quality is of great importance. If the water quality is poor and it contains a lot of solids it may lead to the fouling of the system during the cleaning and afterward, during the operation phase. (Bott T., 1995)

2.2.2. Nozzle design

The importance of the nozzle design was already mentioned. The nozzle design can entirely change the function and application of the water jetting system. For example, certain types of modified systems allow pulsating and interrupted water jetting – a setup that releases jets in the segment. Pulsating is releasing water segments with rapid phase and interrupted jets release singular shots with extreme pressure reaching very high velocities. In certain scenarios, this approach can improve the effectiveness of the jet on the surface. (Summers D., 1995)

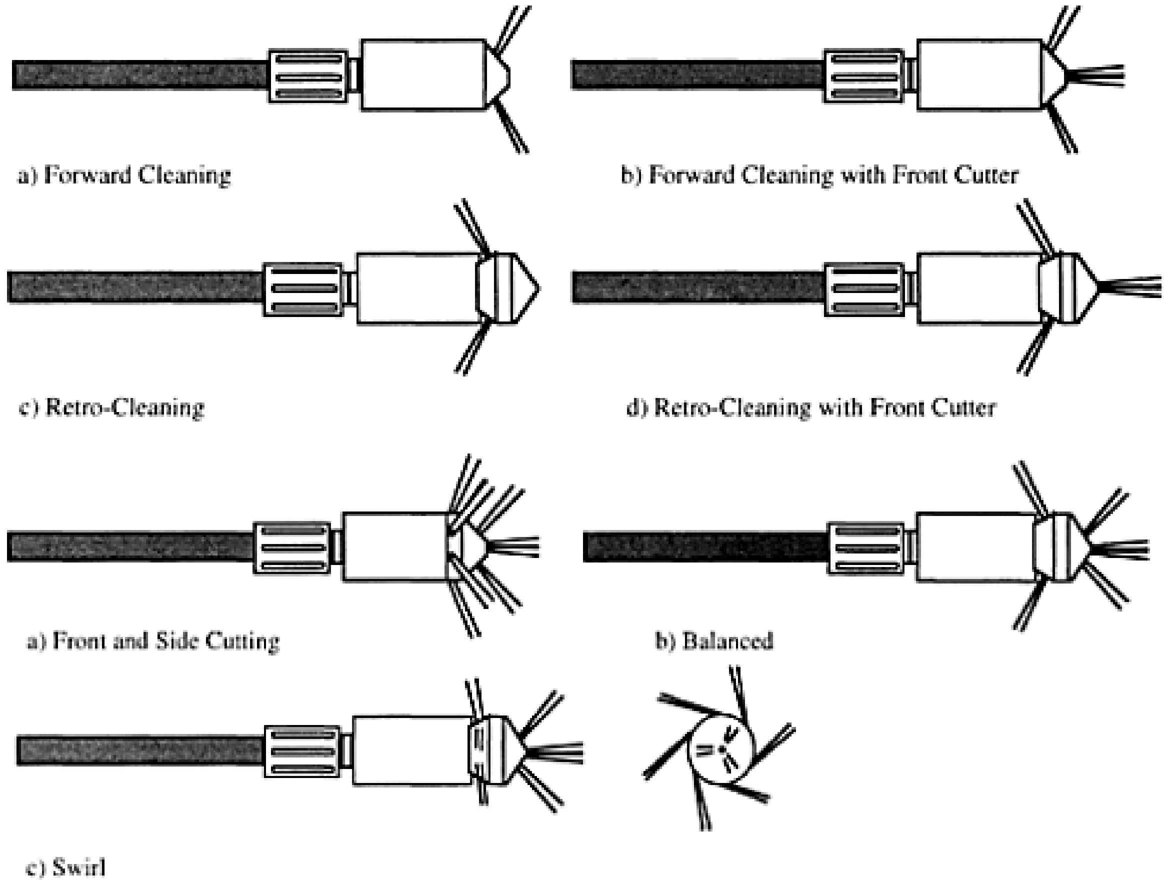

Figure 8. Design examples of nozzles used in tube-side cleaning. (Summers D., 1995)

The nozzle design balances the pressures, energy, and water consumption in the system. It controls several characteristics:

- Number and shape of orifices;
- Spray form and size;
- Flow rate;
- Jet thickness;
- Water distribution;
- Rotation speed and jet overlap.

The most common shape of the nozzle orifice is cylindrical, also known as a round jet. While the impact area is rather small this type of orifice carries well the output energy. The drawback of this setup is that on large surfaces it requires a lot of time, water, and power.

Another common type of orifice is fan jets. It shapes the water jet in a line that facilitates an increase in the effective surface area and cleaning times while maintaining high-impact efficiency. Besides, the uniformity of the jet allows easier operation and equal distribution of the jet on the target surface.

Many other designs of nozzles are used in different applications of water jetting systems. These nozzles have many names in the literature, generally, the systems that are not fan or round are called "shaped jets". (Summers D., 1995)

2.2.3. Jet velocity

To obtain the velocity of a jet flow Bernoulli's law can be applied, according to which the increase in the speed of the jet occurs with the decrease in the pressure (Momber A., 2003):

$$v_j = \left(\frac{2 \times p \times (1 - \frac{p_V}{p})}{\rho_W}\right)^{1/2} \qquad (2.2.3.1.)$$

Where:

p – pressure;
p_V – pressure loss;
ρ_W – density of water.

In this formula, the friction losses in the nozzle are considered, and introducing jet efficiency parameter μ, where $\mu = (1 - \frac{p_V}{p})^{1/2}$, the formula for typical water becomes:

$$v_j = \mu \times 44.71 \times p^{1/2} \qquad (2.2.3.2.)$$

The efficiency parameter depends on nozzle design and pump pressure, and it does not take into account the compressibility of the water and losses due to height difference. This factor was determined experimentally in four researches for some typical sapphire nozzle designs with the range of pump pressures:

Reference	**Pump pressure in MPa**	**Efficiancy parameter μ**
Neusen et al. 1992	69-241	0.92
Neusen et al. 1994	69-310	0.93-.098
Chen et al. 1991	90-350	0.85-0.9
Himmelreich et al. 1991	100	0.92

Table 3. Nozzle efficiency parameter.

The pressure drop occurs due to vertical difference between the supply and outflow as well as the horizontal distance that the flow must travel through the line. There are several approaches to calculate these losses and the horizontal and vertical component must be aligned. For example the water jet hose losses can be calculated with the formula (Labus T., 1989):

$$Pressure\ drop = \frac{0.597 \times Q^2}{100 \times D^5 \times Re^{1/4}} \qquad (2.2.3.3.)$$

Where:

Q – flow;
D – diameter of the line (in cm);
Re – Reynolds number;

Besides, the geometry of the orifice is important. The ideal flow rate is not possible to apply to the nozzle due to the difference in the nozzle design. Same nozzle diameters result in a wide range of actual flow and cross-sectional area rates. The coefficients for the most common orifice shapes are provided in the literature. (Labus T., 1989)

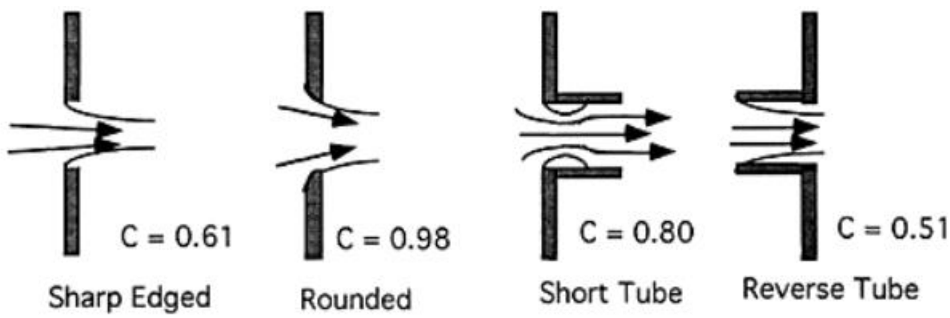

Figure 9. The shape of orifice factor. (Labus T., 1989)

2.2.4. Operating

Manual and automated systems

Operating a water jet system can be done manually or automatically. Some modern technologies allow the operator to control the water jet remotely decreasing the risk to health and safety. The decision of what type of system to use depends on the fouling scenario, the design of the equipment that needs to be cleaned, and other risk and efficiency factors. Automated water jetting systems can achieve higher pressures and larger coverage areas, and many nozzles can be used at once on especially large objects. Besides, automated usage is very safe since it can be used remotely for the most part. However, the manual application is more flexible when the automated approach is not feasible or not cost-effective, due to higher prices for the cleaning equipment and operation or when the dismantling of a maintained object is needed before cleaning. (Epstein N., 1983)

Experienced manual operation gives much better results than automated systems, especially in terms of footprint and cost efficiency, since the properties of fouling material deposition are not distributed uniformly on the surface, in reality, the cleaning might require slight adjustments for a particular area that are easier or harder to clean. (Summers D., 1995) The trapping and disposal of the cleaned fouling material and water needs to be considered accordingly to the volumes and type of cleaned material.

If the system is not controlled remotely sufficient lighting, ventilation, and bracing are required for an operator. The provision of personal protection equipment, good training, and information on the water jet cleaning setup and expected operational requirements of the cleaning event. The fouling material also has different behavior during the cleaning that can require additional safety measures and training. (Summers D., 1995) On average operators can safely withstand around one-third of their body weight. (Summers D., 1991) The reaction force can be calculated with the formula (Momber A., 2003):

$$I_j = m_w \times v_j = 0.743 \times Q \times p^{1/2} = F_R \qquad (2.2.4.1)$$

Where:

I_j – Jet impulse flow;
m_w – water mass flow rate;
v_j – jet velocity;
Q – flow;
p – pressure;
F_R – reaction force.

The weight of the operator can be translated to newtons and compared with the reaction force to determine whether the application of manual cleaning is safe.

2.2.5. Stand-off distance and impact angle

The stand-off distance is one of the determining decisions in water jet cleaning. It is a distance between the nozzle and the working surface, that can alter the power and area of work, also known as the resulting jet. By changing this distance, the energy applied on the surface is also changing exponentially, due to the many complex mechanisms, such as friction of the liquid stream in the air. It also changes the size and distribution of applied energy on the working surface or working piece. Moreover, if the distance is less than optimal the liquid does not exit the feed line fast enough and therefore it accumulates at the outlet creating shock absorption or even jamming. While if the distance is more than optimal it will lead to a lack of force applied and therefore a waste of water and energy. (Jurisevic et al., 2004)

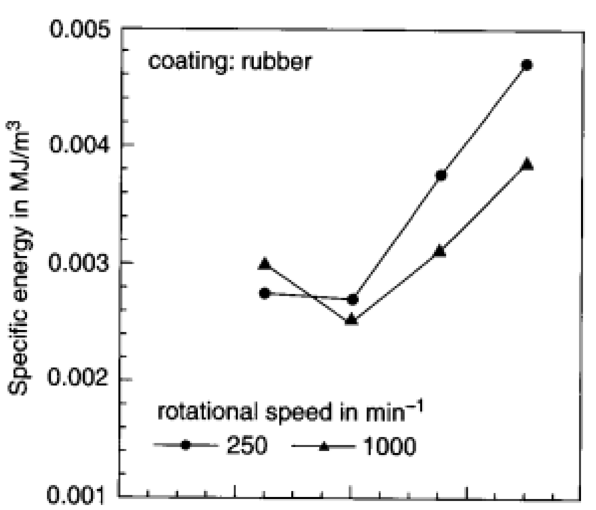

Figure 10. Impact angle influence. (Wright et al., 1997)

The determination of the optimum angle of impact depends on the type of surface, fouling material at the target, and water jet gun setup. The angle can be regulated manually in handheld systems and shell-side cleaning. In tube side cleaning the angle is mainly regulated by the design of orifices in a nozzle. The angle setup influences the removal rate of fouling materials and depending on the type of material the optimal angle can be different. The guide to water jetting describes that the impact angle of forty-five degrees is three times more effective than ninety degrees in metal removal, while if the thick rust layer is present the optimum angle of impact changes to 90 degrees. (Summers D., 1995) The article regarding coating removal suggests that the optimal impact angle in the case of coating material removal by application of water jets is in the range between 75 and 80 degrees. In coating removal perpendicular impact is the least effective in terms of energy efficiency, while the range from 45 to 60 degrees did not considerably affect cleaning efficiency. (Momber, 2004). Wright et al. (1997) showed the ratio between specific energy and jet angles for the removal of rubber coating that can be seen in the graph

In the literature, this difference is explained by the failure mechanisms of relative ductility and brittleness. (Summers D., 1995)

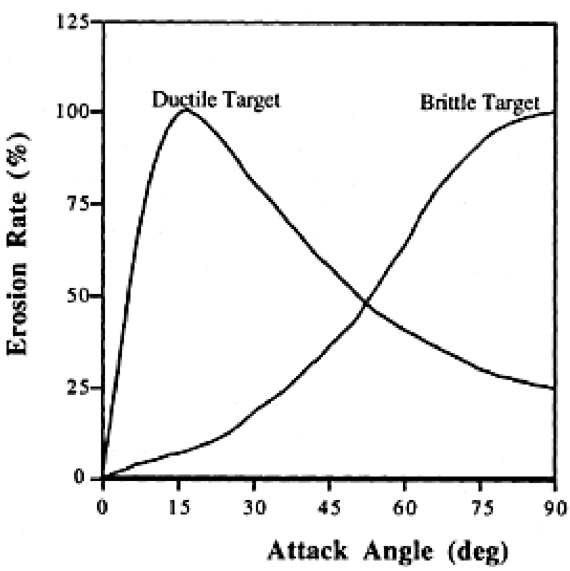

Figure 11. Ratio between the erosion rate and impact angle for brittle and ductile materials for abrasive water jets. (Summers D., 1995)

There are two types of material classification: ductile and brittle. Ductile materials have the ability to deform temporarily, or elastically, until a point called yield strength. After the yield strength threshold has been reached any strain is permanent, or plastic. Brittle materials on the other hand show no or neglectable amount of deformation.

Generally, the brittle materials will fail due to the cracking growth of the cracks that effectively occur at sharper angles. The ductile material on the other hand will fail due to the cut or plastic deformation of the material, that is easier achievable with the shallower angles. For a detailed overview of the phenomena refer to the literature. (Padavala R., 2004; Summers D., 1995)

2.2.6. Traverse speed

Traverse speed is the speed with which the nozzle moves over the target surface. Lower traverse speed means that the water jet stream will be acting on a particular area of a target surface longer. There are numerous ways to determine optimal traverse speed and the procedure is different for tube side and shell side cleaning. On the tube-side cleaning, numerous passes inside a tube will rarely be a cost-efficient solution, therefore the determination of the precise optimal effective time that the jet should impact on a particular area is required. The traverse speed for in-tube cleaning can be calculated with the formula (Summers D., 1995):

$$V_t = K \times D^2 \times P^{1.5} \times N \times E_f \div \rho^{1.5} \times CE \quad (2.2.6.1)$$

Where:

V_t –linear traverse speed;
K – standardized constant;
D – nozzle diameter;
P – jet pressure;
N – number of passes required per length;
E_f – overlap factor;
ρ – fluid density;
CE – relative energy factor.

Overlap occurs when more than one orifice acts on the surface at a time. The formulas related to overlap were not provided by the author, however, this phenomenon is closely connected to the design of the water jet nozzle and its operation. Therefore, these values can be determined for a particular water jetting system design and the formulas and models can be adjusted accordingly. The values for CE are shown in table 6. Some additional formulas related to traversing speed and application of polymers in water jetting (e.g. Super water) can be found in the literature. (Summers D., 1995)

2.2.7. Water jetting setup designs

Steam and heated water jets

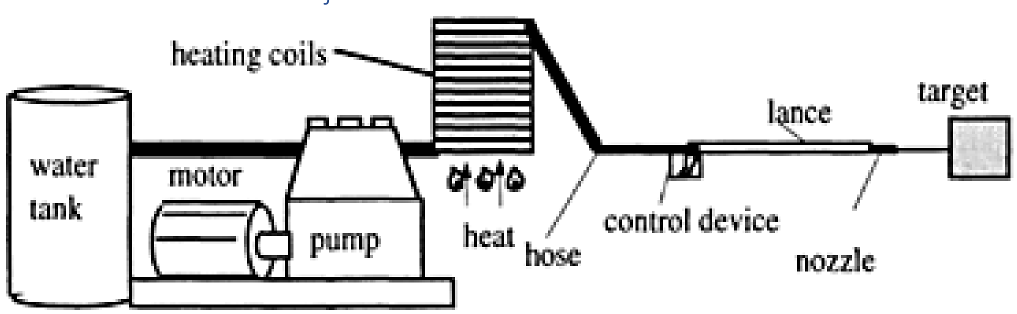

Figure 12. Schematic of heated water jetting system. (Summers D., 1995)

The first applications developed in the field of jetting techniques were mainly steam systems and heated jetting systems. To implement this system addition of the heating device to the regular system is needed. Such systems allow altering the temperature or state of matter of fluid in the system and in some material cases significantly improves cleaning rates. (Summers D., 1995)

In predominantly-steam water jets the additional heat losses appear, due to the length of the delivery line and the velocity and heat loss as the jet moves through the air towards the target surface. While there are some techniques that allow to decrease the losses, like insulation of the delivery line, these losses need to be calculated to reach desirable energy at the target. Due to the lesser degree of losses the heated water jets became more favorable than the steam systems. (Summers D., 1995)

Abrasive waterjets

Abrasive injection - has increased the range of products that can be cut including glass and metals. If the water is not enough to cut certain materials like glass or metals, the addition of abrasive particles like fine grade sand or aluminum oxide can increase the cut capabilities of the system. (Summers D., 1995) Another author confirms application of abrasive water jets for the cleaning of the fouling materials from the HEX equipment, however author stresses that it may be used only with care, if the risks for the equipment are taken into account and is justified, for example if the deposit strength is above the capability of the ultra-high pressure water jet. (Bott T., 1995)

Soluble abrasives are the dry particles added just before the jet leaves the outlet – after impact these particles dissolve, helping clean-up of the site after water jetting is done. (Summers D., 1995)

Cavitating waterjets

In modern designs of the water jet technique, it is possible to create cavitation inside of the water jet under certain circumstances. The analogy of this technique can be found in ultrasonic baths used for jewelry cleaning. By using vibration, alternating tensile and compressive waves created, tiny jets appear in the bath and clean the dirt even from the smallest cracks and holes in jewelry. (Summers D., 1995)

In a water jet, cavitation is achievable by applying tension to the water body before releasing it from the water jet. This creates small gas bubbles that are formed to fill the gaps between the water particles. After that, the water is pressurized again and the bubbles collapse, creating “tiny jets” that are formed just before they collapse. A very high impact pressure can be created when the jet passes through these bubbles. According to the water jetting guide, cavitated water jet with a pressure of 1000 bar can penetrate ceramic materials that cannot be penetrated by a regular water jet of 4000 bar. (Summers D., 1995)

Polymeric additives

Polymeric additives used in the water jet can adjust the properties of water in the system and reduce system losses. These additives, often long-chain molecular polymers, reduce the wall friction of the water stream going through the lance. Besides these polymeric additives can change the properties of the water in a way that helps keep the stream together after the jet leaves the outlet, therefore increasing the jet stream concentration and effectiveness of the work. (Summers D., 1995)

2.2.8. DOW and Hexxcell model

To calculate the efficiency of water jetting cleaning event of shell and tube heat exchangers condition-based simulation model was created by the client and Hexxcell. This model optimizes the setup of water jetting system according to the characteristics of the maintenance event. The model is only considering the tube side cleaning of shell and tube heat exchangers. It takes into account system's characteristics, like hoses, length, diameters and pressures. Model was created to optimise cost factors like: minimisation of fuel consumption at the pump level, reduction of labour cost and cost of equipment.

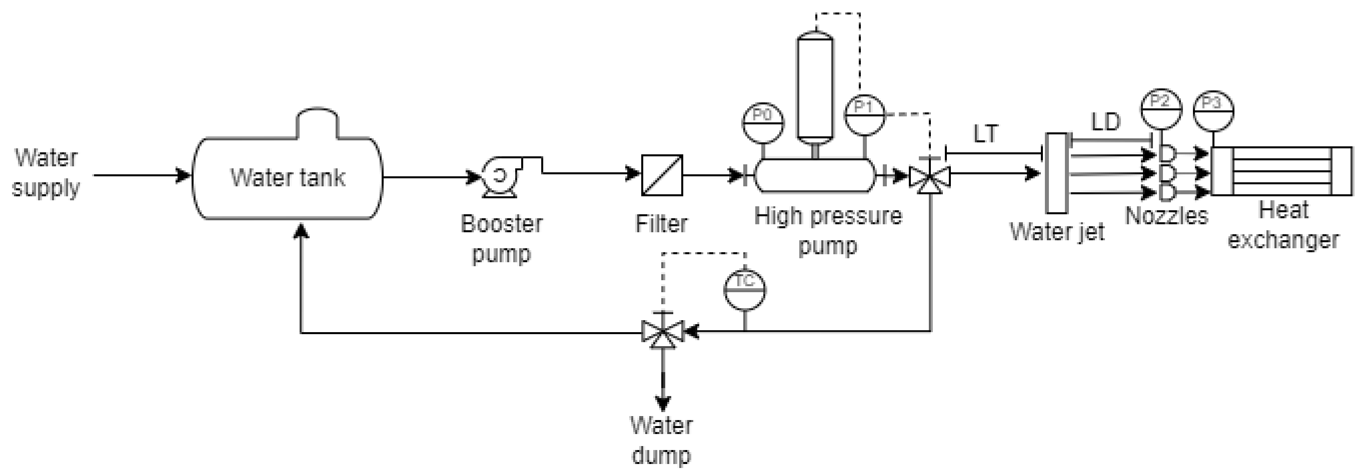

Figure 13. Water jetting system. (Hexxcell and DOW)

The water supplied enters the pump at pressure P_0 and discharged at pressure P_1.

Afterwards, the water flows through two sections of hoses at a flow F_T – through transportation zone and distribution zone. In both of these zones there are input values of length L, diameter d and roughness ε. In distribution zone the total flow is distributed among number of hoses and output nozzles.

The water reaches the nozzles with the pressure P_2 and a flow rate F_n.

In nozzles output the pressure P_3 is reached with velocity v_n.

Other inputs required for this model include: density and viscosity of fluid, friction losses in transportation hoses, distribution hoses and nozzles.

Model makes several assumptions:

- P_0 around 5 bar
- P_2 is determined from fouling conditions in heat exchanger (target pressure);

- No fluid velocity before pumping ($v_0 = 0$);
- No significant level difference along the system ($z_3 - z_0 = 0$)
- Total friction losses account for transportation hoses, distribution hoses and nozzles
- Roughness values estimated from specific commercially available hoses
- Flow rate in distribution zone split equally among nozzles

After the output pressures were calculated they can be compared with the fouling material at the target. Model includes the state of tube bundle, including quality and quantity of fouling material in tubes.

This model uses assumption that all fouling materials are either softer or harder, depending on the frequency of cleaning events. The graph below shows the required fouling material (scaled) pressure and weeks since the last cleaning event.

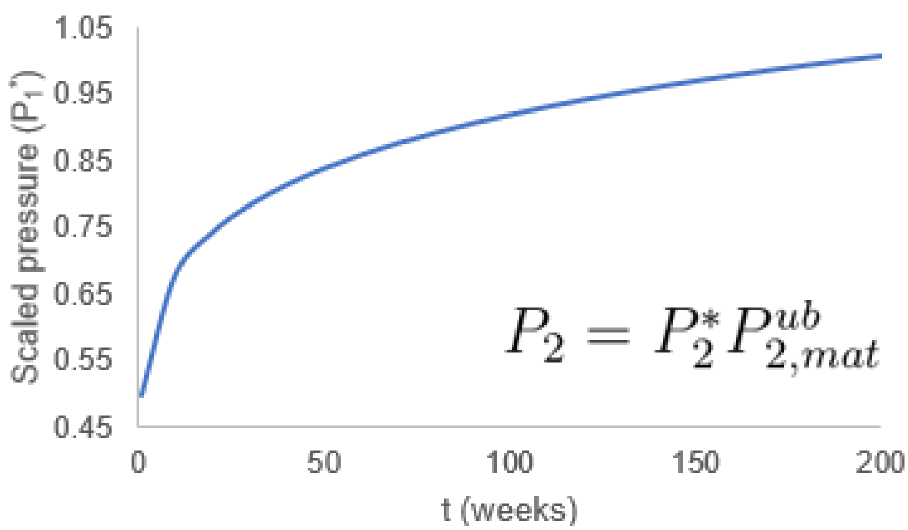

Figure 14. Graph of required pressure for a fouling event. (Hexxcell and Dow)

This determined factor for fouling "hardening" is expressed in the table below:

HEX usage time (weeks)	Type of fouling	Scaled pressure value
1	Soft	0.50
50	Medium soft	0.84
100	Medium hard	0.92
200	Hard	1.00

Table 4. Classification of fouling depending on the exploitation rate of HEX. (Hexxcell and Dow)

2.2.9. Target material of construction thresholds

MoC	PSI	Bar
Aluminum	5,800	400
Concrete	3,625	250
Carbon Steel	21,750	1,500
Stainless Steel	21,750	1,500
Copper	5,800	400
Copper-Nickel	5,800	400
FRP	3,625	250
Titanium	5,800	400
Niobium	7,250	500

Table 5. Maximum pressure thresholds for different types of MoC. (DOW)

The client uses the Industrial cleaning hydro blasting pressure thresholds, that were determined during the tests. These tests were performed on fixed conditions – use of only potable water and no fouling in tubes present, therefore just clean tubes. Some variable conditions were used in the test – different material of construction (MoC), different types of nozzles with 3 to 8 orifices, the nozzle was never fixed on a specific location for more than 5 seconds, high-pressure pumps ranging from 14500 PSI (1000 bar) to 35500 PSI (2450 bar) were used, the test was done with moving and static position of the water jetting lance. The damage was verified by the change in the wall thickness.

Figure 15. Test results, 750 bar, 10 cm stand-off of the perpendicular jet. Copper-Nickel on the left and Aluminum on the right. (DOW)

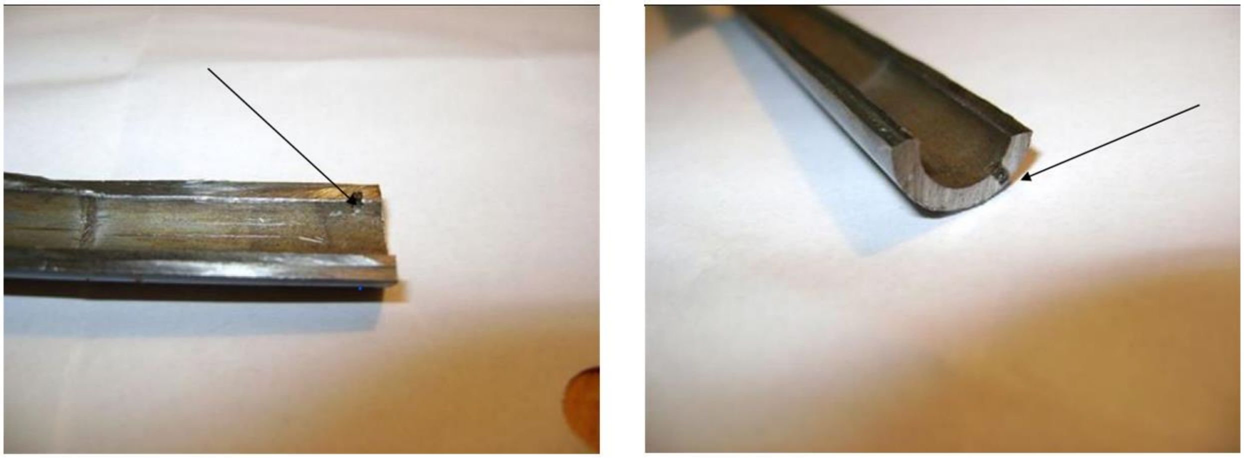

Figure 16. Test results. 2450 bar, 15 liters per minute, 1.5 minutes of static jetting. (DOW)

Figure 17. Test results. 2450 bar, 20 liters per minute. 2 minutes of dynamic jetting on the left and 1.5 minutes of static jetting on the right. (DOW)

2.3. Fouling materials

2.3.1. Classification of fouling

Fouling is the deposition and accumulation of material on the processing equipment that is undesirable due to altering and compromising of the processing operation. It is a multidisciplinary complex phenomenon. Fouling is considered one of the most important challenges in heat transfer equipment. (Awad M., 2011)
Instead of considering fouling types to be only soft and hard as in the model in chapter 2.2.8, the approach that considers properties of the material is needed.

According to DOW guideline, the common types of fouling materials that appear in Shell and Tube heat exchanger that the client is interested in is:

- asphaltene;
- cokes;
- cooling-water products;
- corrosion;
- dust;
- oil;
- paraffin;
- polyethylene;
- waxes.

That can be divided in the two scale type classes:

- organic scale type;
- inorganic scale type.

In the literature, a list of the most commonly encountered fouling material types in industrial operations of fluid heat exchangers suggested (Bott T., 1995):

Inorganic materials:

- airborne dusts and grit;
- waterborne mud and silts;
- calcium and magnesium salts;
- iron oxide.

Organic materials:

- biological substances, like bacteria, fungi and algae;
- oils, waxes and greases;
- heavy organic deposits, like polymers and tars;
- carbon;

In the literature about the fouling of heat transfer surfaces, the division of the fouling materials into several groups is suggested. (Epstein N., 1983; Awad M., 2011; Bott T., 1995) According to the authors, the classification of the fouling material for maintenance purposes should be done by its' key physical or chemical process essential to the particular fouling phenomenon. The literature identifies five (Epstein N., 1983) to six main categories (Awad M., 2011; Bott T., 1995):

Fouling mechanism	Approaching species	Deposit transformation
Particulate deposition	Small particles	Agglomeration and bonding at the surface.
Crystallisation	Ions or crystallites	Crystallisation and orientation of crystals into a coherent structure.
Freezing	Molecules either in solution or liquid form	Continuous structure of solid material.
Corrosion	Aggressive ions or molecules	Chemical reaction with the surface producing "new" chemical compounds that may form a continuous structure.
Chemical reaction	Ions, free radicals or molecules	Larger molecules or polymers.
Biofouling	Micro-organisms and nutrients	Matrix of cells and extracellular polymers.
Mixed systems	Any mixture of the above	Complex matrix of particles and chemicals held together in extracellular products.

Table 6. Fouling types deposit transformation and species. (Bott T., 1995)

Crystallization (precipitation or solidification) fouling

It can be divided into Precipitation fouling and Solidification fouling. This phenomenon appears due to crystallization from the solution of dissolved substances onto the HEX due to the change of temperature. (Epstein N., 1983) Salts of normal and inverse solubility appear on the cooled and heated sides correspondingly. In the literature refiring to scaling or precipitation fouling usually means the hard and tenacious fouling layers of inverse solubility on the heating surface. The normal solubility is porous and mushy, and usually referred to as sludge or softscale. (Awad M., 2011)

This type of fouling is affected by the flow velocity, temperatures on the fouled surface, heat flux at the transfer surface, and the concentration of the suspended particles in the fluid. (Awad M., 2011) Examples: aqueous solutions and other liquids that were cooled or heated. Untreated water, geothermal water, seawater, brine, caustic soda etc.

Chemical reaction fouling

It is classified when the surface material is not acting as a reactant. (Epstein N., 1983) The HEX surface still may act as catalyst, like in case of cracking or cocking. Another cause are thermal instabilities of chemical species, like in case of Asphaltenes, when unwanted chemical reaction takes place during the heat exchange. (Awad M., 2011)

Examples: it can appear in processes like petroleum refining, polymer production, cooling of oils, thermal instability of asphaltenes or proteins, etc. (Awad M., 2011)

Corrosion fouling

Corrosion fouling appears due to a chemical or electrochemical reaction between the HEX surface and working fluid, which leads to the production and accumulation of corrosion products. (Epstein N., 1983) Corrosion fouling can be also produced elsewhere in the process chain and be brought to the surface of HEX as particulate fouling. Corrosion usually takes place when a chemical reaction fouling initially appears, due to that the oxide layer is not formed to protect the HEX surface. (Awad M., 2011)

Particulate fouling

Particulate fouling appears due to the suspension and sedimentation of fine particles on the HEX surfaces from working fluids. Its properties are influenced by several factors, like the concentration of suspended particles, fluid flow velocity, temperatures, and heat flux. Examples: suspended solids in cooling water, salts from a desalination system, mineral particles, etc. (Awad M., 2011)

Biological fouling

Biological fouling includes an accumulation of macro and microorganisms and their products, like generated adherent slimes. A common way for this type of fouling to enter the HEX system is in cooling water obtained from susceptible sources. The products of macro and micro-organisms may also subject the surface of HEX to corrosion fouling. Examples: algae, fungi, bacteria, molds, vegetation, and their products. (Awad M., 2011)

Solidification or freezing fouling

In the latest research of Awad, M. author identifies the sixth fouling type – solidification, or freezing fouling. Typically, it appears when the temperature in the system is relatively low. The solidification of waxes at the cooled contact surface, formation of ice in coolers, or deposition of mixtures of substances like paraffin are the common materials of this fouling type. The key factors affecting this fouling type are temperature and crystallization conditions surface conditions, the concentration of solid precursor in the fluid, and the mass flow rate. (Awad M., 2011)

The authors of these works stress on the fact that sometimes it is difficult to determine the type of a fouling material by this classification, like in the case of crystallization fouling that can appear directly on the surface of the heat exchangers, or it can appear in bulk and accumulate as particulate fouling later. Another example is chemical reaction fouling on the surface of heat exchangers which can be hard to distinguish from chemical precipitation. (Epstein N., 1983) In reality, in most applications of HEX, more than one fouling type appears. This makes the fouling phenomenon very complex due to the synergistic effect. Therefore, making one unified theory to create the model to describe fouling mechanisms is impossible. (Awad M., 2011)

In addition, the results of the experimental research on the interaction between particulate and precipitation fouling in heat transfer systems showed (Wang et al., 2019):

- Bond strength of the particulate fouling material was much lower than precipitation and combined fouling. The bond strength of the precipitation material was the largest or comparable to the combined fouling material, depending on the type of tube (helictical against plain);
- Sticking probability was the smallest for the particulate fouling, the precipitation fouling had roughly three times larger sticking probability, while the combined fouling was from two to fourteen times more probable to stick than a single fouling type;
- Enhanced tubes (helictical) decreased sticking probability, however, due to their shape the strength of the fouling material was increased.

2.3.2. The energy required for material

Each material requires certain energy to be cleaned from the target. This energy comes from the motor that supplies the pump. Any excessive energy is increasing costs and environmental damage.

In the formula (2.2.6.1) that is used to calculate recommended linear traverse speed of the water jet during the tube-side cleaning, the CE factor was introduced. (Summers D., 1995) This factor represents the relative energy required for the removal of different types of fouling materials.

Fouling material	**Relative energy required**
barium sulfate	2.598
silicates	2.226
calcium carbonate	2.041
calcium sulfate	1.670
carbonate-sulfate-silica complexes	1.410
water scales and hydrocarbon complexes	1.187
coal tar	1.113
coke	0.928
waxes	0.742
paraffin	0.445
sludges	0.371
thixotropic materials such as mud	0.297
non-thixotropic materials	0.186

Table 7. Relative energy coefficient required for cleaning different fouling materials. (Summers D., 1995)

Initially, the first model was suggested by Zublin C., which described the application of the water jetting technology for the cleaning of the oilwell tanks. The author suggested an experience-based table of the ratio between fouling material type and energy flux required for cleaning. (Zublin C., 1982) The data provided was not verified in a controlled lab environment and require validation and models to be described, however, some of the material types in this data are common foulants in shell and tube heat exchangers, and fouling and can be useful for indication and comparison.

Another table for hydro blasting cleaning was provided in the literature. (Lester et al., 1982) It compares different foulant types, typical heat exchangers where these foulants types occur, mechanical techniques for removal, and operating pressure for removal. This data can be used for indication and comparison.

Foulant	Typical heat exchanger	Mechanical technique	Operating pressure bar
Airborne contaminants, e.g. dust, grit	aluminium air coolers	Jet washing	2 - 4
Soft deposits, mud, loose rust, biological growths	Shell and tube exchangers, film coolers	Jet washing	40 - 150
Waxes, grease	Condensers, etc.	Hydro steaming	30
Heavy organic deposits, polymers, tars	Condensers	Jet washing with or without pre-treatment with chlorinated or aromatic solvents	300 - 400
Boiler scale, water side and fire side	Boilers, economisers, preheaters	Jet washing, pneumatic percussive or pneumatic abrasive techniques including crushed olive stones	300 - 700
External deposits on heat exchangers, e.g. paint, rust	All types where applicable	Wet sand blasting	Depends on equipment design

Table 8. Foulants and common methods of removal. (Lester et al., 1982)

2.3.3. Properties affecting cleaning

As the results of the analysis of numerous experiments in aeronautic engineering, Springer G. (1976) in his book identified parameters that were described in these models as the properties that affect the erosion rate of the material subjected to the high-speed impacts of the water drops. The important target material properties are:

- Density;
- Velocities of the compression and shear waves;
- Modulus of elasticity;
- Poisson's ratio;
- Endurance limit;
- Ultimate tensile strength;
- Compressive and shear strength;
- Fracture toughness;
- Hardness;
- Grain size;
- Surface roughness;
- Curvature of surface;
- Thickness.

Some of these properties were confirmed by the literature on fouling materials and coating and are discussed in chapter 6.

Temperature

According to the tests, steam and heated water jets with a temperature of more than 85 degrees celcius considerably enhance the cleaning of the surface from hydrocarbon contamination or in cases of fouling containing emulsifiable fats. (Summers, 1995) The key to cleaning these materials is in the reduction of their adhesion and viscosity. The eighty-five-degree mark was determined during the tests since with the closer to boiling temperatures the bacteria at the target surface cultured instead of being washed away. Consequently, it was reported that there is an increase in the rate of contamination around the target surface after nearly-boiling temperature water jet cleaning activities. (Ashton et al., 1993)

Another source suggests that apart from the force applied by the water jet gun, the thermal shock is often a driver of cracking and consequent spalling of the foulant. (Bott T., 1995) However, extensive exposure of the construction material to the higher temperature can lead to damage to the equipment. Therefore it is necessary to determine the optimal temperatures for the material and optimize the quantity of the heated water and the time of application of the heated water jet. (Bott T., 1995) The temperature is affecting the removal rate depending on whether the material is predominantly ductile or brittle. (Momber A., 2004)

Stress and strain

Stress and strain terms are commonly used in material science to describe how material responds to external loads. Stress is a quantity that describes the distribution of internal forces within a body and can be measured in force unit per area unit, like Pascals. The failure of the material occurs when the stress exceeds the strength of the material. Strain is the quantitative value that is expressed in percentages, and it measures the quantity of deformation that occurs in the body. Stress and strain diagrams for particular materials represent this relation.

Mass removal

To determine the mass of removable material or to determine the density of a complex combined fouling sample it is possible to use the basic parameters of fouling material and the area of a circle. For static water jets the removable mass can be calculated with the formula (Momber, 2004):

$$m_c = \left(\frac{\pi}{4}\right) \times w_c^2 \times h_c \times \rho_c \qquad (2.3.3.1.)$$

Where:

m_c – mass removal;
w_c – cleaning width (spray diameter);
h_c – thickness of the material;
ρ_c – density.

2.4. Models

2.4.1. Fouling models

The relationship between three variables of fouling material was suggested (Epstein N., 1983): mass of deposit per surface area, the thickness of deposit, and thermal fouling resistance. This relationship is represented in the formula:

$$dR_f = \frac{dx}{k_f} = \frac{dm}{\rho_f k_f} \qquad (2.4.1.1.)$$

Where:

R_f – thermal fouling resistance;
x – fouling deposit thickness;
m – mass of fouling deposit;
k_f – thermal conductivity of deposit material;
ρ_f – density of fouling deposit.

Thermal fouling resistance can be measured by measuring the heat exchanger tube wall temperature and working fluid temperature in the system at a period of time. The ratio between thermal fouling resistance against mass and thickness is indirect and influenced by the density and thermal conductivity of the deposit material. Harder, non-porous tenacious material will have higher values of $\rho_f k_f$, while softer, porous non-tenacious material will have them relatively lower. (Epstein N., 1983)

Epstein N. identifies another relation in the formula of the removal of deposit:

$$m_r = \frac{B\tau_s m}{\psi} \qquad (2.4.1.2.)$$

Where:

m_r – removal flux;
τ_s – shear stress on the heat transfer surface;
m – mass of the fouling deposit;
ψ – deposit strength.

Removal in the case of this formula is not limited to the cleaning of the surface by hydro dynamic removal, it includes such mechanisms as erosion, spalling, detachment, scouring, release etc. The influence of aging on the decreasing of deposit strength factor was suggested (Epstein N., 1983), however the mechanism behind it is rather complicated, depends on many factors and unclear from the article.

In Kern-Seaton and Watkinson-Epstein early fouling models the fouling net accumulation phenomenon was expressed as material balance. While there were several approaches to describe deposition rates, the removal rate was characterized with layer thickness and shear stress created by the working fluid. (Kern et al, 1958; Watkinson et al., 1968)

Generally, fouling models are based on the material balance, that show the net rate of fouling accumulation. It equals to the deposition rate minus the removal rate.

2.4.2. Water droplet formation

Three drivers lead to the water drop formation in the stream launched by the water jet: external friction, air entrainment, and internal turbulence. (Momber A., 2003) The formula for the average drop diameter is determined in the research on spraying liquids (Schmidt et al., 1984):

$$d_{DS} = \frac{1+3.3\times Oh}{We^{\frac{1}{2}}} \times (\frac{\rho_L}{\rho_F})^{\frac{1}{2}} \times d_N \quad (2.4.2.1.)$$

Where:

d_{DS} – Sauter mean diameter;
Oh – Ohnesorge number;
We – Weber number;
ρ_L – air density;
ρ_F – fluid density.

In fluid mechanics, Sauter mean diameter is an average of particle size. It is always expressed as the diameter of the sphere of the average particle with the same volume and surface area ratio as the real water particle.

Ohnesorge number is a dimensionless constant that describes the tendency of the particle to fall apart or stay intact. The formula for the Ohnesorge number is:

$$Oh = \frac{We^{1/2}}{Re} \quad (2.4.2.2.)$$

Where:

We – Weber number;
Re – Reynolds number.

Weber number is the ratio between drag force and cohesion force, and can be expressed in a formula:

$$We = \frac{\rho_F \times d_N \times v_D^2}{\sigma_F} \quad (2.4.2.3.)$$

Where:

ρ_F – fluid density;
d_N – orifice diameter;

ν_D – fluid velocity (can be expressed as single droplet velocity);
σ_F – surface tension water.

Reynolds number is a dimensionless parameter of the flow that is used to determine whether the flow is laminar and turbulent. A low Reynolds number indicates laminar flow, while a high indicates turbulent. It is expressed as the formula:

$$Re = \frac{\nu_D \times d_N}{\nu_F} \qquad (2.4.2.4.)$$

Where:

ν_D – fluid velocity (can be expressed as single droplet velocity);
d_N – characteristic distance (can be expressed as orifice diameter);
ν_F – dynamic viscosity of water.

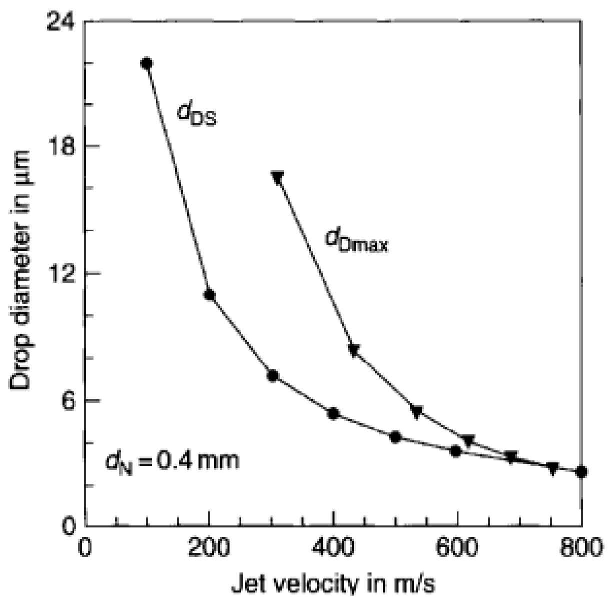

Figure 18. Graph showing relation between drop diameter and jet velocity for 0.4 mm orifice. (Momber A., 2003)

In the literature, the graph of the ratio between the jet velocity on one side and Sauter average drop diameter and maximum drop diameter on the other side was found. (Momber A., 2003) This graph represents this ratio for water jets with the orifice sizes of 0.4 millimeters.

2.4.3. Droplet-erosion model

When a liquid droplet impact on a solid surface it may create erosion of the solid material. Pits, cracks or mass loss of the material can be called erosion.

In aircraft engineering many researches were performed to study the consequences of rain droplets high speed impact on different parts of structural airplane elements, since the damage from them can be significant. Springer G. (1976) has overviewed approaches that were used in many researches, mainly there were 5 types of experiments overviewed: single impact studies, rotating arm tests, rocket sled tests, ballistic tests, and in-flight tests. Private and governmental reports of these experiments were presented as qualitative information in his book.

Note: the book was obtained only partially from the library of the "Technical University of Berlin", the chapter with the reference was not obtained. Springer has many references in his work since these models are the result of many experiments in civil, governmental and military domain, most of which were taken place in between 1960 and 1976. Attempts to recover the references were not successful, therefore, in this research report, the data obtained from this source will be referred to by the name of the author of the book – Springer G., 1976.

In addition to the parameters listed in chapter 2.3.3. affect of the properties of liquid, rain and impact was determined by these models.

Parameters describing the liquid:

- Density
- Velocity of a compressive wave
- Viscosity
- Surface tension

Parameters describing the rain:

- Shape of droplets
- Size distribution of the droplets
- Droplet concentration

Impact parameters:

- Velocity;
- Angle.

Impact pressure

To calculate the impact pressure at the target location the following formula may be used (Springer G., 1976):

$$P = \frac{\rho_L \times C_L \times V \times \cos\theta}{1+\rho_L \times C_L / \rho_S \times C_S} \qquad (2.4.3.1.)$$

Where:

ρ_L – density of water;
C_L – speed of sounds in water;
V – normal velocity;
θ – Impact angle to normal;
ρ_S – density of target material;
C_S – speed of sound in the target material.

The speed of sound is relevant in material science since it allows to measure the speed with which the particles of the materials transfer the pressure disturbance to each other. It has a complex mechanism, however, it is important for understanding that it represents two properties:

- The elastic property of different materials. If the material has higher elastic properties, then the speed of sounds will be higher correspondingly due to stronger bond forces on a molecular level.
- Density, since denser materials have more mass per volume and usually happens because it consists of larger molecules. If it is the case then it will decrease the speed of sound because it takes more energy to make larger molecules vibrate.

Generally, in two materials with the same elastic characteristics, the speed of sound will be slower in the denser material.

Strength

The strength of the material can be determined with the formula (Springer G., 1976):

$$S = \frac{4 \times \sigma_U \times (b_S - 1)}{(1 - 2 \times \upsilon_S)} \qquad (2.4.3.2.)$$

Where:

σ_U – ultimate tensile strength;
b_S – constant;
υ_S – Poisson's ratio.

Poisson's ratio describes how particular materials deform under loading. It defines the ratio of change in the width per unit width of material to the change of length per unit length of material. For example if compression is applied in lateral directions, then the longitudinal direction will expand:

$$\nu = \frac{-\varepsilon_{lateral}}{\varepsilon_{longitudinal}} \qquad (2.4.3.3.)$$

To be able to use Poisson's ratio the assumptions are needed:

- material has the same properties in all direction, therefore it is isotropic
- the material has an elastic region in the stress-strain diagram.

Poisson's ratio may be used to determine the brittleness or ductility of the material. Even though it expresses material response outside of their elastic limits, it also measures the resistance of a material to volume change and its' ratio to the resistant to shape change, that can be linked to the embrittlement at low ν and ductility at high ν. (Greaves et al., 2011) Refer to the source for exact formulas.

The constant b_s is related to the fatigue theorems. To determine it, the formula is used (Springer G., 1976):

$$b_s = \frac{b_2}{\log_{10}(\frac{\sigma_U}{\sigma_I})} \qquad (2.4.3.4.)$$

b_2 – constant;
σ_I – endurance limit strength.

$$b_2 = \log N_1 \qquad (2.4.3.5.)$$

Where:

N_1 – life cycle number corresponding to endurance limit;

The fatigue or endurance limit is described as the stress level below which infinite loading cycles can be applied without fatigue failure of the material. S-N Diagrams are used in literature to describe the stress ratio to the number of cycles before the material will fail and fatigue failure occurs. Even though fatigue theorems were created on the foundation of torsion and bending of bars and due to the differences of these failure mechanism, these two concepts might not have direct ratio for quantitative results. However, the similarities between these tow failure mechanisms show that the fatigue concept can still provide qualitative answers for the erosion. (Springer G., 1976) At the core of this fatigue theorem lies the Miner`s rule, which states that the damage caused to an object at the same stress level in multiple stress repetitions will stay constant. That means that the first repetition will cause the same damage as the last.

For the materials that the client is interested in the author adopts (Springer G., 1976):

Steel, polyethylene, magnesium oxide, and titanium value for b_s = 20.9;

Copper value for b_s = 17.6;

The literature review regarding the fatigue values for other materials that the client is interested in was not successful, however precise values for fatigue limits are obtainable in an experimental setup. For the details refer to Springer G., 1976 or the literature on fatigue tests.

Note, that author introduced two more extended formulas for strength calculation (Springer G., 1976):

1. $$S = \frac{4\times\sigma_U\times(b_s-1)}{(1-2\times\upsilon_s)\times(1+2\times k\times\psi_{SC})} \qquad (2.4.3.6.)$$

Where:

k – number of stress wave reflections in the material;
ψ_{SC} – impedance ratio.

2. $$S = \frac{4\times\sigma_U\times(b_s-1)}{(1-2\times\upsilon_s)\times[1-(\sigma_I/\sigma_u)^{b_s-1}]} \qquad (2.4.3.7.)$$

All three versions of the strength formula are mentioned, however, the author in the overview of models uses only the formula without any additional factors mentioned at the beginning of this subchapter. In short, the first formula also takes into the consideration stress oscillation phenomenon. That additionally may not be applicable in the case of water jetting cleaning. In the second formula the $\sigma_I < \sigma_u$ and $b \geq 1$ for the most materials, therefore, the $1-(\sigma_I/\sigma_u)^{b-1}$ is reasonably neglectable. However, testing these formulas may be of use for future development of the model, if these extended formulas will be of interest – refer to the literature.

Rate of mass loss

The rate of mass loss can be calculated per every droplet impact with the formula (Springer G., 1976):

$$a = 73.3\times10^{-6}\times\rho_f d_{DS}^3(\frac{P}{S})^4 \qquad (2.4.3.8)$$

Where:

ρ_f – density of the material;
d_{DS} – Sauter mean diameter;
S – strength;
P – impact pressure.

This is only applicable beyond the incubation period. Basically, this formula draws an analogy between the behavior of the material that was impacted by a droplet and material that is subjected to torsion or bending fatigue stress. (Springer G., 1976)

Incubation period

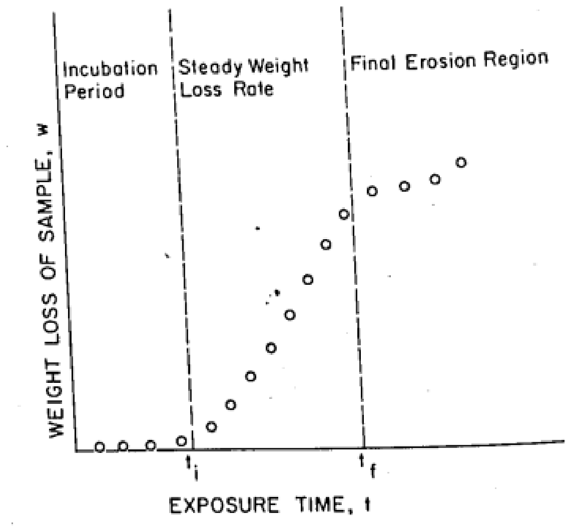

Figure 19. Erosion regimes. (Springer G., 1976)

During the test, the sample materials were subjected to the high-speed droplets impacts imitating the real condition in order to measure the weight loss of the sample. It was shown that initially, the rate of mass loss is low, after some time it increases and keeps an almost linear loss trend, and afterward, it starts to behave unpredictably. Therefore, three erosion regimes were determined. They are indicated in figure 19. In the experiments, it was also noted that the time could be replaced with the volume of liquid per area or the number of impacts per area, in case if the size and shape of liquid droplets are rather uniform.

The author suggests the check, if S/P>8 therefore the incubation period is present in the event and the incubation period can be calculated.

The incubation period per area can be calculated with the formula (Springer G., 1976):

$$n_{in} = \left(\frac{8.9}{d_{DS}^2}\right) \times \left(\frac{S}{P}\right)^{5.7} \quad (2.4.3.9)$$

Where:

d_{DS}- average drop diameter;
S – strength;
P – impact pressure.

This value represents the number of droplets that the material can withstand in one load event during the incubation period. While realistically there are some losses occurring during the incubation period they can be neglected and therefore the incubation period would be considered a zero mass loss period. If this concept will arise interest, please refer to the book, it contains some models and formulas on the phenomena.

2.5. Experimental design

The aim of any laboratory technique is to simulate the conditions that are likely to occur in reality. (Bott T., 1995)

2.5.1. Monitoring

Literature suggests several fouling monitoring techniques that can be used experimentally or analytically. (Awad M., 2011) Some of these fouling resistance measurement methods can be used to determine effectiveness in water jetting cleaning:

- Direct weighing method, that requires an accurate balance to identify even the smallest changes in deposition mass. The sample surface or tube is weighed before and after the attachment of the fouling sample material. Then one more measurement is done after the cleaning event was performed.
- Thickness measurement method, which can be done by the usage of a micrometer or a traveling microscope. Since in some fouling material cases, the thickness may be less than 50 um the measurement can be difficult to perform correctly. To boost precision the measurement can be also done with modern camera equipment for micro shooting. The picture can be done on the scale and then the difference can be seen on a scale or counted by pixels. Besides, while the laser techniques are rather expensive, they will provide accurate data regarding accumulation and removal rates. For some materials like biological fouling, infrared systems may be used.
- Heat transfer and pressure drop measurement methods during in-situ tests. They can be done by tracking the heat transfer efficiency and pressure in the HEX system. Thermal resistance and pressure monitors are needed for these methods. The models for the heat transfer coefficient discussed in chapter 2.4.1 may be used.

2.5.2. Fouling sample properties determination

Literature suggests that dynamic material properties should be used in the models instead of static mechanical properties for erosion calculation if it is possible. The dynamic properties of the material used in aeronautic engineering were determined with "Hopkinson pressure bar" method in multiple experiments. (Springer G., 1976)

Besides, it is important to note that the fatigue behavior and connected to it "b" value from the model, is unknown for the most of materials. It is suggested to plot a graph with an idealized linear fatigue curve for all ductile materials. However, such graphs theoretically cannot represent brittle materials and polymers without testing. According to the multiple aeronautic models, the approximation of the fatigue curves and "b" value gave reasonable results. (Springer G., 1976) If the determination of the fatigue curve is necessary, then determining a cumulative number of cycles at a certain load and application of formulas 2.4.3.4. and 2.4.3.5. will determine "b" value precisely.

Another key property in the model is the speed of the sound of the material. While there are some values suggested in the literature for materials that the client is interested in, since the fouling phenomenon is complex it requires a separate determination of its properties. This study can be done either by the type of material or by the application of the HEX system.

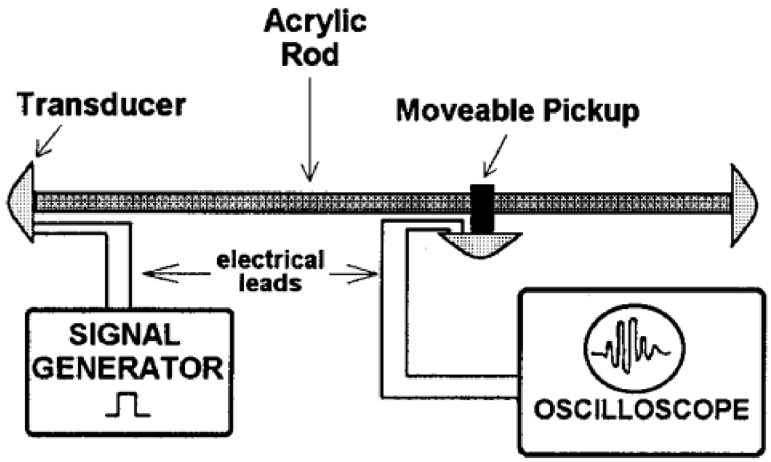

Figure 20. Oscilloscope scheme. (Key et al., 2000)

Measurement of the speed of sounds in the solid can be feasibly obtained with an oscilloscope. It is an electronic test instrument, the main function of which is to display the waveforms by measuring the time needed for a wave to travel along rode, usually made of acrylic. Two measurement devices called transducers are placed on the opposite sides of the sample with the acrylic rod in the middle. The signal generator produces an oscillation, while the oscilloscope that is placed along the rod at a certain distance measures the time that oscillation is needed to travel and generate the first deviation. The experiment can be repeated several times with a different setup to build the graph that will give the required value of the speed of sound. There are several setups and technics for this measurement that can be tested, compared, and evaluated. (Key et al., 2000)

The challenge that may arise in the measurement of the speed of sound of fouling materials is the fact that the material is heterogeneous. In the medical domain, the speed of sound measurements in the bones showed that the results of speed of sound measurements are affected by the sample's properties that were defining its' strength – thickness, shape, and basic composition. (Njeh et al., 1999)

Poisson's ratio can be also expressed in terms of traverse and longitudinal speed of sound. The formula for Poisson's ratio using the speeds of sound (Greaves et al., 2011):

$$\nu = [\frac{1}{2} \times (V_t/V_l)^2 - 1]/[(V_t/V_l)^2 - 1] \qquad (2.5.1.1.)$$

Where:

ν – poisson's ratio;
V_t – traverse speed of sound;
V_l – longitudinal speed of sound.

To calculate density the precise scale and means to measure volume of a sample are required. There are a wide range of techniques of different costs exists for these purposes.

2.5.3. Material

The solid material gathered for the laboratory test and the solid and fluid material obtained after the test may be chemically unstable. The properties of these materials can drastically change during the storing or transportation, therefore it is required to keep the samples safe and/or process them as fast as possible. (Bott R., 1995) The washing water should never be reused in the experimental environment, since after the jet cleaning its chemical properties can not represent the regular process fluid used in the cleaning. (Bott R., 1995)

The foulant and used washing water may be toxic or flammable. It should be processed with care. (Bott R., 1995)

If the used washing water needs to be analyzed it is important to take the settlement of the particles in the storage take into account. Some types of particles will tend to agglomerate to some extent, which may lead to difficulties with the analysis or alter the particle size. (Bott R., 1995)

Creating a setup for biological fouling might be the biggest challenge since it is impossible to recreate ecological conditions that exist in the industrial system. It may affect the presence or distribution of microorganisms as well as their properties. (Bott R., 1995) A potential solution for this issue might be to perform the experiment for the systems exposed to the biological fouling on-site or in the controlled laboratory setup that would imitate fouling in the system for a prolonged time. The research on particulate and precipitation fouling might be a starting point to create such a system, this experiment was taken place continuously for one month. (Wang et al., 2019) The idea is to create a surface inside the experimental model that would imitate the heat exchanger surface.

2.5.4. Experimental set-ups

There are clear lack of published experiments of the fouling removal with the usage of water jetting system. However, the experimental studies in the fields of mining, drilling and cutting with abrasive water jets are well presented. Below two experiments that can be used as a reference for the experimental design in this project are generally overviewed:

Guha et al. setup

The numerical and experimental analysis was performed to study the phenomena of decay of jets pressure and increases the spreading of the jet area due to the traverse distance. Analysis showed that the axial component of this movement has linear relation to the decay of pressure. (Guha et al., 2010) Initially, to check the actual pressure of the water jet impact and particular stand-off distance a test run with the target plate may be performed. The schematic of the experimental set up is below:

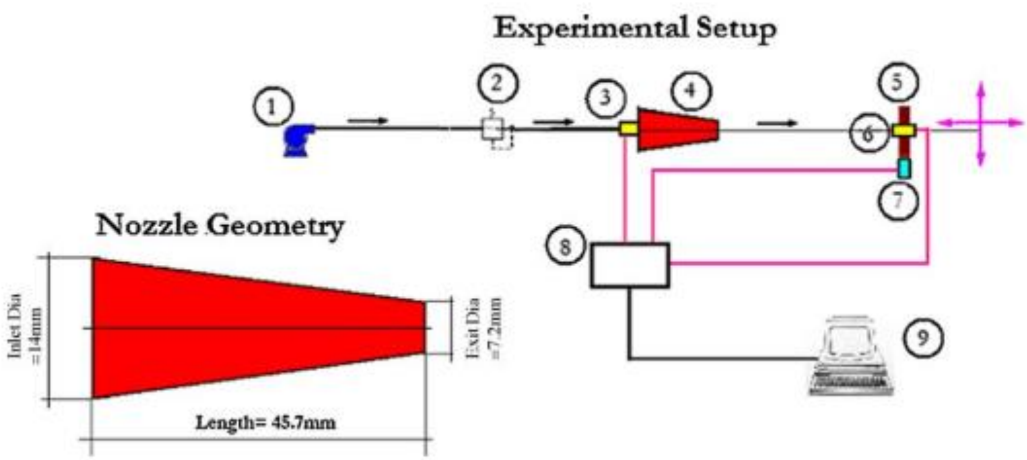

Figure 21. Schematic of the experimental set-up. (1) pump (2) pressure reducing valve (3) pressure transducer (4) converging nozzle (5) plate (6) pressure transducer (7) linear variable displacement transducer (8) A/D converter (9) computer. (Guha et al., 2010)

- The static pressure at nozzle measures with the pressure transducer;
- The mass flow rate of water is measured with the collecting vessel and timer;
- The plate can be moved distantly both in axial and radial direction. The plate has pressure transducer mounted at its center;
- Linear displacement transducer is measuring displacement in both axial and radial direction;
- Signals are obtained by the sensors, the data continuesly record on computer;

Wang et al. setup

Experimental setup was focused to look at the sticking probability and deposit bond strength of particulate, precipitation and mixed fouling. To perform this study the design of the test system was created, to imitate a full scale procedures and environmental of a heat exchanger.

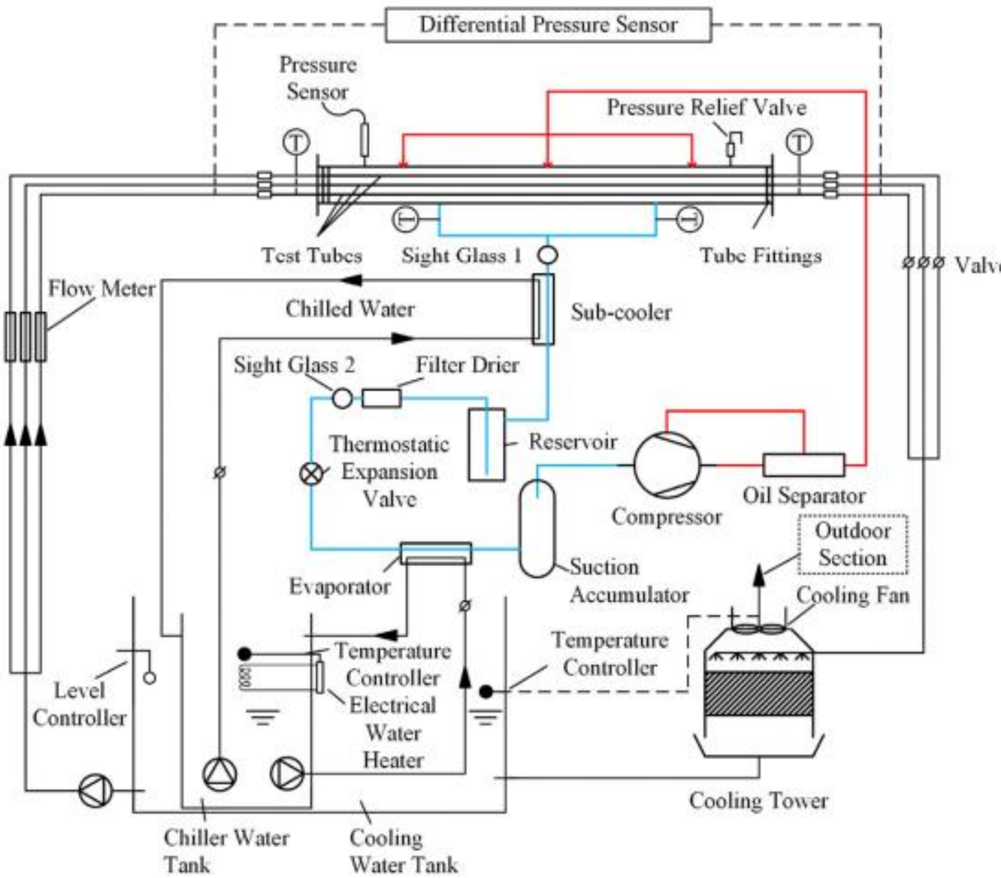

Figure 22. Schematics of the test system. (Wang et al., 2019)

Figure 23. Photo of the test system. (Wang et al., 2019)

It is required that the heat flux of test condenser and water quality should remain constant during the entire testing period. This setup imitates shell and tube system, with the condenser and three tube "bundle". There are many variables that can be adjusted in such test system for a precise experiment. For the details refer to the source.

3. Methodology

3.1. Research strategy

This chapter will provide information regarding the chosen methods and research strategy for achieving the determined scope of goals. The main question of this research is: How to achieve effectiveness in the water jet cleaning used for maintenance of HEX systems that are subjected to different types of fouling materials?

The research will aim to provide accountable answers for the main research question and sub-questions alike. The result will be presented in a form of an analysis of the scientific literature and data provided by the client. One of the major goals of this thesis will be to create a model that may act as a starting point for further developments and experiments. The data from the literature review will be mainly discussed in the theoretical framework chapter. The final products will be presented in results, conclusion, recommendation, and discussion chapters.

To create value for the client and research group the setup of the experimental test is needed, to validate the theoretical finding in a controlled environment. Paramount, this thesis aims to provide necessary recommendations on the topic of fouling material properties and correspondence of water jet cleaning methods in accordance with these properties. However, other aspects of this topic, models, and experimental test setups will be researched in accordance with the available time. Creating value for the client, maintaining a sufficient depth of the research, and meeting the academic requirements of the final thesis graduation are the main goals of this project.

One of the central challenges of this research is the fact that the project requires a multidisciplinary approach, the topic is wide-ranging and complex and to achieve the objectives of the client it is needed to cover many aspects comprehensively. While this research is in progress the research group continues to work in collaboration with each other, providing value to the project. Therefore, focusing on a particular part of the required research work will be done since the tasks are divided.

Even though the issue of industrial fouling is spread and the application of water jetting for cleaning is a common technique, there is an issue with the lack of scientific literature available related to the topic. Another factor is the lack of published guidelines from cleaning companies due to commercial competition. It creates uncertainties regarding the quantity of useful numeric data and qualitative material that can be found during this graduation thesis project. Potentially experimental lab testing may be crucial for the determination of certain aspects that cannot be verified otherwise.

Since there are certain limitations for the duration of this graduating thesis as well as limitations on the resources provided by the client and the cleaning company to the research group, it is not clear whether it will be possible to make a complete model or perform the experimental test in a controlled environment before the graduation thesis will be over. The project is ongoing and according to the In-company supervisor the next researcher will most likely carry on the research topic with a focus on the simulation. Obtaining results of the test or validation of the potential models is not in the scope of this final thesis research.

The material collected and represented in this research will contain two types of data:

- The numeric, also called quantitative data, is gathered by the researcher from the scientific literature or provided by the client, in form of graphs, tables, values, and models. This data can be obtained from modeling, calculations, or results of tests.
- The qualitative data, in form of a literature review of scientific articles, books, papers, and reports. Besides that, qualitative data can be obtained during the consultation with the experts and in-company supervisors.

3.2. Research activities

There are numerous research activities that will be carried out during the graduation thesis according to the topic.

Shell and Tube heat exchangers research

Foundational research on the shell and tube heat exchangers will be done with the literature research and is needed to understand the scope and nuances of cleaning work. It is needed to understand the general approach for cleaning of the different parts of the Shell and Tube heat exchangers. The client provided the research group with some in-company guidelines, and since Shell and Tube heat exchangers are used in many industries and process chains, and fouling problems are unique to these particular processes and designs (Awad M., 2011), a detailed determination of correlation between a particular application or equipment design of HEX on one hand, and types of fouling material depositions is not in the scope of this thesis.

Water jetting

Foundational research on the water jetting cleaning method is needed and will be done with the literature research, analysis of the data provided by the client, and expert surveys. While the information that can be obtained from the client is rather limited, especially the numeric data from the cleaning activities, the formulas, and models for the simulation of the different setups of the water jetting maintenance cases will be needed to look generally at the ratio between the fouling materials required energy and how this energy can be achieved with the water jetting technique. Since there are numerous things that can be adjusted from the side of the water jet setup or operator, a foundational understanding of these relations is required for a model and experimental test setup. Moreover, such things as impact angle, standoff distance, and nozzle setup on one side and the cleaning efficiency of a particular fouling material case on the other side may have some accordance. The models for the water jetting cleaning will be needed in order to set the model for a particular fouling material. Any recommendations on further research of these potential correspondences will be discussed.

Fouling materials

At the moment, for the cleaning of appeared fouling material, in the model guideline of DOW and Hexxcell companies, there is the assumption that divides all fouling materials into two types: soft and hard. While this terminology can be found in the literature it is clear that this division does not allow optimization of the cleaning method just to this classification factor. Instead of this assumption, more developed research should distinguish different types of fouling materials taking into account the properties of these materials that affect the cleaning process and optimal setup for a water jet cleaning method.

Initially, the literature research on the general, foundational data about the fouling materials should be performed. One of the main subjects that need to be looked at is what properties of the fouling material can affect the optimal cleaning setup. The further steps will be dependent on the type and degree of information obtained during the research on the scientific articles. If the data will be sufficient and the model or formula that can express the forces needed for a particular fouling material case can be created or derived from the literature review the experimental test setup will be needed to confirm and adjust the formula or model in the future.

If the model or formula that expresses the optimization of the required setup needed for cleaning a particular fouling material case will not be found in the scientific literature on fouling then this research will focus on providing the necessary information for the determination of such a model. For example, the information may be found in other fields that work with similar phenomena, like the application of water jetting in fields like mining, or instead of fouling cleaning coating cleaning can be researched. All comments on this topic will be delivered and recommendations for further research in the scope of this project will be suggested.

3.3. Model and experimental setup

The model will use the described formulas from the theoretical framework and some common knowledge of geometry, material science, and fluid mechanics. The model is done in Microsoft Excel software and the Microsoft Excel Worksheet file with the model will be submitted together with the final thesis. The stepwise explanation of the model is explained in the Result chapter. Some test setups will be suggested in accordance with the researched properties and values required for the model, however, the model itself will be made user-friendly and can be adjusted or modified if needed. For fouling material and material of construction, the “custom” field was created, in case the properties of some materials will be determined.

The in-lab experimental test setup for water jetting cleaning is a very broad topic that requires comprehensive expertise in many fields, related to material science, hydrodynamics, monitoring and etc. Any framework for a schedule of requirements, procedures, or general recommendations on this topic will create value and will be provided.

4. Results

4.1. Model

4.1.1. Introduction

Incorporating the properties of the fouling material into the water jetting model to optimize the setup of the water jet for a particular case of fouling is the main objective of this model. Consequently, sufficient data can be obtained and with it the creation of a guideline that will lead to the minimization of costs and environmental damage is possible. The model was created with limited data from the client and with data from the researched literature. It will require further development after incorporation with the additional necessary information, e.g. the equipment setup data. These points are discussed and relative recommendations are made in chapter 6.

The model is created in Microsoft Excel software. Please, refer to the "Model.xlsl" file.

The Nomenclature with the symbols used and units is in the model. It is not provided in this report, since some formulas require different units of the same parameter. All these units can be identified in the excel file.

4.1.2. Assumptions and input data

The following assumptions are made in the model:

- All droplets are spherical;
- Distribution of the droplets is uniform;
- All droplets have the same diameter;
- The compressibility of water is neglected;
- The impact velocity is the same for all droplets;
- The number of impacts per area stays constant through time;
- The impact area of the droplet is a round equal to the diameter of the droplet sphere;
- The impact pressure is uniform for the whole area and constant through time;
- The distribution of pressure among several orifices is neglected, the pressure per orifice is equal to the pressure at nozzle;
- The effects of the finite thickness of the materials are neglected, therefore the stress reflection is neglected and stress at the surface always equals to the impact stress;
- The materials are flat. Any curvature or unevenness is neglected.
- The traverse movement of the jet is considered only in one dimension, therefore the geometry of the placed sample is simplified;
- Assumption for Poisson's ratio – the material is isotropic (same properties in all directions);
- Pressure decay of a jet going through the rain is neglected;
- Head losses due to height difference are neglected, assuming no height difference between the pump and the nozzle.

Model requires the following input data:

Construction material	• Density; • Ultimate tensile strength; • Poisson's ratio; • Speed of sound; • Fatigue constant;
Fouling material	• Density; • Ultimate tensile strength; • Poisson's ratio; • Speed of sound; • Fatigue constant; • Thickness; • Overall area;
Water	• Flow; • Density; • Average (Sauter) drop diameter; • Speed of sound.
The water jet and pump	• Pump pressure; • Pump efficiency parameter; • Losses in line; • Diameter of orifices; • Nozzle efficiency parameter; • Shape of the orifice(s); • Jetting area diameter; • Impact angle.

The model already has properties for several materials. These properties were obtained during the literature review and the tables with references can be found in Appendix A.

- Fouling material: Polyethylene and Magnesium Oxide;
- Construction material: Steel, Titanium, Copper;
- Water.

Water and construction materials are in alignment with their real properties. All fouling material types that the client was interested in were searched, however, there are no usable data regarding the properties of these materials available to the best knowledge of the researcher. While polyethylene and magnesium oxide (salts) are among the materials that the client was interested in these properties needs to be tested, since they can be different from their fouling counterpart. For polyethylene, the properties of a polyethylene coating were used, while for magnesium oxide the ultimate strength is of the magnesium oxide ingot, and the rest of its properties are found in the aeronautic literature but without any additional explanation. Most likely it is of coating as well, since magnesium oxide is also used for these purposes.

If the properties of certain materials are known and determined and needed to be used in a model the model has the option to choose "custom" materials for both fouling and construction.

4.1.3. Calculation process

For the calculation of the pump output energy, the efficiency parameter ψ for the pump and line is needed. For pump efficiency losses, the literature (Summers D., 1995) suggests a range from 0.6 to 0.9, however, this value needs to be input for a particular piece of equipment, while for a calculation of the losses in line, the length and vertical difference between the supply and the end of the hose is needed. Since data about the setup was not provided by the client the parameter of 0.9 was taken for both parameters as an example. When the data will be obtained the formula 2.2.3.3. may be incorporated into the model and additional formulas and data on this topic can be found in the literature (Summers D., 1995; Momber A., 2003)

The next step is obtaining the pressure at the nozzle by applying the pump efficiency parameter and losses in line with the input pump pressure.

With these values, the velocity of the jet stream can be calculated with the formula 2.2.3.2. The nozzle efficiency parameter μ from table 3 is applied and is set to 0.95.

The jetting area will be calculated with the jetting area diameter.

Since the model is based on the "mass per droplet" model from the rain simulations used in aeronautic engineering, the next step is the determination of the droplet Sauter (average) diameter. The calculation can be done for different setups of water jets, knowing the properties of the water, air, and jetting device with the formulas 2.4.2.1.; 2.4.2.2.; 2.4.2.3.; 2.4.2.4.; This model used the data found during the desk research. The graph in figure 18 shows the dependence between jet velocity and drop diameters of a water jet with an orifice size of 0.4 millimeters. This diameter is going to be used in the model, however, if the need will arise same graphs can be drafted for any diameters if the above-mentioned properties will be determined.

By using precise measurement tools this graph was digitalized and put into a model:

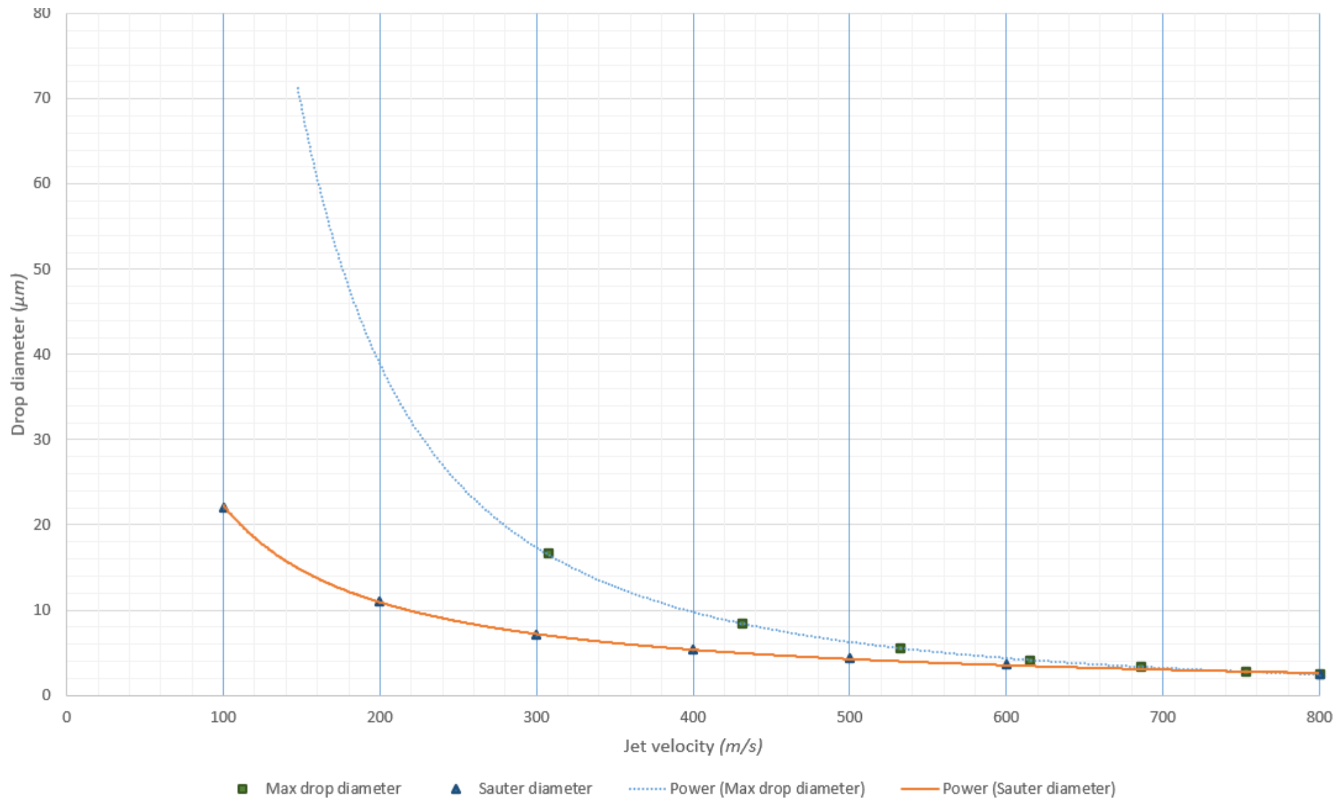

Figure 24. Graph of the relation between Sauter and max drop diameter to the jet velocity for 0.4 mm orifice.

Note, that the maximum drop diameter is not used in the further calculation, however, it can be used as the reference for the verification of the results. If the maximum drop diameter will be needed for the client the calculation can be found in the literature. (Momber A., 2004)

To create readable data for the model the points were fitted in a function. Several function types available in Excel were tested, however, the power function clearly corresponds to the data the most. Now the average drop diameter is available for velocity ranges from 100 to 800 meters per second for orifices of 0.4 mm. The volume of a single average drop diameter is indicated in the result field.

Realistically, a single orifice can provide only a limited amount of flow due to the set velocity of the water and cross-sectional area of an orifice. Therefore, for input data, the check is performed to compare the flow of water, the velocity of the jet, and the cross-sectional area of the orifice. The cross-sectional area is calculated with the incorporation of the shape of the orifice factor from figure 9. This calculation will make a check, and if a single orifice will be insufficient the number of orifices will be suggested in the result field. Besides, the maximum flow per one orifice is shown for optimization purposes.

The next step is the calculation of the impact pressure from the formula 2.4.3.1 from the droplet-erosion model.

Afterward, the calculation of the Strength of the material from the formula 2.4.3.2. can be done. Alternatively, formula 2.4.3.2. can be changed with the formula 2.4.3.6. or 2.4.3.7., for detail refer to chapter 2.4.3.

Consequently, the mass removal per single droplet is calculated with the formula 2.4.3.8. The total amount of droplet impacts can be calculated by comparing the known flow to the volume of the Sauter drop, therefore the impact per second in the jetting area is determined.

Now the known jetting area, density of the fouling material, and thickness of fouling material are sufficient to calculate how much time it will take for a water jet to clean one area in static mode, and how much mass will be removed per every area. Further in the text, this area will be called a section, and this time will be called a cycle.

After this step, it is possible to calculate the time for a whole cleaning process with a given total fouling area. During the first section, the water jet is static until the whole cleaning cycle will not be over. Afterward, the basic principle for the calculation of the total time needed for the whole work duration is that each unit of area must be under the effect of a water jet for the whole duration of the cleaning cycle. After the first section of the material was cleaned the jet area starts to move with constant traverse speed spending the same amount of time for every unit area of the total fouling material area.

Resulting in the total mass removed and the time required to perform the whole duration of work being calculated.

Note: In addition, by using the model with properties of the target material, the determination of the duration of the incubation period duration can be done with the formula 2.4.3.9. If the incubation period is present at the fouling material in water jet cleaning the pressure can be considered insufficient, therefore the check is needed only to determine that the incubation period is not present.

This concept can be useful since the client is interested in avoiding damage to material of construction, and in some cases, this data can be useful. Please refer to the strength limit stresses for construction materials that were discussed in chapter 2.2.9. Therefore, for a material of construction, after the incubation period check is performed by comparing “Strength” and “Stress at Surface”, if the check is passed, the number of droplets per area during the incubation period can be calculated with the formula 2.4.3.9. Then this value is compared with the flow and average drop diameter, since the jetting area is known it is possible to determine how much time material of construction can be subjected to droplet impacts during the incubation phase.

However, for the stronger materials the incubation period gave contradictive results in comparison to the removal rate. These results are discussed in chapter 6.

4.1.4. Test runs

Three test setups were tried. The data provided in this chapter was withdrawn directly from the model, however, it can be seen and adjusted in the excel model worksheet. The comments on results will be discussed in chapter 6.

First setup

In the first setup, the polyethylene fouling sample needs to be cleaned from the steel sheet. The input parameters are below:

Choose the material from the list:		**Fouling material**	**Construction material**	
		Polyethylene	**Steel**	Units
Density	$\rho_{f\ or\ s}$	920	7600	kg/m^3
Ultimate tensile strength	σ_u	9.65	593	Mpa
Fatigue constant	b	20.9	20.9	dimensionless
Poisson's ratio	$\nu_{f\ or\ s}$	0.2	0.3	dimensionless
Speed of sound	$C_{f\ or\ s}$	1473	5182	m/s

Waterjet and Pump setup			
	Symbol	*Value*	*Unit*
Pump pressure	P_{pump}	36	Mpa
Pump efficiency parameter	ψ_{pump}	0.9	Dimensionless
Losses in line	ψ_{line}	0.9	Dimensionless
Diameter of orifice	d_N	0.4	mm
Total flow	Q	8	l/m
Nozzle efficiency parameter	μ	0.95	dimensionless
Normal impact angle	θ	0	degrees
Jetting area diameter	x_c	0.15	m
Water properties			
Density fluid	ρ_L	1000	kg/m^3
Speed of sound	C_L	1463	m/s
Target dimensions			
Thickness	h_c	0.1	m
Overall fouling area per orifice	A_c	0.3	m^2
Choose the type of orifice from the list:			**Rounded (0.98)**

The result of the model run is below:

RESULTS			
Pressure at nozzle	P_{noz}	29.160	Mpa
Jet Velocity	v	229.362	m/s
Average drop diameter	d_{DS}	9.478	µm
Volume of avg drop diam	Vd_{DS}	445.871	$µm^3$
Area of orifice	A_{Or}	0.123	mm^2
Area required	A_{req}	0.581	mm^2
Minimum orifices	Or	5	
Flow per orifice	Q_{or}	1.600	l/m
Maximum flow per orifice	Q_{max}	1.695	l/m
Water Hammer	P_{wh}	335.557	Mpa
Jetting area	A_j	0.018	m^2
Strength and Impact			
Impact pressure (stress at surface)	P	161.358	Mpa
Strength	S	1280.233	Mpa
Mass loss per Orifice			
Mass loss per impact	a	2.66929E-12	kg/Impact
Impacts per second in section	n_{imp}	59808012876	impacts/s
Mass loss in section per second	m_{sec}	0.160	kg/s
Mass removed per section (cycle)	*m*	1.626	*kg*
Time needed per section (cycle)	t	10.184	s
Optimal traverse speed	V_{noz}	0.015	m/s
Mass removed total	M_{tot}	27.600	kg
Time needed total	t_{tot}	183.068	s
Fouling material incubation			
Incubation period check	(S/P)>8	Fail	
Number of impacts in incub period	n_{in}	Not applicable	impact/m2
Impacts in incub period for the area	n_{area}	Not applicable	s
Duration of incub period	t	Not applicable	s
Duration of incub period	t	Not applicable	h

The first setup shows that with 36 MPa applied from the pump, it is needed to continuously apply water jetting for 10 seconds per section to remove the polyethylene layer of 10 centimeter thickness.

Second setup

The second setup uses the same input data as the first, besides the pump pressure that is set at 41 MPa instead of 36 MPa in the first setup.

RESULTS			
Pressure at nozzle	P_{noz}	33.210	Mpa
Jet Velocity	v	244.773	m/s
Average drop diameter	d_{DS}	8.864	µm
Volume of avg drop diam	Vd_{DS}	364.695	$µm^3$
Area of orifice	A_{Or}	0.123	mm^2
Area required	A_{req}	0.545	mm^2
Minimum orifices	Or	5	
Flow per orifice	Q_{or}	1.600	l/m
Maximum flow per orifice	Q_{max}	1.809	l/m
Water Hammer	P_{wh}	358.102	Mpa
Jetting area	A_j	0.018	m^2
Strength and Impact			
Impact pressure (stress at surface)	P	172.200	Mpa
Strength	S	1280.233	Mpa
Mass loss per Orifice			
Mass loss per impact	a	1.41357E-11	kg/Impact
Impacts per second in section	n_{imp}	73120501598	impacts/s
Mass loss in section per second	m_{sec}	1.034	kg/s
Mass removed per section (cycle)	*m*	1.626	*kg*
Time needed per section (cycle)	t	1.573	s
Optimal traverse speed	V_{noz}	0.095	m/s
Mass removed total	M_{tot}	27.600	kg
Time needed total	t_{tot}	28.275	s
Fouling material incubation			
Incubation period check	(S/P)>8	Fail	
Number of impacts in incub period	n_{in}	Not applicable	impact/m2
Impacts in incub period for the area	n_{area}	Not applicable	s
Duration of incub period	t	Not applicable	s
Duration of incub period	t	Not applicable	h

As the result, the cycle duration for the second run is around 1.5 seconds per section. The difference between the cycle duration in the first and the second setups is more than 6.5 times, with the difference in pressure at just 5 MPa.

Third run

In the third setup, the magnesium oxide fouling sample needs to be cleaned from the copper material. Magnesium oxide is a strong material, therefore the maximum pressure for the material of construction (copper) of 40 MPa is used. Input parameters are below:

Choose the material from the list:		**Fouling material**	**Construction material**	
		Magnesium Oxide	**Copper**	Units
Density	$\rho_{f\ or\ s}$	3570	8100	kg/m^3
Ultimate tensile strength	σ_u	44	221	Mpa
Fatigue constant	b	20.9	17.6	dimensionless
Poisson's ratio	$v_{f\ or\ s}$	0.2	0.3	dimensionless
Speed of sound	$C_{f\ or\ s}$	9100	2390	m/s

INPUT			
Waterjet and Pump setup			
	Symbol	*Value*	*Unit*
Pump pressure	P_{pump}	40	Mpa
Pump efficiency parameter	ψ_{pump}	0.9	Dimensionless
Losses in line	ψ_{line}	0.9	Dimensionless
Diameter of orifice	d_N	0.4	mm
Total flow	Q	10	l/m
Nozzle efficiency parameter	µ	0.95	dimensionless
Normal impact angle	θ	0	degrees
Jetting area diameter	x_c	0.1	m
Water properties			
Density fluid	ρ_L	1000	kg/m^3
Speed of sound	C_L	1463	m/s
Target dimensions			
Thickness	h_c	0.05	m
Overall fouling area per orifice	A_c	0.2	m^2
Choose the type of orifice from the list:			**Short Tube (0.8)**

The result of the model run is below:

RESULTS			
Pressure at nozzle	P_{noz}	32.400	Mpa
Jet Velocity	v	241.769	m/s
Average drop diameter	d_{DS}	8.978	µm
Volume of avg drop diam	Vd_{DS}	378.879	$µm^3$
Area of orifice	A_{Or}	0.101	mm^2
Area required	A_{req}	0.689	mm^2
Minimum orifices	Or	7	
Flow per orifice	Q_{or}	1.429	l/m
Maximum flow per orifice	Q_{max}	1.458	l/m
Water Hammer	P_{wh}	353.708	Mpa
Jetting area	A_j	0.008	m^2
Strength and Impact			
Impact pressure (stress at surface)	P	338.466	Mpa
Strength	S	5837.333	Mpa
Mass loss per Orifice			
Mass loss per impact	a	1.29482E-12	kg/Impact
Impacts per second in section	n_{imp}	62841958501	impacts/s
Mass loss in section per second	m_{sec}	0.081	kg/s
Mass removed per section (cycle)	*m*	1.402	*kg*
Time needed per section (cycle)	t	17.229	s
Optimal traverse speed	V_{noz}	0.006	m/s
Mass removed total	M_{tot}	35.700	kg
Time needed total	t_{tot}	455.971	s
Fouling material incubation			
Incubation period check	(S/P)>8	Pass	
Number of impacts in incub period	n_{in}	1.23664E+18	impact/m2
Impacts in incub period for the area	n_{area}	1.23664E+17	s
Duration of incub period	t	1967853.921	s
Duration of incub period	t	546.6265265	h

The maximum safe pressure results in a cleaning cycle of 17.2 seconds per section. However, the fouling material incubation check was passed. Adjustments to the pressure show that the incubation check fails only if the pressure at the pump is set above 186 MPa, while the cleaning speed at 66 MPa with the same setup equals 0.01 second.

4.2. Experimental design

In this chapter the recommendation and general schedule of requirement for the designing of experimental setup is given. This setup will focus on the determination and verification of the test fouling material sample properties, and it will validate the model from the chapter 4.1.

4.2.1. Schedule of requirements

General

- During the lab tests it is needed to take notes of all the steps of the experiment;
- Calibration and verification of the measuring and test devices must be performed before the experiment.
- The data needs to be visualized. Several products might be delivered, including the lab report and spreadsheets or graphs of quantitative data. The determination of the most suitable forms of representation of obtained data is the most important part of data processing. The data must be organized and labeled properly.
- All team members must be instructed on health and safety procedures, sign the corresponding form, and have knowledge how to act in an emergency event.
- All people involved in the experiment must wear PPE items required for the experiment. The operator of the water jet must have all PPE required for the operation, while the rest of the team must wear PPE required for their level of exposure to the material, e.g. particles flying, toxicity, flammability.
- There should be an accessible way to shut down experiment for all team members.
- The first aid kit, fire extinguisher and additional safety tools must be accessible.
- All sources of uncertainties and malfunctions of any sort must be noted for a future discussion in the lab report.
- The data should be recorded manually or automatically as soon as possible during or after the experiment.
- Lighting, ventilation, and bracing in case of the manual water jetting is required.
- Risks related to the cleaning of a particular material must be taken into account, e.g. toxicity due to evaporation or flying particles;

Water jetting system

- The water jet should not cause any damage to the target surface, like deforming;
- The water jet must be safe to use according to the Health and Safety standards (H&S);
- The pump limitations should be met, in terms of pressures, flows, water properties, usage cycles and connected equipment;
- The power consumption of supply pump should be optimized and monitored;
- The pressures at the pump, nozzle and target should be measured at all times of the experiment;
- Water jet system must maintain set pressure at all times;

- The properties of the water should be known and put in the system. Otherwise, the viscosity, temperature, and, density must be measured before the experiment. Other properties of water might be checked in case of the usage of additives, like polymers.
- Any used waste water with the fouling material that will not require further analysis must be properly disposed or reused/recycled. The rest of the fluid and solid samples that require further analysis must be stored properly to minimize the change of their properties.
- The usage of static water jetting device is suggested to avoid any uncertainties and variation of results due to manual operation.

4.2.2. The first phase

In the first phase the key properties of the fouling material case must be determined. The methods explained in the chapter 2.5.2. will be used.

The fouling sample material properties should be measured before the water jetting experiment. Several fouling sample materials of the same kind must be present to perform numerous repetitions of the tests to verify the results, or in case of the failure of the experiment. Since the fouling material formation is a very complex phenomenon, all samples from the same fouling cases should be tested, since the variation of the properties is expected. In reality deposit layers are not uniform and may have different properties, like density or speed of sound, depending how the layers of fouling were formed.

There are several ways of obtaining the material. The most preferable one is to get the material from the operating heat exchanger. The withdrawal of the material should take place with minimal possible disturbance. The second method is to create a test setup of heat exchanger simulation for fouling accumulation, refer to chapter 2.5.4. The system equipment and fluid should be as close as possible to the real full-scale operation. The most important factor of a success of experiment is to simulate the properties of the processes and equipment in the system, like working fluid speed, temperature, the temperature of the surface, material of the surface, present sedimentation or micro-organisms in the water, number of cycles, etc. Certainly, some simplification on neglection can take place to avoid extreme costs. The third option is applicable only in case if the key properties of the fouling material case are known. In this case the test sample with the same properties as fouling material can be created. However, to maintain a high degree of similarity between the reality and the test sample will be challenging and will require high costs.

4.2.3. The second phase

In the second phase the imitation of the water jet cleaning of the attached fouling material sample will be performed. The jetting setup may use the experimenting layout of Guha et al., 2010. The properties of the fouling material, water jet system and material of construction should be put in the model. The model uses several simplifications, and it needs to be adjusted depending on the water jetting equipment used. For this information refer to the discussion and recommendation chapter.

The standoff distance and impact angle shall be held constant. Check chapter 2.2.5. for the data and references on the topic. The standoff distance is neglected in the model due to the lack of data provided regarding the nozzle design, coverage area, and overlap. Some literature suggests that the maximum impact pressures can be achieved if the stand-off distance is equal to 150 times of nozzle diameter. (Leach et al., 1966; Shavlovsky D., 1972). Besides, experimental observations have shown that the cleaning width is not as wide as the jet diameter and is affected by parameters including standoff distance, traverse speed, water pressure, nozzle diameter, and coating material (Geskin et al., 1995; Meng et al., 1996; Leu et al., 1998). Minimal standoff distance is also important to avoid shock absorption or jamming of the water jet gun. All this data requires experimental tests to confirm. Generally, it is recommended to perform the initial test of the removal rate with the static nozzle, without any lateral or traverse movement of the jet area.

The actual pressures at the impact are hard to determine with the model, since many variables affect this factor. The losses coefficients need to be verified and adjusted. It is required to measure a particular water jetting gun design the pressure measuring plate may be installed for a test run of the water jetting gun setup, to determine real impact pressure and compare results with the model.

The equipment, like motor, suction, pump, water jet gun or automated device need to be tested prior the experiment, to check the correctness of their functioning. Some variables or factors could be checked to determine the real properties of the system or the actual losses in the system, for example, these properties could be checked: the output power, the flow, pressures at different parts of the jetting system, the nozzle and behavior of orifices, etc.

There should be a capturing tank under the experimental surface to trap the water that was used in the washing. This water could be analyzed if the need will arise, for example, if the sample was taken from the HEX and require additional analysis after cleaning

Several monitoring techniques from chapter 2.5.1. may be used. Heat transfer coefficient and pressure drop measurement are not suitable during the first static tests, since these methods are more suitable for the measurement of the fouling resistance in the operated HEX than to measure the cleaning efficiency of a water jetting setup against a particular fouling deposit case since the required simulating conditions will increase the costs significantly.

Usage of the inspection cameras is essential. By visual validation and measurements done by the video, it is possible to identify the cleaning rate, the nozzle setup performance especially in the tube side cleaning. If the angles for the recording are chosen right it is possible to use pixel method to calculated the removal rate and change, however the precise measuring before the test need to be used.

The data needs to be measured continuously during the whole experiment. If the data regarding the cleaning speed and intensity is not aligned with the data from the model the determination of the factors between the reality and anticipated modeled results must be drawn.

Any unexpected behaviors of the material must be noted for further discussion. There are numerous properties that affect the cleaning of the fouling materials according to the literature, only several of these properties is used in the model. However, determination of the properties listed or noting the behavior of the material will benefit the development of the model and experimental design. The knowledge of a particular fouling sample case's additional properties might help to find relationships between the variables or build new models and verify them with the obtained quantitative data about the samples.

The HEX cleaning requires two separate approaches, for the tube side and the shell side cleaning. The goal of the model was to link fouling material properties to the water jet cleaning. The initial experimental tests do not require in-site tests, since the properties of fouling materials are poorly studied yet. Determining of these properties, linking them in the model and verifying them in the experimental tests should be the first step in optimization of water jet cleaning. The complexity of shell side and tube side cleaning with their nuances of cleaning and geometrical variety make them non preferable for the first tests. Besides, precise monitoring and measurement of the effect of certain pressure on particular fouling material is harder to execute and might be more expensive.

However, after the initial tests with the static sheet, if the material properties will be studied and the model will be validated this model and experimental design can be modified to create separate numerical and experimental setups for tube side and shell side cleaning.

5. Conclusion

Shell and tube HEX systems have many applications, the fouling material that appears in the system is connected to the operational setup and type of application that the HEX system is used for. Fouling reduces the cross-sectional area of the working fluid, this layer has a low thermal conductivity and it increases the thickness of the materials between fluids, which leads to a decrease in the efficiency of heat transfer and causes operational risks. Among all parts of equipment shell side and tube side maintenance are the most common cleaning activities, these two types of maintenance require different considerations, approaches, and equipment.

One of the main advantages of the water jetting technique for the cleaning of HEX is the possibility to adjust pressures depending on the fouling material case that needs to be cleaned. Therefore, the technique of optimization is based on the balancing of having enough power to remove the fouling on one hand and not enough power to deform or damage the surface material on another. Any excessive energy or unreasonable time spent within these boundaries will lead to additional costs and unnecessary environmental damage.

The pressure, water flow, nozzle design, stand-off distance, and impact angle are the most important factors that can be regulated in water jet cleaning. By adjusting them the effect of the water jetting system can be completely altered. There are some suggestions that the angle of impact is connected to the brittleness and ductility of the material. The temperature clearly has an effect on some materials, besides heat cleaning causes phenomenon of thermal shock that leads to increased removal rates. However, heating systems need to be used with care to avoid damage to the material of construction and to avoid an increasement in the rate of fouling after the cleaning event.

Water jetting has several additional techniques that can be implemented in the maintenance strategy of HEX. Polymeric additives may lead to better impact pressure, due to reduced system losses. In the case of the extremely hard fouling material, the abrasive waterjets may be used with care if the other water jetting techniques are insufficient. Cavitating waterjets may achieve greater results with certain materials, however, they need to be studied in accordance with the fouling material type.

The fouling phenomenon is a complex problem, however, there are many properties of the fouling material that have an effect on the optimization of a cleaning rate. Density, speed of sound, ultimate strength, and Poisson’s ratio of the materials are influencing the removal rate. These properties were connected and linked to the water jetting model. The studying and determination of these properties of the fouling material cases are necessary to continue the cleaning optimization development.

Several studies suggest classification of the fouling materials by their key mechanical and chemical properties discussed in literature review. This classification can be used to determine required maintenance strategy, however the fuidelines suggested in the literature are not sufficient to make an applicable maintenance strategy.

Alternatively, this research suggests to study fouling material cases instead. This classification can be based by the type of work that HEX is used for and additional factors like material of construction and working fluid properties. If the properties of these fouling material cases will be studied and will be linked to the number of working cycles or aging phenomena, it will help to predict the fouling material properties without demand for regular tests, decreasing costs for monitoring and maintenance.

The model is running and connected to the erosion per droplet impact and water jetting. While there are still many assumptions and simplifications, the model can be used to start the testing and verification of this method of linking fouling material properties to the water jetting removal rate. The properties of the materials used in the model are referenced, however, these properties do not represent the real properties of the fouling materials and were used because of the lack of better alternative.

The methods are given to determine the fouling material in the experimental setup. After these properties will be determined and the model will be adjusted with the lacking data, the experimental setup for water jet removal rate determination can be performed.

6. Discussion and Recommendation

Maintenance strategy

The potential pressure limits in water jetting is way above the strength of the construction materials, as mentioned hydro blasting is widely applied even in mining and steel cuting. Therefore, in cases of very strong fouling material and relatively weak material of construction, it is required to carefully choose the pressures to avoid the breaking of the last. Water jetting is a versatile technique but it might benefit from combining it with other cleaning methods in one maintenance strategy then it is possible to combine two or three cleaning methods in one strategy, covering the ineffectiveness of particular cleaning methods to certain fouling materialor due to nuances related to the effectiveness for a particular part of the equipment of HEX. Desk research showed that none of the cleaning methods are universal, and optimal cleaning must be chosen for every fouling scenario. (Awad M., 2011; Bott T., 1995) The cleaning method might be linked to the combination of properties in the model and to the classification of the fouling material, discussed in chapter 2.3.1.

Relevance of the aeronautic rain models in water jetting

While the main difference between water jet cleaning and the aircraft moving through the rain is the fact that in water jetting the water particles are sprayed by the water jetting gun and are sent by the pump, therefore the water moves towards the target surface. In the case of aircraft engineering, the opposite happens, the high-speed body is moving through the rain. However, in both of these cases, the impact between the target material and the water droplet surface is happening under a certain angle and speed. Both of these parameters are comparable. The range of angles in both cases is not limited, however, it is still needed to confirm that the speeds of the water jetting and the potential speed range of an aircraft in the models are comparable. According to the literature, typical abrasive water jet velocities with orifice diameters in the range of 0.2 to 0.6 millimeters vary between 300 to 850 meters per second. (Osman et al., 2004) While the models overviewed by Springer contained calculations for both ultra-high-speed airplane jets and cases of the cruising speeds of a typical long-distance commercial aircraft. The typical speeds of commercial aircraft are usually in the range of 200 to 260 meters per second, while the speed of military ultra-high-speed jets in modern aviation can reach way beyond 850 meters per second. Therefore, this comparison is considered relevant.

Besides, in the book, the author stresses the fact that the term “rain” is used in a broader sense, and can be related to any water droplet impacts. (Springer G., 1976) Instead of the calculations related to the rain intensity and size distribution, the data from the water jetting coating cleaning model was taken, therefore Sauter mean diameter used in the model is taken from the field of water jetting. (Momber A., 2003)

It is important to note that in the aeronautic models, the strength, mass removal rate, and other factors are more connected to the ductile type (coating) of material behavior since the brittle materials could fail because of the different mechanisms. However, it was mentioned that there are little data on brittle materials available from the experimental designs, and it mainly corresponds to the aeronautic models and collate with the reality. Therefore, it may be used as a starting point for brittle materials as well. (Springer G., 1976)

Fouling material classification

The lack of models and data related to fouling materials properties and water jet application for fouling removal shows the importance of conducting the further development of theoretical concepts and physical reasoning. Obtaining empirical results via experiments is crucial for jet cleaning optimization. As discussed, the phenomenon of the fouling material is very complex and requires careful multidisciplinary analysis. Clearly, the fouling material cases consist of multiple types of materials that were formed by different processes, in many potential combinations. Besides, these materials can be layered in a certain way or mixed with each other depending on these phenomena. It creates a lot of uncertainties in the development of the fouling material models.

To solve it the fouling material classes may be studied separately, and the properties and optimal cleaning strategies may be connected even stronger to the classification of the material by their key physical and chemical processes. (Epstein N., 1983; Awad M., 2011; Bott T., 1995) However this approach is subjected to the challenge of the tendency of fouling materials to be mixed together, settle in layers, or even due to the fact that the fouling classes are connected to each other and one fouling class can cause the appearance of another in the system.

One of the potential solutions that can simplify to a certain extent the complex task of determination of fouling properties is to unbind the fouling cases from the particular fouling material or even fouling material classes and start experimenting with the fouling material cases linked to certain industrial activities in HEX. Since HEX has many applications the optimization of the cleaning process can be started with the most widespread applications. As the result, the determination of the key properties and mass of the fouling material case for modeling could be predicted by the type and frequency of the application that the HEX system was used. For example, certain operation of the heat exchanger is performed at intervals. The test subject fouling material could be studied in certain intervals without cleaning, with some material being withdrawn for material and water jetting testing.

Tube and shell side cleaning

After the verification of the model and determination of properties for several material cases, the model can be modified to two separate models: for tube side and shell side cleaning. The equipment used for cleaning, the cleaning approaches, the challenges, and even the fouling materials found on these equipment parts are different. However, with some adjustments and modifications, the model most likely can be fitted in both scenarios. The starting point might be the book of Summers, especially for tube side cleaning. The information in the book is mainly qualitative, while the quantitative part will require some additional research and determination. Potentially these solutions can be found already either in cleaning companies or at the manufacturers of water jetting systems.

Pump and motor

Additionally, it is clear that if the system will use more pressure than needed the excessive amount of fuel that powers the motor will be wasted. The simplification was made for the calculation of the pump output pressure. According to the literature the required pressure for a pump does not have a linear ratio with the values of flow, and velocity, however, it is a function of the nozzle area, volume flow, fluid velocity, and jet pressure. (Summers D., 1995; Lobus T., 1989) The ratio between the pressure of the pump, flow, and power consumption is not linear as well. Water jet pumps provide ultra-high pressure for a relatively small flow. Additional data like UHP pump curves for water jetting should be obtained and adopted according to the equipment used for realistic calculation of the cost and environmental impact. Therefore, if the model will be applied to the tube and shell side cleaning the detailed calculation of the fuel consumption can be linked to the model knowing the parameters of the pump and motor.

Nozzle and droplets

As the most common type of water jet nozzle, the round jet is used in the model. The distribution of the droplets is considered uniform in the whole cylindrical target area. However, in reality, there are numerous nozzle designs that can redistribute the cross-sectional area either towards the perimeter of the jetting area or completely change the shape of the water jetting target area, like in the case of the widely used fan jet with the straight-line area. Usually, in dynamic cleaning of the water jet, the traverse speed of the water jet nozzle is constant, therefore in case of the unevenness of water distribution within the target area, the further complexion of the model with redistribution of the water droplet intensity will be unjustified. However, there are several additional factors that influence the distribution of the water in the jet, like rotation speed and overlap between orifices. The client did not provide any additional data or models on the water jetting devices that are used by a cleaning company. The model may be adjusted according to the equipment used.

For nozzle-orifice calculations, several methods were attempted, however, due to the lack of information on the nozzle design and distribution of pressure among several orifices, this factor was neglected in the model. Clearly, if a certain pressure is required at the surface or at the nozzle, then the number of orifices changes the total outflow area and affects the pump pressure requirement. This needs to be verified with the cleaning company or water jetting equipment manufacturer to determine real energy costs.

Losses for the water jetting pressure occurring in the system can be reconsidered. The model used a diamond orifice efficiency parameter since the losses for this type of orifice were found during the literature review. However, if the client or the cleaning company possesses formulas or models to determine losses of different setups of water jet guns it would complement this model and make results closer to reality for the range of setups.

Pressure

There are several alternative ways to calculate impact pressure in the literature. Some authors point out the fact that the actual impact pressure at the target location may be completely different from the results from the formulas, some recommend checking the alternative ways to calculate, like water- hammer formula. (Momber A., 2004; Summers D., 1995) In the model, the formulas from the aeronautic engineering used in drop calculation were implemented since it takes into account the properties of the target material, and besides, it is used later in the calculation together with the "Strength" formula from the same source. (Springer G., 1976).

Incubation concept

The incubation concept is a great representation of the fatigue limits of the materials, and they can be useful for further studies and experiments related to the determination of limits of construction material. However in this model the incubation calculation failed. This can be linked either to very strong materials or to the fact that incubation calculation is not fitting into the water jetting models. Potentially it can be because of the different nature and properties of the water droplet size and impact intensity in water jetting in comparison to the rain models in aeronautic engineering.

Impact angle and standoff

Some models in aeronautic engineering suggest that at very high impact velocities the tangential component of the impact pressure can be responsible for the damage. (Springer G., 1976) However, the literature review on this topic did not give applicable results, besides some general knowledge of the connected phenomenon, like brittleness of the material or failure mode. Some authors stress the importance of determining of optimal angle for materials, however only limited graphs show the ratio between jet angle and specific energy needed for the material removal. (Mombers A., 2004; Summers D., 1995; Wright et al., 1997) These graphs can be found in chapter 2.2.5. and may act as a starting point. Potentially, cleaning companies already have knowledge on this topic from the practical domain, however, this data still needs to be collected and validated in the experimental environment.

Taking into account above mentioned points and due to the lack of a better option it was decided to use a normal, perpendicular angle for this model since the angle from the aeronautic models (Springer G., 1976) is not representing these factors and clearly, the formula connected to angle does not represent the reality.

Determination of the effect of standoff distance is necessary for further modeling. While the researched published literature has little information on this topic the starting point for optimization of this factor may be a collaboration with the cleaning companies. Comparing and analyzing the guidelines of these commercial organizations are of great importance for model development.

Hardening concept

The classification of hard and soft fouling material in the discussed Hexxtec and DOW model provided by the client basically corresponds to the ratio. It is clear that the author of the model simplified the "hardness" factor. The author of the model uses the above-mentioned scaled pressure value factor that changes target pressure at the nozzle inlet depending on the “hardness” of the material. However, the determination of the “hardness” is related to the time and number of HEX operations since the last cleaning activity, and the relation between the hardness and the fouling material properties is not defined. In further models other properties of the material will be used and

Other

If the tube and shell side cleaning models will be developed they should include the factor of uneven surface. Springer G., identifies a model of uneven surface impact, however it could not be obtained. Theoretically, it can be linked to the dependence between impact angle and removal rate for different materials discussed in this research.

The area of the water jet impact is the input jetting area diameter. Realistically, this value can be obtained with the jet setup parameters, like orifice overlapping, spray distribution and stand-off distance (Summers D., 1995), if this data can be obtained the model can be adjusted.

Literature review

Initially, the approach of this research was to find and link the strain-stress curves of the fouling materials to the models that studied water jetting. This approach has failed since there is a clear lack of conducted and published research on this topic to the best knowledge of the author. Certainly, the literature on paint and coating removal in comparison to fouling are well presented and can be found in public access and since the phenomenon of coating and fouling removal is physically comparable with fouling removal the approach changed to compare coating and fouling material. However, these models focus on the water jetting part mainly and lack applicable data regarding the properties of the coating or materials, while several sections in the models are incomplete and unclear. In some cases, the method is suggested however a lot of data is lacking to start modeling and perform experimental tests. Furthermore, the available literature on the topic varies in age, with some research reports dated more than forty years ago. Certain research papers could be obtained only partially and were not available online.

The main challenge in literature research might be connected to commercial competition since most likely some of the chemical or cleaning companies have developed the models for the optimization of such processes as fouling removal in HEX, however, to the best knowledge of the author material published is very limited and is not enough for modeling.

The phenomenon of mass removal by the water droplet can be looked at in more detail. For example, Springer’s book (1976) on erosion by liquid impact provides information and advanced models on internal forces and wavefront of each drop impact, however, that requires more experiments and determination of many uncertain properties. Besides, it may lead to over-complication of the model, especially at the initial stages of its development.

The study of the comparison between coating and fouling is recommended to start with the book “Hydroblasing and Coating of the Steel Structures” written by Momber A. Moreover, the book of Summers contains a lot of general information and references to many existing studies for all kinds of applications of water jetting. Bott T. has extensive work on fouling material types and classes, while the book has a lot of information mainly it focuses on chemical properties rather than mechanical ones.

The experimental research of Guha et al., 2010, has information on the anatomy of the high speed water jet movement, numerical simulation of a water jet as well as experimental set-up. After determination of the data related to the water jet equipment this research may complement the model of this thesis. Beside, it has well described information regarding the experimental design that was used in the study.

Therefore, the following literature is suggested as a starting point for further research:

- Springer G., 1976;
- Momber A., 2003;
- Summers D., 1996;
- Bott T., 1995;
- Guha et al., 2010;
- Wang et al., 2019;

Mainly, all sources looking at fouling models that are not connected to water jetting are considering density, thermal conductivity, and thickness as the main parameters of the fouling material. Some of them introduce the “deposit strength” factor, however, the extensive desk research did not find any connected parameters, tables, or any other quantitative or useful qualitative data that could be used to draw a model. (Taborek et al., 1972; Kern et al., 1958; Watkinson et al., 1968; Epstein N., 1983)

The overview of early models for the fouling phenomenon can be found in the article on predictive methods for fouling behavior. (Taborek et al., 1972) This overview showed that half of the early models do not use any properties of the fouling for a determination of the removal rate, and only some make the removal rate proportional to thickness and shear stress. In this article, the parameters related to the strength of the material should be determined experimentally.

Models from Epstein N., 1983 and the research work of Awad M., 2011, look in detail at different fouling material types (check chapter 2.3.1), and unfold the topics of formation, chemical properties, and cleaning nuances. The information gives a great inside into the chemical and material science side of the fouling problem.

Models from the book of Summers D., 1995, have extensive information on the water jetting and hydraulic systems physics and principles of work. This book is a great introduction to water jetting. However, aside from several formulas that may be connected to a model with some additional data from the water jetting and HEX setup, this book provides little to no information on fouling material. There are several tables, however, most of the materials of not interest to the client, the data is uncertain, some formulas lack units, etc. Still, the models that could use the data on the mechanical properties of fouling materials are lacking.

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Appendix A

Physical properties of selected materials

Material	ρ	C	E	ν	σ_u	σ_f
Acrylic plastic*	1.22	1943	2.07×10^6	0.2	–	4.48×10^4
Alkathane	1.18	1331	2.07×10^6	0.33	4.14×10^4	1.65×10^4
Alkathane Z	1.16	1350	2.07×10^6	0.33	4.14×10^4	1.65×10^4
Alumina	3.88	5563	1.19×10^8	0.25–0.3	1.71×10^4	1.24×10^4
Aluminum*	2.7	5200	7.10×10^7	0.33	1.12×10^5	4.48×10^4
Aluminum 1100-0	2.7	5200	7.10×10^7	0.33	8.96×10^4	3.59×10^4
Aluminum D.T.D. 423B	2.7	5200	6.89×10^7	0.33	4.14×10^5	1.31×10^5
Aluminum* 1145-H19	2.7	5200	7.10×10^7	0.33	1.65×10^6	6.62×10^4
Aluminum* 2024-T6	2.7	5200	7.10×10^7	0.33	4.76×10^5	1.31×10^5
Aluminum* 5052-0	2.7	5200	7.10×10^7	0.33	1.93×10^5	7.72×10^4
Aluminum* 6061-T6	2.7	5200	7.10×10^7	0.33	2.76×10^5	1.10×10^5
Aluminum* 7075-T6	2.7	5200	7.10×10^7	0.33	5.72×10^5	1.31×10^3
Cobalt	8.23	5003	2.07×10^8	0.3	9.65×10^5	4.83×10^5
Cobalt-chromium alloy	8.23	5100	2.07×10^8	0.3	9.65×10^5	4.83×10^5
Copper (electrolytic)	8.1	2390	4.48×10^7	0.3	3.65×10^5	1.39×10^5
Copper alloy* B5 1483	8.1	2390	4.48×10^7	0.3	2.21×10^5	8.83×10^4
Epoxy	1.77	3531	2.21×10^7	0.35	2.21×10^5	4.76×10^4
					-2.62×10^5	-5.65×10^5
Glass	2.24	5410	6.62×10^7	0.19	4.94×10^3	–
Iron	7.8	5130	2.07×10^8	0.3	2.83×10^5	1.41×10^5
Magnesium alloy* O.T.D. 259	1.8	5150	4.48×10^7	0.065	3.45×10^5	1.21×10^5
Neoprene*	1.55	135	2.81×10^4	0.2	8.27×10^3	8.27×10^3
Nickel	8.1	5055	2.07×10^8	0.3	3.17×10^5	1.27×10^5
Plexiglas	1.16	1536	2.76×10^6	0.35	5.52×10^4	2.21×10^4
Polyester	1.82	3200	1.93×10^7	0.25	3.95×10^5	3.86×10^5
Polyethylene*	0.92	1473	2.07×10^6	0.2	9.65×10^3	4.14×10^3
Polyimide	1.93	3708	2.62×10^7	0.25	3.86×10^5	3.45×10^5
					-5.10×10^5	
Polyphenylene oxide	1.06	1580	2.55×10^6	0.4	7.24×10^4	2.90×10^4
Polyurethane	0.99	274	7.52×10^4	0.2	–	1.38×10^4

Table 9. Properties of materials. (Springer G., 1976)

Material	ρ	C	E	ν	σ_u	σ_I
Silicon	2.26	5716	–	0.16	4.94	–
Silicon carbide	3.22	1092	3.86×10^8	0.2	1.57×10^5	1.03×10^5
Steel*	7.6	5182	2.07×10^8	0.3	5.93×10^5	–
Tantalum	16.6	5532	1.86×10^8	0.35	7.58×10^5	–
Teflon*	2.25	536	6.55×10^5	0.33	2.21×10^4	8.27×10^3
Titanium*	4.47	5182	1.26×10^8	0.3	2.21×10^5	–
Udimet	8.41	4100	2.07×10^8	0.3	1.38×10^6	–
Water*	1.0	1463	–	–	–	–
Zirconia	6.5	5410	8.27×10^7	0.3	6.89×10^5	–

Table 10. Material properties. (Springer G., 1976)

Material	Density in kg/m^3	Speed of sound in m/s	Acoustic impedance in $kg/m^2 \cdot s$	Ψ_{SC} Eq. (2.43)	Ψ_{FC}	Γ_1	Γ_2	Γ_3
1	2	3	4	5	6	7	8	9
Acrylic	1220	1943	$2.37 \cdot 10^6$	0.89	−0.24	1.557	0.358	1.215
Epoxy	1770	3531	$6.25 \cdot 10^6$	0.73	−0.63	1.185	0.156	1.457
Polyester	1820	3200	$5.82 \cdot 10^6$	0.74	−0.61	1.199	0.166	1.451
Polyethylene	920	1473	$1.35 \cdot 10^6$	0.93	0.025	1.976	1.976	0.976
Polyamide	1930	3708	$7.16 \cdot 10^6$	0.69	−0.67	1.156	0.135	1.463
Polyurethane	990	274	$0.27 \cdot 10^6$	0.99	0.68	6.089	0.836	0.329
Water[1]	1000	1450	$1.45 \cdot 10^6$	–	–	–	–	–
Steel[2]	7600	5182	$39.38 \cdot 10^6$	–	–	–	–	–

[1] Projectile material.
[2] Substrate material.

Table 11. Acoustic parameters (Momber, 2004)

Material	Property				
	Young's modulus E_M in GPa	Tensile strain ε_T	Poisson's ratio ν_C	Ultimate strength σ_U in MPa	Endurance limit σ_I in MPa
Epoxy binder	0.4–0.8	30	–	14	–
Epoxy polymer	0.6–1.0	35	–	–	–
Methacrylate binder	0.7	100–200	–	3–8	–
Polyester binder	0.24–0.62	30	–	14	–
Polyurethane binder	0.3–1.0	150–600	–	6–10	–
Acrylic	2.1	–	0.20	–	45
Epoxy	22.1	–	0.35	221	48
Polyester	19.3	–	0.25	395	386
Polyethylene	2.1	–	0.20	10	4
Polyamide	26.2	–	0.25	386	345
Polyurethane	0.07	–	0.20	–	14

Table 12. Mechanical properties. (Momber, 2004), adapted from (ACI, 1993; Springer, 1976)

Material	ρ	C	ν	$\sqrt{L_o}/K_c$
Calcium aluminate	2.95	9350	0.29	3×10^{-5}
Magnesium oxide	3.57	9100	0.2	1×10^{-5}
Polycarbonate	1.2	1425	0.25	40×10^{-10}
Polysulfone	1.24	1425	0.4	80×10^{-10}
Quartz	2.5	5300	0.2	45×10^{-10}

Table 13. Properties of materials. (Springer G., 1976)

"The top parts of magnesium ingots have the highest tensile strength (44 MPa), which is mainly due to the presence of a large amount of the coarse MgO." (Chen et al., 2020)