Improving the cleaning process of bulk carrier holds

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Improving the cleaning process of bulk carrier holds

by

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Summary

Bulk carriers make up around 20% of the global merchant fleet, and thus have a vital position in the operations of the maritime sector. These ships load and unload at places like the EMO terminal, where enormous quantities of bulk solids, mostly iron ore and coal, pass through. In every operation that involves particulate solids, efficient storage and handling of the material is an essential part.

The loading and unloading of bulk carriers that dock at the EMO terminal is largely automated so that if a ship has docked, a crane with a grab will start digging out the hold to 95%. For the last 5%, a front loader is used to move the cargo together so the grab can also unload this material. Material also remains in various places such as walls and stairs due to sticking and compaction. To clean the stairs personnel are using various hand tools to remove this material. After this has happened and the access to the bottom of the hold is clear, a front loader and excavator can be lifted into the hold to clean off the remaining material in the hold. The process of clearing the stairs takes many manhours and can be dangerous. Cleaning the rest of the hold is also dangerous because the grab simultaneously works in the hold. The machines in the hold can be used to clean the wall, but they are not usable on areas such as stairs. The use of these machines also can damage the ship resulting in extra costs. The high docking and demurrage costs also make any time savings financially attractive.

The aim is to develop a method and/or equipment that can clean the stairs so that people do not have to do this task and that the time spent in the danger zone and risks are minimized. This solution should also be able to clean the other parts of the hold where material is stuck. This solution should not damage the hold so that no extra costs are incurred. If the stairs have been cleared and a safe access has been created, the bottom of the hold can still be cleaned by a local human operator in a front loader. Making the whole unloading/cleaning process autonomous such that no people are needed is the ultimate goal of EMO. The research question of this report is: Is it possible to clean the hold of a coal bulk carrier by machine, and have the hold be cleaned faster and with less damage?

The problem is further analyzed and literature about bulk handling and unloading is studied. This includes a look at the properties of bulk material and its dangers, discharge aids in silos, bulk conveying methods. A stakeholder analysis is also done to understand who is involved with this project.

Information learned by practice is gathered from EMO and commercial products are gathered. A variety of state of the art products that are used for industrial cleaning and material dislodging and moving are studied including a water gun, water lance, a wall riding robot, and high-pressure water jetting. The things that EMO has already tried include a hydraulic hammer, a vibration plate tamper, vibrating needles, an air cannon, a low-pressure water jet, and multiple excavator attachments.

The system and environment at the EMO terminal are analyzed. The minimum standard of cleaning required is determined to be “shovel clean”. The damage done to holds and the associated costs are analyzed, it shows that the machines in the hold did €36K of damage. The safety incidents during cleaning are shown and the potential improvement is almost 80%. Also, the speed of cleaning a hold is determined to be up to 6-8 hours.

The functional specifications of the system are noted, from these specifications the design requirements are generated. The dimensions of a large hold, and the space available on deck and the quay are shown. The specifications and design requirements are split into 3 categories: requirements, recommendation and optional. Some requirements are: no damage to the ship, no excessive dust generation, works on all ships, as safe and fast as the current process, and possible to automate. Some corresponding design requirements are: no hard contact with the ship, low airflow rate, a specified minimum horizontal and vertical reach, does not create dangerous situations, specified maximum average hold cleaning time, can be automated.

A description of multiple concepts is made and the best are selected using a multi-criteria analysis and a feasibility study after the design is elaborated on. The concepts are split into 2 functional categories: cleaning the hold and reaching the cleaning area. The cleaning concepts that scored highest in the multi-criteria analysis are a low-pressure water washer, air compressor and a high-pressure water washer. The best reaching concepts are the currently used CAT 329 excavators and a scissor lift. After further study, the concepts chosen from this selection are a high-pressure washer and an excavator.

The technical specifications are drawn up, a design concept is made, and a simplified prototype is built. The concept includes a CAT 329 excavator with a high-pressure pump of at least 200 bar and a water tank of at least 1 m^3. The counterweight is removed from the back, and the pump and tank are placed on a constructed frame. High-pressure hoses are run from the tank to the pump and from there over the boom and arm to a simple attachment with one or multiple (types of) nozzles. The steps toward automation are also discussed.

Then a pilot is done where the concept is tested, and the results from the testing are analyzed. The first tests include measuring the impact of a water jet using a load cell at operating pressures of 100, 140 and 180 bar. This is done using 3 types of nozzles: a round jet, a flat planar jet and a rotating jet that forms a cone-shaped spray. The standoff distances are 0.5, 1 and 1.5 m. The standoff distance has little influence on the measured impact force, but an increasing pressure clearly causes larger forces. Nozzle 1 and 3 mostly have similar impact forces, but nozzle 2 always generates the largest force. Regarding the impact pressure, nozzle 1 is the best, then nozzle 2, and then nozzle 3.

The second tests are jetting on a piece of painted steel to see if a hold would be damaged during cleaning. This is done by measuring the paint layer thickness with an ultrasonic thickness gauge. The same nozzles and distances as in test 1 are used, but only at 180 bar. The measurements showed that no damage was done.

The last tests measure the duration of cleaning of a section of sheet pile wall, since a ship hold is not available to be used. This is done using the same nozzles and distances as before, but only at a pressure of 180 bar. Nozzle 1 was the quickest, then nozzle 2 and lastly nozzle 3 was incapable of cleaning its section. In this test, increasing distance did result in longer cleaning times due to decreased impact pressure. A rough calculation shows an entire hold would take between 6 and 18 hours to clean.

Some of the conclusions that are drawn regarding the performance of the concept are as follows: The noise level seemed acceptable, the hold would not be damaged, the water flow rate was not too high, the excavator can reach everywhere in the hold. It is not known how well the concept performs cleaning a hold, especially regarding time. So regarding the research question: The hold can be cleaned with a high-pressure water system without damage, but it is uncertain how well the concept would perform on stairs in the hold where the standoff distance could be as much as 2-3 m. So if the concept performs well in a hold, which can be tested next, large savings in the form of time, money and safety can be realized.

Recommendations are made for further study and/or improvements. These include further research into oscillating flow, the effect of multiple, different, moveable nozzles. Also, further testing regarding nozzle types and nozzle sizes is suggested. And lastly, investigating how an automatic (dis)connecting system between an excavator and a shore crane can work, and looking into developing a way to scan a hold and have an excavator operate autonomously in that hold.

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Contents

1 Introduction

A bulk carrier is a ship that transports bulk quantities of cargo. This type of bulk cargo is unpacked and loose. This means that there is no ordered packing structure, e.g. grains, ore, and coal, but also liquids and gasses such as oil and other chemicals. Some of these ships can unload their own cargo but others depend on port equipment for unloading. Bulk carriers make up around 20% of the global merchant fleet [1], and thus have a vital position in the operations of the maritime sector.

The largest amount of bulk products is in particulate form. The handling processes of bulk solids are wasteful with respect to energy and improvements can cause large savings over a spectrum of industry. Our understanding of particles compared to gases and liquids is not very advanced, since the problem is complicated and has many facets. Particles interacting with each other, and gas or liquid is an important aspect in describing the behavior [2].

These goods are transported all over the world by bulk carriers loaded with hundreds of thousands of tonnes of material. These ships load and unload at places like the EMO terminal, where enormous quantities of bulk solids, mostly iron ore and coal, pass through. In every operation that involves particulate solids, efficient storage and handling of the material is an essential part. To design the storage and handling equipment so that it works correctly, knowledge of the material properties is required. However, bulk carriers transport materials with many different properties. So in this case the design of port equipment needs to work for all types.

The loading and unloading of bulk carriers that dock at the EMO terminal is largely automated, but not completely. If a ship has docked, a crane with a grab will start digging out the hold, it can do this for 95% of the material. For the last 5%, a front loader is used to scoop the material together in the center of the hold so the grab can also unload this material. However, material also remains on the walls, on walkways, stairs, and other components in the hold due to sticking and compaction. To remove the material on the stairs personnel are using various hand tools to remove this material. After this has happened and the access to the bottom of the hold is clear, a front loader and excavator can be lifted into the hold to clean the remaining material in the hold. The excavator can be outfitted with various attachments and is then used to clean the walls. This is done in tandem with the digging of the grab.

The process of clearing the stairs takes many manhours and can be dangerous due to the nature of the work and the location: working on stairs and digging coal or iron ore in a hold with the potential for dangerous gasses and dust. This process uses water to clear the stairs, which gets mixed into the product. This is an unwanted consequence that has an impact on the quality of the cargo. Cleaning the rest of the hold is also dangerous to a lesser degree, due to the combination with activities of the ship unloader crane.

The attachments used by the machines in the hold can be used to clean the wall, but they are not usable on more difficult-to-reach areas, or areas with flat horizontal surfaces, such as stairs. The use of these machines also can cause damage to the ship resulting in extra costs. The high docking costs, and potential demurrage costs, of bulk carriers also make any time savings financially attractive.

Research has been done about optimizing the moving of loaders between ship and shore [3], the optimization of the unloading strategy [4], the virtual prototyping of grabs [5], systematically optimizing grabs for multiple cargo types [6], and many studies about hopper discharge [7–11]. But for this study no specific scientific literature has been found about the cleaning of large fractions of stuck material in bulk carrier holds, which makes this topic worth investigating.

The aim of this project is to develop a method and/or equipment that can clean the stairs so that people do not have to do this task and that the time spent in the danger zone and risks are minimized. This solution should also be able to clean the other parts of the hold where material is stuck, since the method presently used for this is suboptimal. This solution should not damage the hold so that no extra costs are incurred.

This can happen fully automatic by means of scanning the hold of the ship but this is an unlikely outcome and the focus will not lie here. The control system for this is not easy to make since it not only needs to cover every area, but also be controlled such that the area is cleaned adequately and know when the area is clean (in difficult lighting and dust conditions) without damaging the hold.

The other option is to use a person to control the equipment. If the core of the machine is located in the hold (in contrast to outside reaching in), a remote controller should be used, because the machine still needs to clear the access to the hold. This means that the only access to the hold is with a special personnel basket lifted by the ship unloader crane, which is undesirable to EMO. It would be ideal if the wall cleaning process can happen when the front loader is also working in the hold, so that the process is as efficient as possible.

If the stairs have been cleared and a safe access has been created, the bottom of the hold can still be cleaned by a local human operator in a front loader. Making the whole unloading/cleaning process remote such that no people have to go into the hold, or even automating the process, is the ultimate goal of EMO.

The following questions will be answered so that the research question ultimately can be answered: Is it possible to clean the hold of a coal bulk carrier by machine, and have the hold be cleaned faster and with less damage?

- What is the problem with the current unloading process at EMO and what is available in the literature?
- What is the state of the art regarding cleaning in general and at EMO?
- What is the system and its conditions in which the solution operates?
- What is the new concept design?
- Does the prototype satisfy the requirements & wishes?

The approach of the project is as follows.

- Defining the problem:
  - The problem is defined
  - A literature and practice study is done
- Measuring
  - The functional specifications of the system are noted
  - From these specifications the design requirements are generated
- Analyzing
  - A description of multiple concepts is made and the most valuable is/are selected using benchmarking and a feasibility study
- Designing
  - The technical specifications are drawn up
  - (input for) a tender is set up

    - A design concept is made

- Verification
    - (Tendering)
    - A prototype is (partially) built, a pilot is done where the concept is tested and verified.

The design process of this project follows the double diamond method [12, 13]. It has four stages: discovery, definition, development, and delivery.

The discovery phase consists of gathering data, learning more about the different variables that affect the problem and its possible solution. The objective of this stage is to identify the actual problem. The definition phase comprises filtering through the gathered data in the first stage and elaborating on it. The definition stage aims to elaborate on aspects such as finances, resources, logistics, and market situation before designing anything. It also sets the context for product development, assesses the realism of what can be done, and analyzes how this project agrees with the corporate brand. The development stage is the actual design, making of the solution to the problem defined in stages one and two. Many possible solutions are sought, and creativity and co-operation are important aspects. The delivery phase includes the testing and releasing of the product. In this phase you can test multiple solutions on a small scale and discard the things that do not work. The things that do work are continued to be developed. This often includes testing it against regulation and legal standards, damage and/or compatibility testing. This phase is also used to assess the impact on customer satisfaction, in order to quantify the impact on the brand and customer relations.

In Chapter 2 the problem is further analyzed and literature about bulk handling and unloading is studied, and in Chapter 3 information learned by practice is collected from EMO and commercial products are gathered. In Chapter 4 the system and environment at the EMO terminal are analyzed. In Chapter 5 the final concept is chosen and a concept design is made. In Chapter 6 the new concept is tested and the results are analyzed. After that in Chapter 7 the shortcomings of the testing methodology are discussed. Finally, in Chapter 8 conclusions are drawn regarding the performance and usefulness and recommendations are made for further study and/or improvements.

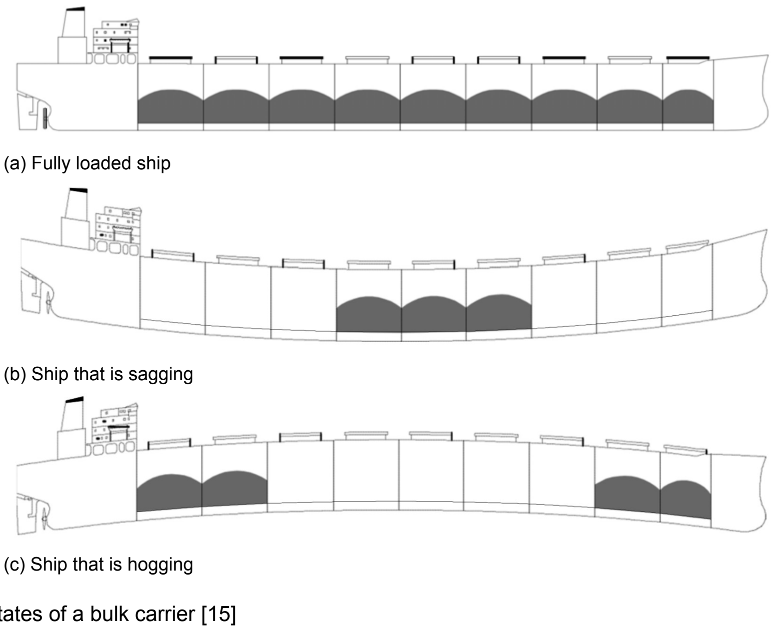
2

Problem analysis and literature review

This chapter will analyze how the cleaning of holds happens in practice at EMO, it analyzes the various aspects of the problem, and has a literature review of bulk material and handling techniques. To better understand bulk material and its properties the following is investigated in the literature. Properties of bulk materials are shown and some consequences with the focus on coal. Silo discharge aids are also analyzed followed by conveying equipment, since this is relevant for the central problem in this study. Unfortunately, no literature was found on the specific topic of cleaning sticky material from holds. Lastly, a stakeholder analysis is done to understand the relation of the people involved.

2.1. Current unloading process at EMO

The unloading of vessels by a shore-based gantry crane with grab, is regulated by guidelines [14–16]. A bulk carrier has a number of holds where cargo is stored. In Figure 2.1a is a full ship depicted. Following a certain loading plan makes sure that the hull of the ship is not overstressed. If this would not be the case and a crane starts unloading only the center holds, the ends of the ship will have a large load, causing a large bending moment and possibly breaking the hull of the ship, this is visible in Figure 2.1b. The inverse of this is depicted in Figure 2.1c.

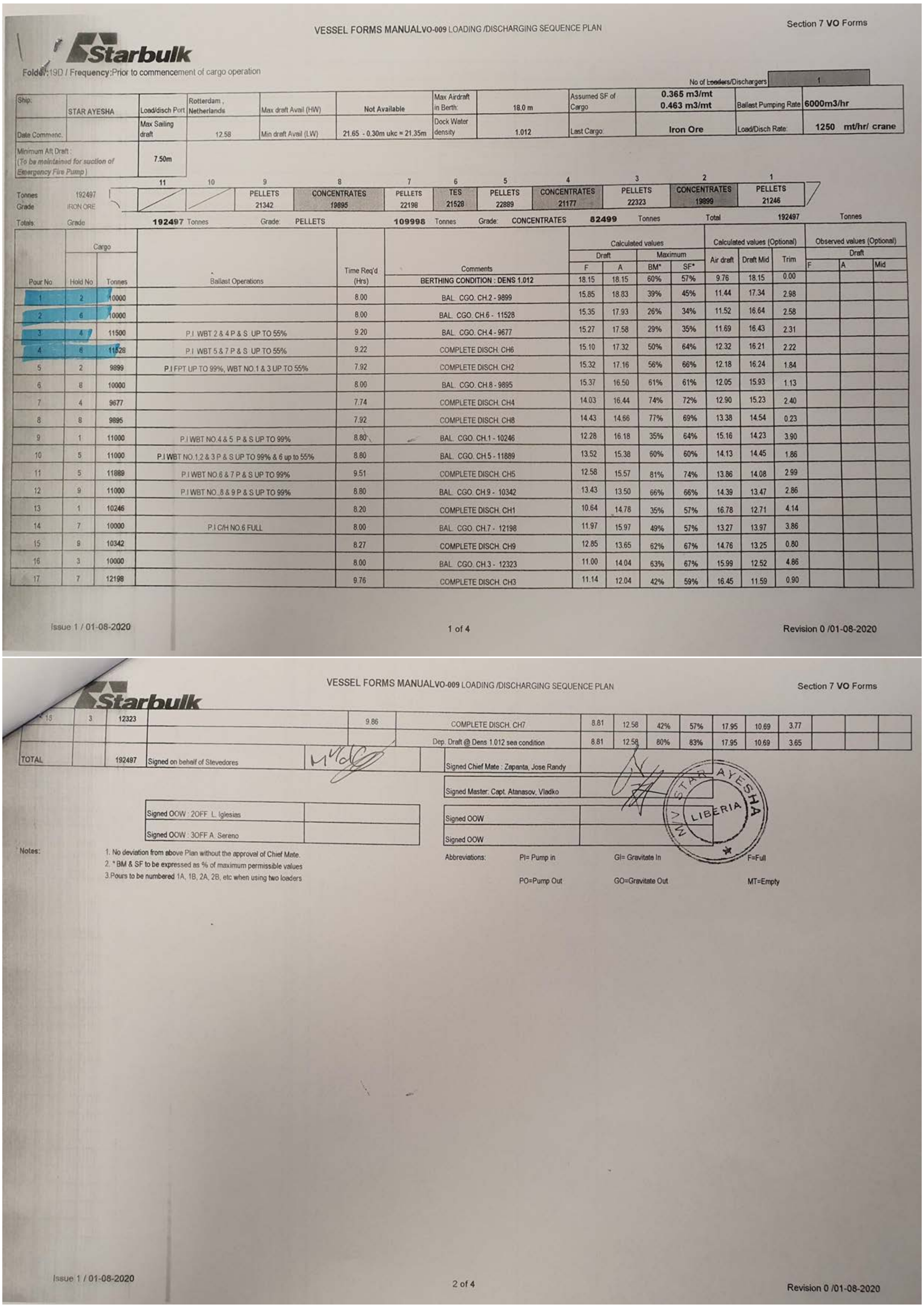


(a) Fully loaded ship

(b) Ship that is sagging

(c) Ship that is hogging

Figure 2.1: Loading states of a bulk carrier [15]



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VESSEL FORMS MANUAL VO-009 LOADING /DISCHARGING SEQUENCE PLAN

Section 7 VO Forms

Folder: 19D / Frequency: Prior to commencement of cargo operation

No of ~~Loaders~~/Dischargers: 1

Ship:	STAR AYESHA	Load/disch Port	Rotterdam , Netherlands	Max draft Avail (HW)	Not Available	Max Airdraft in Berth:	18.0 m	Assumed SF of Cargo	0.365 m3/mt 0.463 m3/mt	Ballast Pumping Rate	6000m3/hr
Date Commenc.		Max Sailing draft	12.58	Min draft Avail (LW)	21.65 - 0.30m ukc = 21.35m	Dock Water density	1.012	Last Cargo:	Iron Ore	Load/Disch Rate:	1250 mt/hr/ crane
Minimum Aft Draft : (To be maintained for suction of Emergency Fire Pump)		7.50m									

Hold	11	10	9	8	7	6	5	4	3	2	1
Tonnes 192497 / Grade IRON ORE			PELLETS 21342	CONCENTRATES 19895	PELLETS 22198	TES 21528	PELLETS 22889	CONCENTRATES 21177	PELLETS 22323	CONCENTRATES 19899	PELLETS 21246

Totals: Grade 192497 Tonnes Grade: PELLETS 109998 Tonnes Grade: CONCENTRATES 82499 Tonnes Total 192497 Tonnes

Pour No	Cargo Hold No	Cargo Tonnes	Ballast Operations	Time Req'd (Hrs)	Comments	Calculated values Draft F	Calculated values Draft A	Maximum BM*	Maximum SF*	Calculated values (Optional) Air draft	Draft Mid	Trim	Observed values (Optional) Draft F	A	Mid
					BERTHING CONDITION : DENS 1.012	18.15	18.15	60%	57%	9.76	18.15	0.00			
1	2	10000		8.00	BAL. CGO. CH.2 - 9899	15.85	18.83	39%	45%	11.44	17.34	2.98			
2	6	10000		8.00	BAL. CGO. CH.6 - 11528	15.35	17.93	26%	34%	11.52	16.64	2.58			
3	4	11500	P.I WBT 2 & 4 P & S UP TO 55%	9.20	BAL. CGO. CH.4 - 9677	15.27	17.58	29%	35%	11.69	16.43	2.31			
4	6	11528	P.I WBT 5 & 7 P & S UP TO 55%	9.22	COMPLETE DISCH. CH6	15.10	17.32	50%	64%	12.32	16.21	2.22			
5	2	9899	P.I FPT UP TO 99%, WBT NO.1 & 3 UP TO 55%	7.92	COMPLETE DISCH. CH2	15.32	17.16	56%	66%	12.18	16.24	1.84			
6	8	10000		8.00	BAL. CGO. CH.8 - 9895	15.37	16.50	61%	61%	12.05	15.93	1.13			
7	4	9677		7.74	COMPLETE DISCH. CH4	14.03	16.44	74%	72%	12.90	15.23	2.40			
8	8	9895		7.92	COMPLETE DISCH. CH8	14.43	14.66	77%	69%	13.38	14.54	0.23			
9	1	11000	P.I WBT NO.4 & 5 P & S UP TO 99%	8.80	BAL. CGO. CH.1 - 10246	12.28	16.18	35%	64%	15.16	14.23	3.90			
10	5	11000	P.I WBT NO.1,2 & 3 P & S UP TO 99% & 6 up to 55%	8.80	BAL. CGO. CH.5 - 11889	13.52	15.38	60%	60%	14.13	14.45	1.86			
11	5	11889	P.I WBT NO.6 & 7 P & S UP TO 99%	9.51	COMPLETE DISCH. CH5	12.58	15.57	81%	74%	13.86	14.08	2.99			
12	9	11000	P.I WBT NO..8 & 9 P & S UP TO 99%	8.80	BAL. CGO. CH.9 - 10342	13.43	13.50	66%	66%	14.39	13.47	2.86			
13	1	10246		8.20	COMPLETE DISCH. CH1	10.64	14.78	35%	57%	16.78	12.71	4.14			
14	7	10000	P.I C/H NO.6 FULL	8.00	BAL. CGO. CH.7 - 12198	11.97	15.97	49%	57%	13.27	13.97	3.86			
15	9	10342		8.27	COMPLETE DISCH. CH9	12.85	13.65	62%	67%	14.76	13.25	0.80			
16	3	10000		8.00	BAL. CGO. CH.3 - 12323	11.00	14.04	63%	67%	15.99	12.52	4.86			
17	7	12198		9.76	COMPLETE DISCH. CH3	11.14	12.04	42%	59%	16.45	11.59	0.90			

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VESSEL FORMS MANUAL VO-009 LOADING /DISCHARGING SEQUENCE PLAN

Section 7 VO Forms

Pour No	Hold No	Tonnes	Ballast Operations	Time Req'd (Hrs)	Comments	F	A	BM*	SF*	Air draft	Draft Mid	Trim	F	A	Mid
18	3	12323		9.86	COMPLETE DISCH. CH7	8.81	12.58	42%	57%	17.95	10.69	3.77			
					Dep. Draft @ Dens 1.012 sea condition	8.81	12.58	80%	83%	17.95	10.69	3.65			
TOTAL		192497	Signed on behalf of Stevedores												

Signed Chief Mate : Zapanta, Jose Randy

Signed Master: Capt. Atanasov, Vladko

Signed OOW : 2OFF. L. Iglesias

Signed OOW : 3OFF A. Sereno

Signed OOW

Signed OOW

M/V STAR AYESHA LIBERIA

Notes:
1. No deviation from above Plan without the approval of Chief Mate.
2. * BM & SF to be expressed as % of maximum permissible values
3. Pours to be numbered 1A, 1B, 2A, 2B, etc when using two loaders

Abbreviations: PI= Pump in, GI= Gravitate In, F=Full, PO=Pump Out, GO=Gravitate Out, MT=Empty

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Figure 2.2: The unloading plan of a ship at the EMO terminal

The master of the vessel and the terminal representative need to agree on a loading plan before starting (un)loading, see Figure 2.2 for a plan as used by EMO. The sequence of this plan is visualized in Figure 2.3. It can be seen that most holds are first emptied halfway by the crane, then the crane moves to another hold where it empties it, see Figure 2.4, the numbers denote the order in which the holds are emptied. And later the half-empty holds are completely emptied by the crane grab.

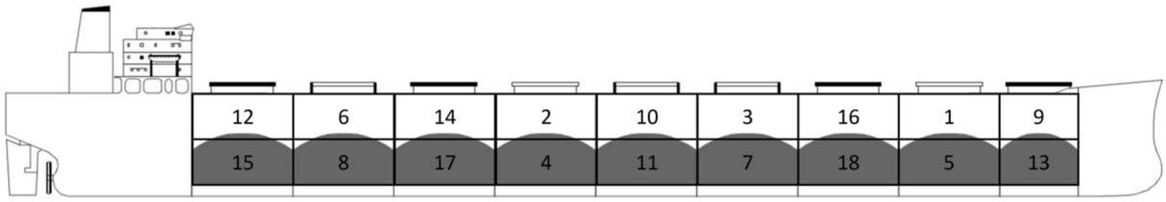


Figure 2.3: Unloading sequence visualized

(a) Shore-based gantry crane unloading a ship

(b) A half-emptied hold of coal

Figure 2.4: The unloading process of a bulk ship

Depending on the cargo, material will remain on ladders, see Figure 2.5a. A hold always has two accesses, but only one needs to be clear so that people can descend into the hold. It is also possible in an emergency to use a basket and the gantry crane to lift people. One set of stairs is then cleaned by personnel that positions themselves on the ladder/stairs and uses medium-pressure water hoses to blast the coal off until it is clean, see Figure 2.5b.

(a) A full straight ladder

(b) A cleaned spiral staircase

Figure 2.5: Accesses to the hold

After that the grab is uncoupled from the crane, and a CAT 966 front loader is lifted into the hold by the gantry crane, see Figure 2.6a. This machine moves the remaining material on the floor to the center so that the grab can also transport this to the shore. If the cargo is not self-trimming and remains on the walls, a CAT 329 excavator is also lifted into the hold with the same procedure, see Figure 2.6b. This uses a rough steel brush and as can be seen in Figure 2.7, the wires bend and lose functionality after cleaning a few holds according to EMO personnel.

(a) CAT 966 front loader

(b) CAT 329 excavator with brush attachment

Figure 2.6: Machines being lifted into the hold

(a) The attachment with a brush (b) Closeup of the damaged brush

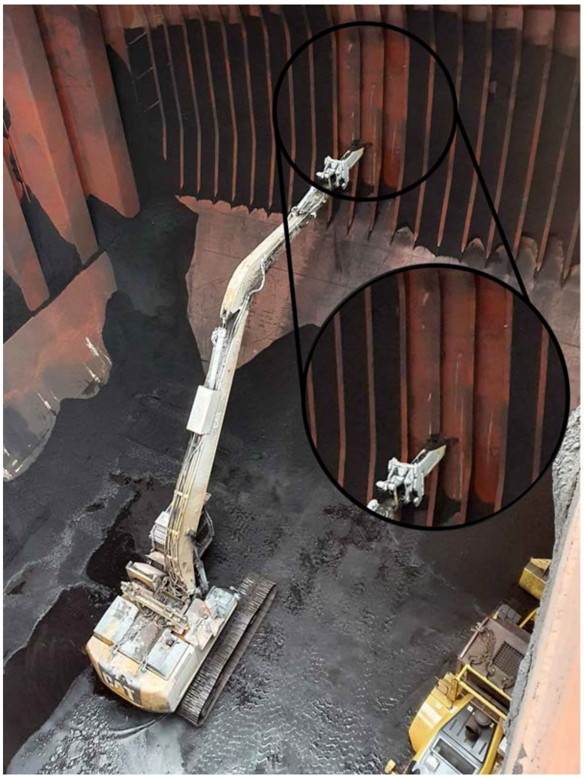
Figure 2.7: Excavator with the brush attachment

In Figure 2.8a the side shell frames of the hold are visible with a lot of stuck material. In Figure 2.8b the corner can be seen, where horizontal plates are large surfaces for material to remain after emptying. In Figure 2.8c is a (fragile) sounding pipe visible with coal stuck behind it. Lastly, in Figure 2.8d the excavator is cleaning the side of the hold. Visible in it is the (superficial) damage done to the hold. This machine is sometimes also used to clean the other set of stairs as best as possible. When a hold is clean the machines can be lifted out to the shore, or left in so they can be moved directly to another hold that is nearly empty and thereby saving time.

(a) Side shell frames full of coal

(b) Corner full of coal

(c) Stuck coal behind a sounding pipe in a transverse bulkhead



(d) Cleaning the sides of the hold

Figure 2.8: Stuck coal and the cleaning of it

2.2. Bulk material properties

To understand what happens to the coal and problems of the cleaning process some knowledge about material properties is necessary. A bulk solid material is composed of many particles that are different in size and possibly other properties, and are grouped together. The character of the material, the way it behaves in handling, storage, and its properties, are determined by multiple factors. The characteristics of the material are an important consideration in the design or selection of handling and/or storage equipment. The variation of bulk materials being handled is enormous, ranging in value from waste to gold and in quantity from grams to millions of tonnes. Bulk materials have many properties including the following [2]:

- particle size, shape, size distribution and surface area
- particle and bulk density
- cohesive properties, flowability and fluidizability
- hardness, compressibility
- toxicity, flammability, and explosibility
- optical, thermal, magnetic and chemical characteristics
- hygroscopicity (ability to attract moisture).

The importance of specific properties is dependent on the environment and operation of the material. For the following handling operations below, the more important properties with influence on the behavior of the bulk material are mentioned [2]. Storage and gravity discharge are important here because these properties determine the behavior of cargo when unloading the bulk carrier at EMO. Thus, these properties are relevant for the unloading process and will be further explained.

In Table 2.1 the relation between particle size and flow behavior is outlined. It can be seen that the smaller the particles are the more difficult flow is. For EMO this means that if a ship is going to be unloading a material with small particle size, the material is probably not free-flowing, and thus a lot of material will remain on the problem areas in the hold, requiring more cleaning effort.

Size range (μm)	Component	Bulk	Characteristic
3000-30,000	grand and lump	broken solid	Free-flowing, but could cause mechanical arching
100-1000	granule	granular solid	Easy-flowing with cohesive effects if large percentage of fines
10-100	particle	granular powder	May show cohesive effects and some handling problems
1-10	particle	superfine powder	Highly cohesive, very difficult to handle
<1	particle	ultrafine powder	Extremely difficult to handle

Table 2.1: Different particle size ranges and the typical flow characteristics

EMO handles many materials that all have different properties, this means that they have different handling properties. Iron ore is received as pellets (balls), carajas (fine and wet ore), and coarse ore [17]. Coal comes in dry, greasy, fine, and coarse kinds. Coking coal is often very cohesive and results in difficult to clean holds.

- Storage and gravity discharge:
  - Size, size distribution, shape, particle and bulk density, cohesive and frictional properties, fluidizability, flowability, explosibility, toxicity, and compressibility.
- Pneumatic and mechanical conveying:

    – Size, size distribution, shape, particle and bulk density, friability, toxicity and explosibility

- Hydraulic conveying:
    – Size, size distribution, particle density, friability and dispersibility

2.2.1. Cargo properties & behavior

A particulate material has a certain bulk density, which is defined as the weight per unit volume of a group of particles [2]. This means that the bulk density is lower than the density of the material itself, because there are voids between the particles, this can be seen in Figure 2.9. On the left is a lot of air between the particles, on the right only moisture. Measuring the bulk density is not difficult, since multiple standard methods exist. The problem is the interpretation of the measurements, since multiple definitions of bulk solids exist. For example aerated or loose, packed, tapped, fluid and average (mean of aerated and packed). The bulk density of a cargo material can be denoted by one value, but when it arrives it has been compacted by the motion of the sea and the vibration of the engine of the ship during the journey, resulting in a higher bulk density.

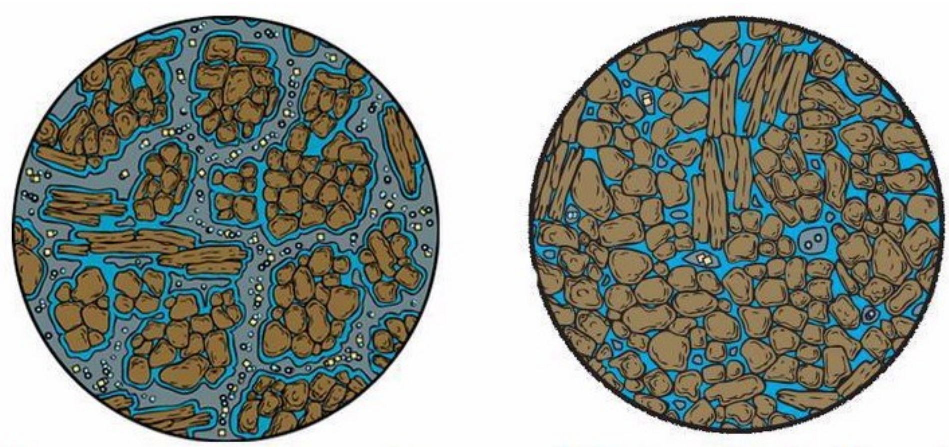


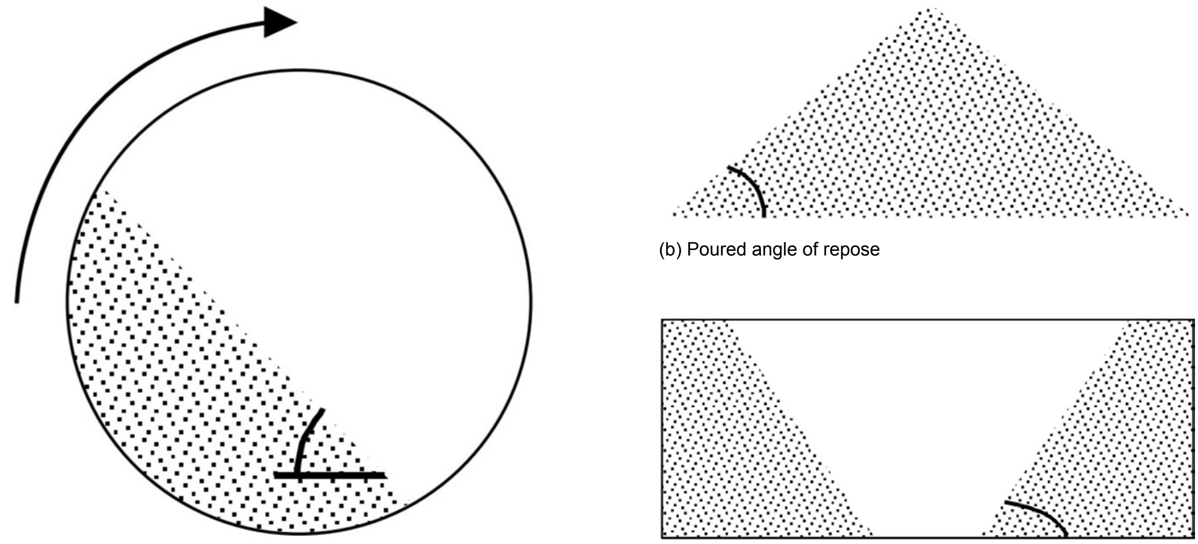
Figure 2.9: Difference in bulk density illustrated [18]

During transport, cargoes like various ores are exposed to agitation. This comes from the ship's rolling, wave impact, and engine vibration which results in compaction, or the reduction of porosity, of the cargo [19, 20]. The standard methods for bulk material compression by vibrations are based on individual equipment. The parameters of the vibrations have not yet been defined. The physics of material compaction is getting more complicated with smaller particle sizes. This means that the compaction process is not theoretically describable. An alternative is the experimental determination of the compaction for precisely defined parameters.

For some materials time inside the hopper can lead to consolidation and a considerable increase in bulk strength [21]. For some materials this increase in strength depends principally upon the period of storage, this may range from minutes to months. From the start of storage, time consolidation effects start due to loss of air, settling, and re-orientation of the particles within the bulk. This process tends to be enhanced by vibrations present in any bulk materials handling plant. These effects cause closer packing of particles which results in an increase in bulk strength. Free-flowing materials likely have negligible gain in strength.

This all causes the material to remain on the walls and stairs in a hold when most of the cargo is unloaded by grab.

Granular materials form a slope on the top surface. The critical slope on which granular materials can remain stable, the angle between the surface of a pile of material on a horizontal board to the horizontal plane, is known as the angle of repose [22, 23]. There are numerous methods for measuring the angle of repose, some are shown in Figure 2.10. The results differ between exact methodologies. Such tests are only relevant to powders that are at most somewhat cohesive, these form a specific angle when poured (or drained). The angle of repose also says something about the flowability of a material as shown in Table 2.2, a steeper angle of repose means that a material flows less easily, and thus there remains more material in the hold.



(a) Rotating angle of repose

(b) Poured angle of repose

(c) Drained angle of repose

Figure 2.10: Various methods for determining the angle of repose of a material [24]

Angle of repose (°)	Flowability
25-30	Very free-flowing
30-38	Free-flowing
38-45	Fair-flowing
45-55	Cohesive
>55	Very cohesive

Table 2.2: The flowability of a material correlated to its angle of repose [21]

A study done about the bulk density of coal showed increasing the median particle size decreases bulk density to a minimum and then increases [25]. Particle size distribution does not significantly affect the angle of repose. The increase of moisture content decreases the bulk density and increases the angle of repose significantly. The increase of oil addition increases the bulk density while decreasing the angle of repose significantly. The correlation between bulk density and angle of repose can also be observed: the higher bulk density, the lower angle of repose. The results suggest that larger external loading increases bulk density significantly.

Another study shows that for increasing moisture content in a coal blend, the bulk density decreased [26]. The latter reached a minimum when the moisture content is at about 7%. Further increasing the moisture content results in larger bulk density. The addition of oil decreases the bulk density of dry coal, but for coal more than 2% moisture, oil addition increases bulk density which reaches a maximum for coal containing about 6% moisture. The increase in bulk density gradually decreases as the moisture content further increases. Once the coal moisture exceeds about 10%, the addition of oil decreases the bulk density. Another observation is that for larger moisture percentages, the coal does not flow easily due to bridging. The operator needed to “poke” the coal at a moisture level >7% to ensure flow.

Using DEM, piles of wet particles are studied [27]. It is shown that the angle of repose and the porosity, increase with the moisture content until saturation. The porosity level is comparable to that of a packed material and shows a linear correlation with the angle of repose.

It is shown that higher bulk density can be created when drying the coal or with an excess of moisture by agglomeration [28]. This is confirmed by another study that mentions that for minerals such as coal and metal ores, there is a general relationship between bulk density and moisture content [29]. This relationship is such that bulk density decreases to a minimum and then increases with increasing moisture content. This is explained by that if the moisture content is lower than 6.5%, the mechanisms of agglomerate density, inter-particle friction, and tightened size distribution cause a lower bulk density. When the moisture content is large, the mechanism of agglomerate deformation is also effective, first causing the bulk density to reach a minimum and to increase.

2.2.2. Material hazards

A non-combustible, non-toxic dust is a nuisance for people when present in the air at concentrations greater than 10 mg/m^3 [2]. If the material is also toxic then this is very dangerous for the people involved. And if abrasive dust is in the air in high enough concentration, it can cause considerable damage to equipment. The most serious dangers in bulk solid handling are dust explosions and health hazards.

It is recognized that most combustible particulate materials can cause an explosion provided that [2, 30]:

- A sufficient amount of fine particles are dispersed in the air to form a dense dust cloud.
- Sufficient amounts of oxygen are present in the air
- An ignition source is present to initiate the explosion.

When these conditions are present to support such a quick combustion, large amounts of heat and hot gases are produced. The gases expand quickly and the pressure climbs and propagates with speeds of up to 300 m/s. This is what is called a dust explosion. There are many studies on the explosibility of coal dust [23, 31–33].

Furthermore, coal is a fuel that undergoes combustion [34]. If spontaneous oxidation happens and the released energy is trapped, the coal is self-heating. The result is that the temperature rises and this can continue to combustion of the coal. Self-heating coal can result in secondary dangers such as the production of carbon monoxide and other toxic and flammable gases. Also, the combustion of coal consumes oxygen, so care needs to be taken in enclosed spaces. During the coal production process, gases like methane can become trapped in the coal, which then later the coal will emit again, filling a hold with combustible gas.

Fine particles dispersed in the air can enter the human body by inhalation, and are damaging to the recipient. The size and density of a dust particle determine what happens to it in the body [2]. Particles with a diameter between 15 to 25 μm are filtered in the nasal passage or are seized by impact against the moist wall of the respiratory system. These particles are displaced to the exits, the nose and mouth, by cilia cells. These are fine, hairlike cells covering the respiratory passages and are capable of moving these particles. Some say that particles with a diameter between 0.1 to 1.0 μm are usually exhaled from the body during the normal expiration and that particles smaller than 0.1 μm present the greatest dangers, since they can go deep into the lungs and could enter the bloodstream [2]. In occupational hygiene studies however, respirable dust is defined as dust having an aerodynamic diameter of less than 5 μm [30]. The aerodynamic diameter is defined as the size of a sphere of unit density that would have the same falling speed as the dust particle. The precise value of this size varies slightly over the world. The aerodynamic diameter of coal particles is smaller than the physical size of the dust particle. This is because coal has a lower density than that of the nominal material. Respirable dust is considered a major cause of lung diseases.

2.3. Discharge aids

Silos often have flow problems when the material is not completely free-flowing. This can have causes such as ratholing, arching, bridging, and funnel flow. To improve the flow and make sure the silo is completely emptied, discharge aids are used. Since no specific discharge equipment for bulk carriers can be found, silo discharge aids are investigated since their functions are largely comparable. All discharge aids for silos work using one or more of the following principles [35]:

- Dilation of the material. The flow function of dilated material exhibits significantly lower unconfined yield strength thereby making it flow better.
- Induce stresses that exceed the strength of the bulk material.
- Reduce the friction between particles and the wall of the flow channel.
- Modify the flow regime to one more favorable to flow.
- Alter the bulk material flow properties by additives or surface modifiers.

They can be broadly classified into the following categories based on the form of flow promoting mechanism employed:

- Active devices
  - Pneumatic
  - Vibratory
  - Mechanical
- Passive devices
  - Hopper shape
  - Low friction liner
  - Insert systems

The stress in the material in a bulk carrier hold can be compared the stress in the material in a silo under some conditions e.g. after filling. Stress in a bulk solid in the vertical direction σ_v, also causes stress in the horizontal direction σ_h [36]. The ratio of these stresses is called the lateral stress ratio, denoted by K. This ratio is material dependent, a perfectly rigid inelastic solid body that is subject to vertical stress would have no horizontal stress ($K = 0$), while a fluid would have equal vertical and horizontal stress ($K = 1$). Usual bulk solid materials have a value of K between 0.3 and 0.6.

When an empty silo has been filled with material, a stress diagram as shown in Figure 2.11 is the result. This shows the wall-normal stress σ_w, resulting from the lateral stress ratio, and the mean vertical stress σ_v. In the straight part of the silo, these increase towards the bottom and approach a maximum, which is there due to wall friction. The left part of the image shows the major principal stress lines. In this silo section the vertical stress is the larger stress, which causes the horizontal stresses according to the lateral stress ratio. Near the wall, the direction of the principal stress bends horizontally because of the wall friction. Near the walls of a bulk carrier hold these stress lines are similar to a silo, while in the middle of the hold they are (nearly) vertical, because a hold has a smaller height to width ratio.

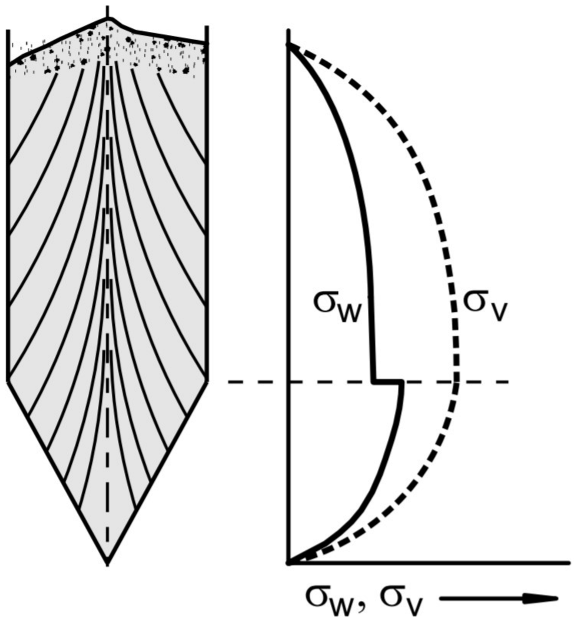


Figure 2.11: Major principal stress lines in a filled silo [36]

While a silo is emptied by opening the bottom, a bulk carrier hold is dug out by a large grab. The flow regime in a silo can be characterized in multiple ways, such as mass flow and funnel flow, as illustrated in Figure 2.12. When funnel flow happens there are stagnant zones where the material does not flow. When a grab is digging out a hold a similar situation can develop at the wall between holds, as can be seen in Figure 2.13.

The focus will be on the active discharge devices, since these are most relevant for the central problem of this study. The hold of the bulk carriers can not be modified, so low friction liners, reducing wall friction, are not possible. Flow regime change is also not possible, this would require geometry changes to the hold. And lastly, the bulk material that is unloaded can not be altered, so additives are not allowed to be added.

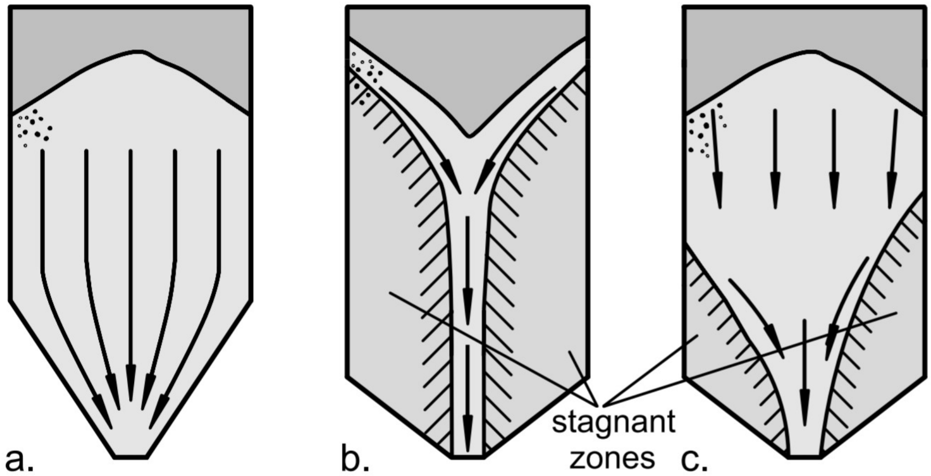


Figure 2.12: Flow profiles in a silo. Silo a has mass flow, silo b has funnel flow with large stagnant zones, silo c has stagnant zones in the lower part of the silo [36]

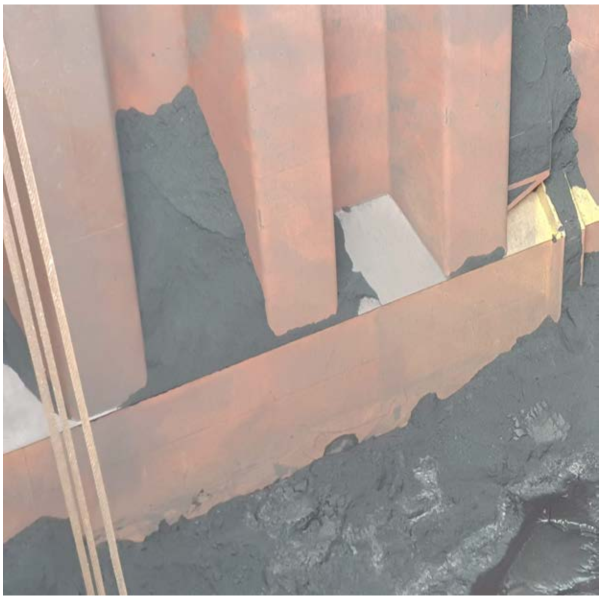


Figure 2.13: Stagnant zone in a bulk carrier hold

2.3.1. Pneumatic Discharge Aids

A wide range of pneumatic discharge aids are available in the market, namely

- Aeration pads
- Pneumatically inflated air pillows
- Directed air-jet type (continuous and pulsed)
- Air cannons

Aeration pads

This discharge aid relies on the dilation of bulk material [21, 35, 36]. This is done by injecting air into the space between the particles, illustrated in Figure 2.14. Powders can behave like fluids when they are fully aerated, but this is not necessary to create a steady flow of a bulk material. Bulk materials that are (partly) comprised of particles with a size less than 75 μm, are suited for aeration. But powders that are made up of particles that are much smaller, around 10 μm, are difficult fluidize, since channeling is prevalent.

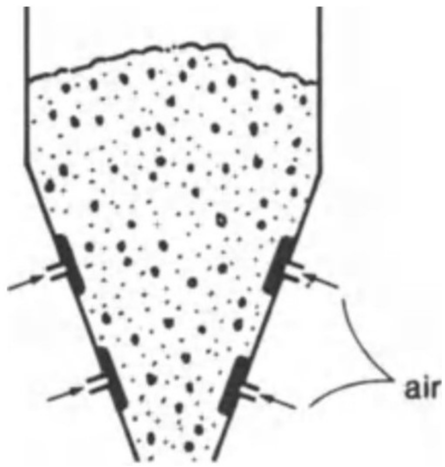


Figure 2.14: Aeration pads in a silo [21]

There are two options for aeration:

- Injection of air during discharge. This method reduced the bulk strength of the material, especially near the outlet.
- Continuous injection of air during storage. This method impedes time-dependent settlement and de-aeration, and thus the gain of bulk strength of the material. Very little air is required for very fine powders for this process, but this method is not suitable for particles that are larger than 200 μm because de-aeration is very quick. This method is not possible for cleaning holds, since the material has already compacted during the journey.

If air is introduced at the time that the product is to be discharged the material is fluidized, this reduces the friction between the solid particles and between the particles and the wall. Important is that there is a uniform distribution throughout the product. Introducing the air through a high-resistance porous surface, such as sintered metal is often used.

Inflated pillows

This is a flexible bladder that is mounted on the walls of a silo, see Figure 2.15 [35]. When they are pressurized, the bladders expand and force the material to move away from the wall. In this way, they can break ratholes and arches. These devices should only be used when the outlet is open and the material can flow, otherwise compaction will happen and further hinder the flow. Materials with sharp or abrasive properties, the bladders are vulnerable to damage by puncture or wear.

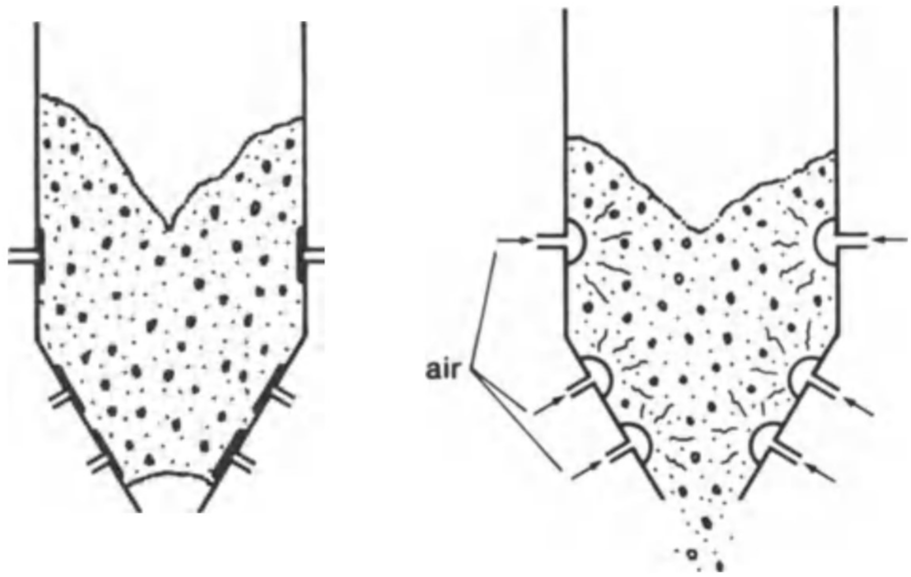


Figure 2.15: Air pillows in a silo [21]

Directed air jets

Directed jets use the kinetic energy of the air to dislodge material and initiate flow, see Figure 2.16 [21, 35]. The effective range of these jets is small, around 0.5 m. That is why the location of the jets is important so that the necessary area is covered. It is possible to not run the jets continuously, but pulse them so gas consumption is lower. These air expansion devices can also cause problems, e.g. dust generation resulting from the quantity of expanding air.

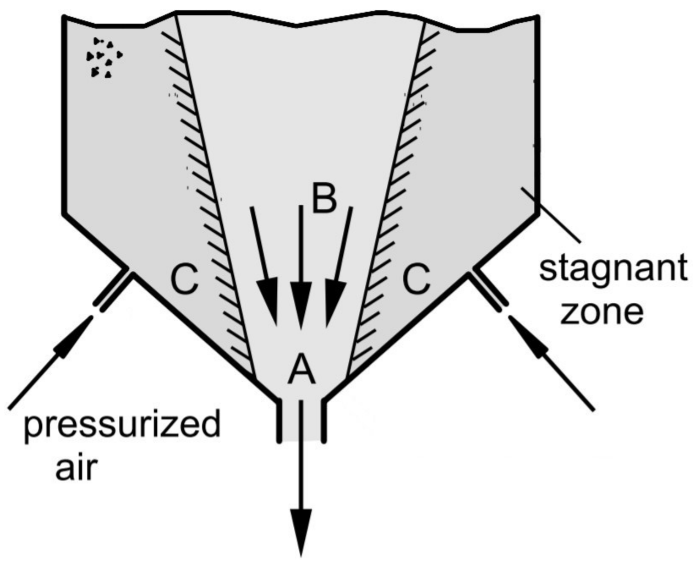


Figure 2.16: Air jets in a silo [36]

Air Cannons

Air cannons are similar to air jets, but work slightly differently [35, 36]. They inject blasts of high-pressure gas in a short duration, this causes a stress wave to travel through the material structure. This happens faster than the air pressure wave moving through the pore structure of the bulk solid, this breaks arches or ratholes. Air cannons need to be located where the material can flow into a channel, see Figure 2.17. They are typically used with sticky, wet, adhesive, fine, caking, and fibrous materials. They are also used to knock sticking materials and residual clumps of material from the walls of the storage container. In contrast to continuous air injection, air cannons are also suitable for use with coarse-grained bulk solids that suffer from time consolidation, since a positive action can be achieved by the impulsive injection of air even if the airflow resistance of coarse-grained bulk solids is low. The range of air cannons is also larger than systems that use slow air injection. Air cannons are an important piece of equipment for bulk solids that have strong time consolidation effects.

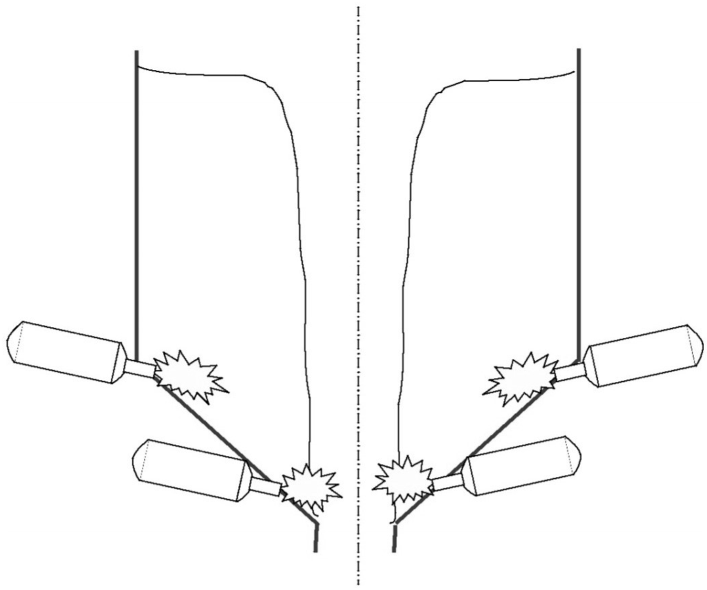


Figure 2.17: Air cannon in a silo [35]

Studies of silo discharge using pneumatic aids

A study has been done about the aerated discharge characteristics of cohesive pulverized coal from a hopper [37]. This cohesive coal displays different fluidization behavior than the normal profile. Saw-tooth-shaped pressure curves were found for increasing aeration velocity. The main mechanisms for discharge have been analyzed and verified using experiments.

Experimental research has been done about the fluidization behavior of fine coal in a column and a hopper [38]. The pulverized coal was difficult to fluidize and the fluidizing velocity was greater than expected. Multiple aeration rates in a hopper were studied, four flow regions were developed, and the prevailing phenomena that occurred during discharge were studied.

A study has been done with a pilot-scale system to analyze the discharge behavior of pulverized coal [39]. Several experiments with an aerated hopper and with several aeration rates have been done. An earlier developed model was used to estimate the discharge. A correlation was found between the voidage between particles and the gas velocity from fluidization experiments and applied to the model for aerated discharge. Agreement was found between the model and experiments discharge rates.

The aerated discharge of multiple cohesive powders with different particle sizes, densities, and flow properties is studied [7]. Discharge rates and residual mass were measured as a function of the aeration rate. The results were used to predict the solid discharge rate with some accuracy. It is stated that this makes some fluidization experiments unnecessary for the estimation of discharge rates.

A study has been done to create design criteria for aeration devices and aeration intensity that is necessary to avoid arching [9]. Experiments were carried out in an aerated silo measuring the aeration rate when the arch collapses and the size of the arch. A model has been proposed to predict the minimum aeration rate for discharge flow with no arching.

The effect of pulsated aeration in a hopper on discharge characteristics of cohesive and non-cohesive powders has been studied to see the effect of square-wave pulsated airflow [8]. The frequency of pulsation was varied between 0 Hz (continuous aeration) and 50 Hz. Two flow patterns, intermittent and smooth, have been observed for different aeration rates and frequencies. Pulsated aeration has a negative effect on the flow of non-cohesive powders. However, it had a positive effect on the discharge of cohesive powders. The maximum discharge rate is higher for pulsated aeration and it is more uniform.

The studies above have researched the discharge of materials using pneumatic aids. It is clear that aeration helps with the discharge from a hopper of cohesive materials such as pulverized coal, although fluidization can be difficult. Air cannons and similar aids such as air jets were not a topic popular in literature.

2.3.2. Vibratory discharge aids

Vibration as a means of aiding the discharge of a bulk solid from a hopper is widely used, and many different types of equipment are available [21, 30, 35, 36]. Vibratory discharge aids can be attached externally to the wall of a silo or attached to internal elements. These devices are used to solve problems including arching, bridging, ratholing, build-up, and caking to walls. The principle that is used here is that the vibrations decrease the bulk strength of the material, thus increasing the flowability and decreasing wall friction. Additionally, the vibrations increase the stress in the bulk solid, and if the yield limit is attained, the vibration breaks arches or ratholes. If the material is contained in a closed container, vibration at low frequency often causes compaction. High-frequency vibration can cause compaction or dilation, depending upon various factors. Vibration should not be applied when the outlet is closed, as this could result in a strengthening of the material. Flow promotion depends on the ability of the bulk material to transmit vibration energy from the source through the mass to the problem region. The transmission of vibration energy decreases with increasing fineness and compressibility of the material, because this increases the absorption of the vibrations.

Design considerations

The action of vibrations is best at frequencies above 100 Hz and amplitudes of 1mm or less according to some [24, 35]. However, depending upon the design of the equipment, the frequency can range from 14 Hz to 1300 Hz and amplitude from about zero to more than 60 mm [21]. Frequencies between 2 and 100 Hz have been used to achieve fluidization of bulk material, with amplitudes being such that the accelerations were below 10 g [30].

The area of vibration of bulk solids has not received much attention, and this is possibly due to the difficulty associated with modeling and theoretically analyzing such materials under dynamic conditions. The consequence is that much of the research has mainly been experimental investigation producing empirical results. The design of vibrating devices mounted on a silo wall is complicated, because the properties of the structure, such as wall thickness and stiffness, have to be taken into account. Care must be taken as vibration may segregate the material or cause structural problems for silos that were not designed to withstand vibrating loads [22]. The concept of resonance in the case of a bulk solid is complex, especially defining the mass and stiffness in the vibrating system.

Discrete frequency sinusoidal vibrations and broad-band random vibrations have both been examined. The results indicate a sensitivity of the flow to the input frequency, that is dependent on material properties. Consistent performance has been observed by using broad-band random vibrations. Narrow-band vibrations were largely unsuccessful in promoting flow. For this reason, broad-band random excitation, which consists of an infinite number of frequencies represented in the bandwidth, has advantages over discrete-frequency sinusoidal type excitation.

Studies of silo discharge using vibratory aids

A 2D DEM simulation of cohesive particles has been created to study point source vibrations for inducing flow in wedge-shaped hoppers [40]. It is shown that vibration can enhance the flow. The study showed the influence of vibrator location and vibration amplitude in enhancing flow, while varying frequency had negligible influence. A related study analyzed the same problem further, but used a 3D DEM simulation [41]. Here was also the importance of the height of the vibration source shown for optimal flow enhancement. The model also shows that low-frequency high-amplitude vibration can increase flowability through small ports.

Numerical simulations have been done where vibration in a hopper is created by two vibrating balls in the corners, where most often the flow has problems [10]. The results indicate that the total number of discharged particles changes linearly with time. The average velocities of the particles are increased by vibrations, especially in the corners.

The influence of continuous vibrations on the outflow of a hopper has been studied experimentally [42]. Outpouring material can be achieved for aperture sizes below the jamming limit of non-vibrated hoppers. Even for aperture sizes that are equal to the particle diameter, granular flow persists, using finite vibration amplitudes.

The influence of vibration on the flow of cohesive particles with an average particle size of 1 μm was investigated using a shear tester [43]. The results show that vibrations lead to a significant reduction of the shear strength, wall friction angle, and unconfined yield strength. The unconfined yield strength decreases with increasing vibration velocity, however the angle of internal friction is nearly independent of vibration intensity.

Another study has focused on physical phenomena observed in bulk materials affected by vibration [44]. They present three characteristic regimes of vibration defined as vibro-fluidisation, vibrocompaction, and vibroboiling. The analysis of air resistance, wave effects, and particle oscillations decay that influence the behavior of vibrating bulk material. A new regime is introduced that is defined as vibro-hovering. The analytical solutions were experimentally validated.

Experiments have been done to investigate the discharge of glass spheres in a planar wedge-shaped hopper that is undergoing horizontal vibrations [45]. Without vibration, funnel flow is observed where material discharges from the central region of the hopper and stagnant material at the sides. The discharge rate increases with the velocity of vibration compared to discharge without vibration.

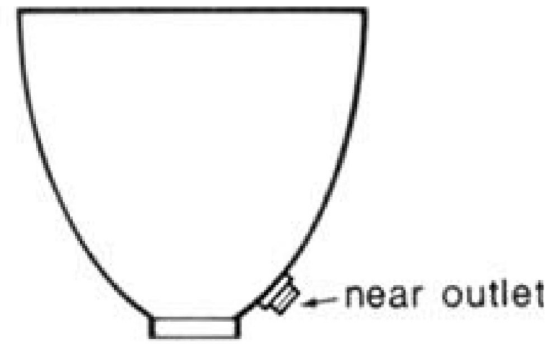
A similar study has researched the effect on the discharge of granular material from a hopper that experiences vertical vibrations using experiments and DEM simulations [11]. The discharge rate for a vibrating hopper is at its maximum at a dimensionless velocity amplitude a bit larger than 1. The discharge rate decreases for larger velocities. This decrease is explained by a decrease in the bulk density when vibrations are applied. The experimental and DEM results show the same trends in the data.

The first three studies mentioned in this section were purely numerical, while the rest are either experimental or have been validated experimentally. The results of these three are therefore less trustworthy since there can be a lot of uncertainty and unaccounted variables in a numerical simulation. However, from this section it can still be concluded that vibration promotes flow in many situations by among other things reducing shear strength and wall friction angle. This means that vibration could be used in cleaning bulk carrier holds by initializing flow in material that is stuck to the walls.

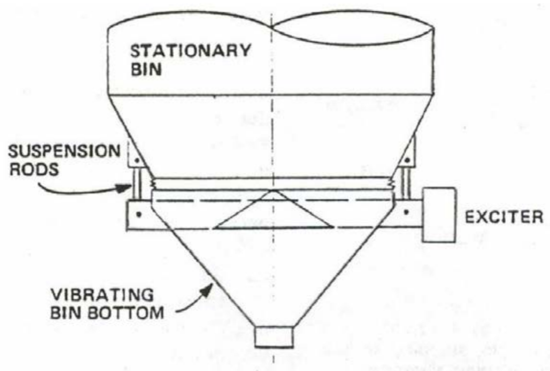
Types of vibrators
The vibration devices can be put into two groups [21, 35]:

- Linear (electromechanical or air-operated)
- Rotary eccentric (electromechanical or air-operated)

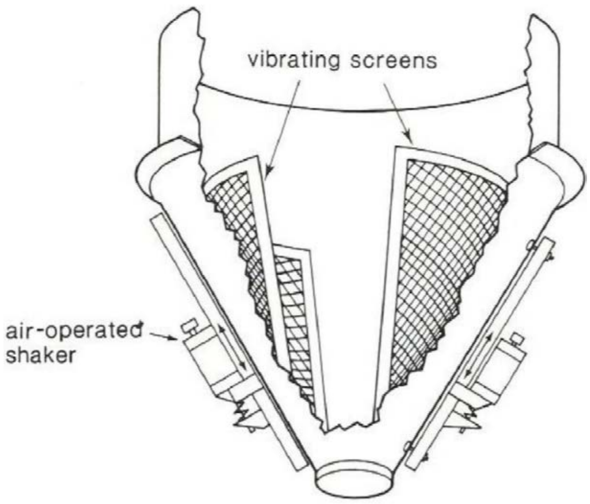
These vibrators can also be used in different ways of agitating the material, this is shown in Figure 2.18. In Figure 2.18a the vibrator is mounted on the outside near the outlet, in Figure 2.18b the bottom of the silo is uncoupled from the rest and is excited by the vibrator and in Figure 2.18c vibrating screens are present in the silo.



(a) Vibrator mounted on the outside [21]



(b) Vibrating bottom of a silo [35]



(c) Vibrating screens in a silo [35]

Figure 2.18

The air-powered piston vibrator resembles most closely simply beating the outside surface of the hopper with an object. Linear electromagnetic vibrators have a similar effect, they both create vibrations perpendicular to the wall of the vessel. Electromagnetic and linear (piston type) vibrators have a frequencies range of 20 to 120 Hz.

Rotary eccentric vibrators are generally more expensive than the linear types and typically have a shorter lifespan [21]. They produce a radial impulse so that the wall also produces stresses parallel to the wall. These vibrators generally run at higher frequencies and lower amplitudes than the linear types. Dual rotary vibrators that are mounted in a parallel axis setup will tend to run synchronously. This cancels the forces acting in one plane to create a linear oscillating force. Rotary vibrators can create unwanted resonant frequency during startup and shutdown, so they are not always suited for situations where intermittent vibration is required. However, they have achieved a reputation for being successful in keeping difficult materials flowing. Rotary electric vibrators generally operate between 10 to 60 Hz. Higher frequencies between 100 to 500 Hz, can be generated by pneumatic vibrators.

In general, rotary vibrators are recommended for dry, cohesive products. This vibrator type is mounted rigidly on hopper walls. Linear vibrators are used for sticky or wet products. They are most effective when there is some flexibility in the walls. But there is a large overlap in the use cases of rotary and linear vibrators.

Externally mounted vibrators can be very loud. Allowed noise levels in the surrounding area may inhibit some types of vibrators from being used. Linear impacting vibrators that act as a hammer, can be as loud as 115 dB. Rotary vibrators can create noise levels up to 95 dB, but other models top out at 75 dB. Multiple measures can be executed to lower the sound level, e.g. proper mounting, insulation, larger vibrator with lower speed operation, and avoiding resonance of the structure.

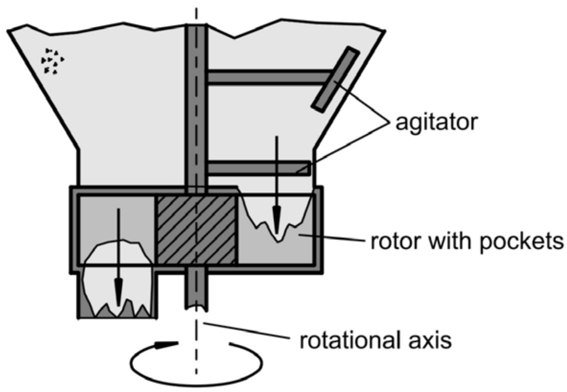
Related to this are sonic horns, they are used to dislodge sticky or adhesive powders and fluidize powders using sound waves [35]. High-frequency airwaves are produced to break the structure of a bulk material. Noise considerations are an important aspect of these devices to be considered since they can produce 150 dB.

2.3.3. Mechanical discharge aids

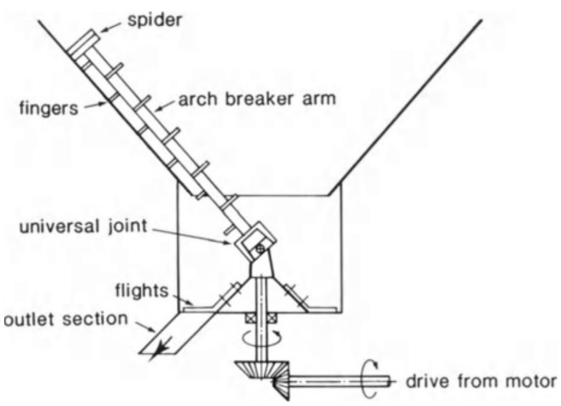
The traditional way to mechanically break up bridges or ratholes in a bulk material is to use holes in the wall where people can manually poke the material with rods [21, 35, 36]. This method is not much better than pounding the walls with objects, since the effect is insignificant and the process is damage-prone. One solution that works for large particles is hanging chains vertically in the vessel, these can then be pulled upwards if there are flow problems so that possible arches are destroyed.

There are also multiple types of powered mechanical dislodgers, such as vertical and horizontal stirrers, see Figure 2.19a. A reliable version is a circular bin discharger. This is an arch-breaker arm that is driven by a universal joint and works in the conical bin, see Figure 2.19b

There are also agitator blades that ensure that the flow zone covers the entire cross-section of the hopper. Agitators come in horizontal and vertical axis versions. They are also combined with screw feeders to ensure that problematic bulk solids flow into the feeding screw.



(a) Horizontal stirrer in a silo [36]



(b) Arch breaker arm in a silo [21]

Figure 2.19: Mechanical agitators

2.4. Bulk conveying methods

This section discusses how bulk material is handled, so insight is gained into how the cargo could be moved from the hold to the storage area.

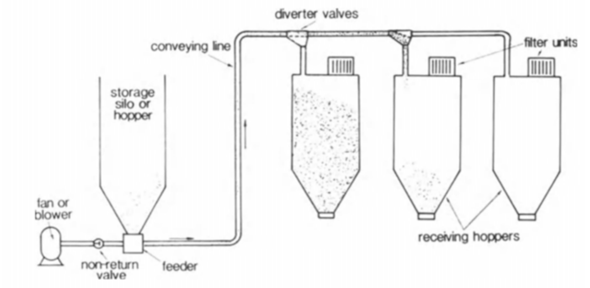
2.4.1. Pneumatic conveying

Pneumatic conveying of particulate solids is widely used in the process industry [2]. Some examples of bulk materials that have been transported by a pneumatic system include, food and pharmaceuticals, soap powder, paper pulp, fertilizers, metal ores, cement, coal, and nuclear fuel particles. There is evidence that suggests that the variety of suitable materials for pneumatic conveying is increasing continuously. This is due to more efficient conveying systems that are capable of handling larger throughput and longer conveying distances.

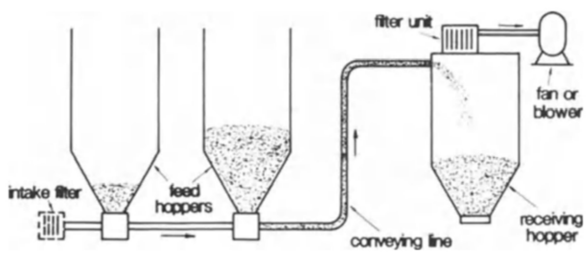
Principle

The basic components of any pneumatic conveying system are:

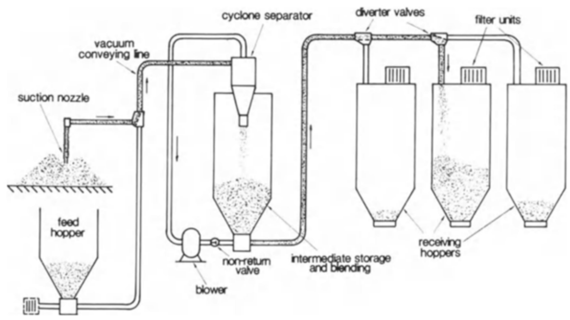
- The transport pipeline.
- The gas mover. purpose including:
- The product feeder.
- Product/gas separator
- Control and instrumentation



(a) Positive-pressure system [21]



(b) Negative-pressure system [21]



(c) Combined positive-pressure and negative-pressure system [21]

Figure 2.20: Pneumatic conveying systems

In Figure 2.20 some example setups can be seen of pneumatic systems. Pneumatic systems come in positive-pressure and negative-pressure variants. The difference is whether the fluid pressure in the conveying pipe is above or below atmospheric pressure. A negative-pressure system can be fed solids into the conveying line from several intakes and discharged at one exit. For a positive-pressure system the opposite is true, material is fed in one point and can be discharged to several locations. A combination of negative and positive pressure systems is also possible. This creates the possibility to have the product be collected at several points and delivered to several points.

However, negative-pressure conveying has a short distances limitation because of the limited pressure differential. This is at most 1 bar, because this is the difference between atmospheric pressure and vacuum. That is why this type of conveying has not received a lot of attention in the literature.

Some of the main advantages and disadvantages of pneumatic transportation of bulk solids are outlined in Table 2.3.

Advantages	Disadvantages
The product is enclosed	Particles need to be dry and free-flowing
Changes in flow direction are easy	Not suited for friable materials
Space saving potential since pipe can be above ground level	Oxidizing material needs an inert carrier medium
Automation is relatively easy	Abrasive material will cause excessive wear

Table 2.3: Advantages and disadvantages of pneumatic conveying

Studies of pneumatic conveying

A study has been done about the prediction of pneumatic conveying behavior of large coal particles using simulations and has been compared to experiments [46]. The simulations are carried out under similar conditions to the experiment, the results show that the model is feasible for the prediction of horizontal pneumatic conveying of large coal particles. Research has also been done using numerical simulation to study the influence of particle shape and flow pattern on the fragmentation of large coal particles in pneumatic conveying, the influence of swirl strength on the capture speed of particles was studied using experiments, and the particle breaking process of large coal particles in pneumatic conveying using different pipeline structures and swirl strengths was studied [47–49]. Simulations and experiments have been done to study the pneumatic suspension behavior of large irregular coal particles [50, 51]. The suspension speed for different particle sizes and the influence of structural parameters of 5–30 mm coal particle on injection performance has been studied.

These studies show that it is possible to pneumatically convey large coal particles under some conditions. However, the maximum particle size of the coal that arrives at EMO is often an order of magnitude larger than researched above, so there is still uncertainty regarding the behavior of these particles.

2.4.2. Hydraulic conveying

The hydraulic transport of particulate solids concerns two types of material. These are settling suspensions and non-settling slurries. If the mixture has large and/or heavy particles (>40 µm), this forms a settling suspension. If there is little turbulence in the fluid, the particles will quickly settle to the bottom. They will stay there or move along the bottom depending on the conditions. A non-settling slurry contains fine particles (<30 µm). Solids concentrations above 50% by weight are common. In these conditions the particles do not really settle, so the suspension can be moved with laminar and turbulent flow. Hydraulic transport systems can be divided into the following four steps:

- Particle preparation
  - This often involves adjusting particle size and size distribution, so that requirements. Standard methods such as crushing and grinding are used for this reason.
- Suspension preparation
  - This is done by mixing the particles and the conveying liquid in an agitated vessel.
- Suspension conveying
  - Most often the suspension is pumped through a pipe using one or more pumps in series. If abrasive powders are transported, these are mixed into the liquid stream after passing through the pump, so that there is no contact between the particles and the pump and thus less wear.
- Solids-liquid separation
  - A high-concentration, non-settling slurry is often in its final form and can directly be used in the next step of the process. An example is a super-fine coal-water slurry used as fuel in a power station burners. Settling suspensions require further treatment after transportation, this includes particle classification and dewatering.

It is also illustrated in Figure 2.21. The cost of this type of transportation can be high, particularly so when large particles are conveyed over long distances. In comparison, preparation and dewatering costs are usually low.

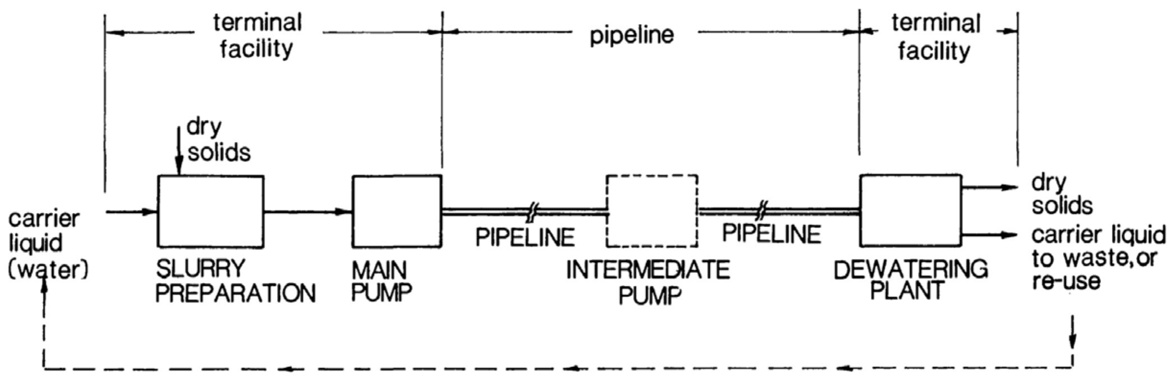


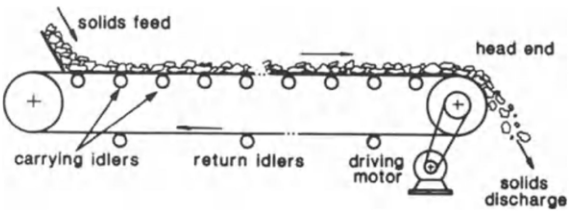
Figure 2.21: Hydraulic conveying system [21]

2.4.3. Mechanical conveying

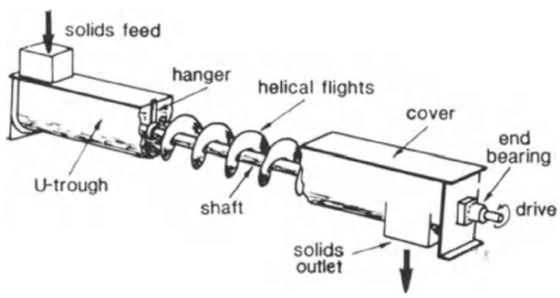
Mechanical conveyors have a critical role in most bulk solids handling plants. They are among other things used for transportation, feeding, and discharging of bulk solids. A crane with a grab is not a conveyor since the transport of material is not continuous. There are many types of mechanical conveyors, these are some of the categories:

- Belt conveyors, Figure 2.22a
- Screw conveyors, Figure 2.22b
- Bucket elevators, Figure 2.22c
- Chain conveyors, Figure 2.22d
- Vibratory conveyors, Figure 2.22e

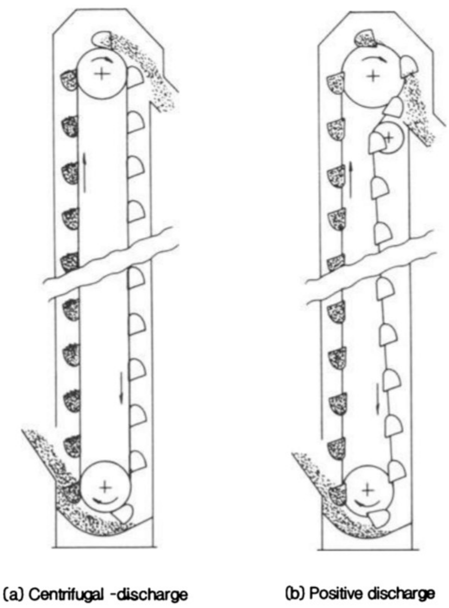
For a particular situation, often multiple options of conveyors are possible. The choice is dependent on parameters such as required capacity, distance, elevation, and many material properties such as density, maximum particle size, abrasiveness, toxicity, and explosibility.



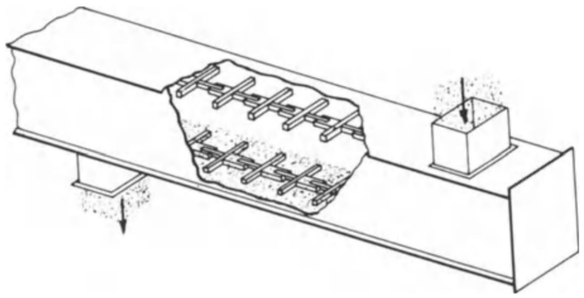
(a) Belt conveyor



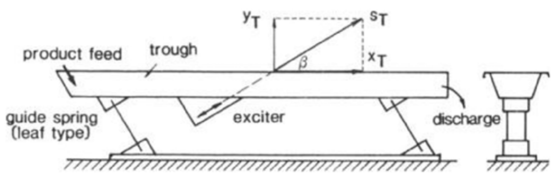
(b) Screw conveyor



(c) Bucket elevator



(d) Chain conveyor



(e) Vibratory conveyor

Figure 2.22: Different types of conveyors [21]

2.5. Stakeholder analysis

To better understand who is involved with the problem and in what way, a stakeholder analysis is done using [52, 53]. It is investigated which people have what level of interest in the project and the amount of power they have for specifically this project. This is then plotted in a diagram so that a distinction can be made between the different groups of people. In Figure 2.23 the results of this are visible.

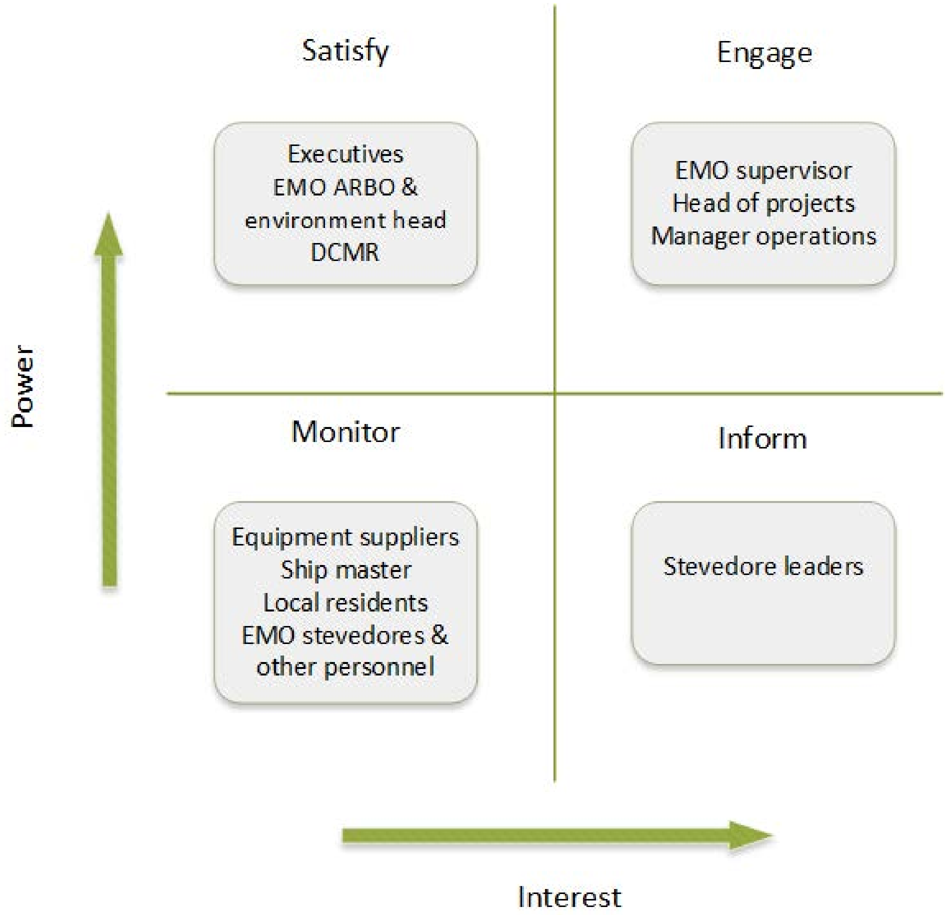


Figure 2.23: Stakeholder diagram

Satisfy

The head of ARBO and environmental regulations at EMO and the DCMR, the local environmental agency, are concerned with the working conditions and environmental aspects of the project. If it complies with the regulations these people will have little interaction. The EMO executives determine the general course of EMO but have little interest in relatively small projects if these are not disruptive. This group of people should be satisfied.

Engage

The supervisor of the project at EMO and the head of projects fall into this category. These people are very interested in the project and closely attached. The manager of the operational department is also involved in the project. This group of people should be engaged and be worked with.

Monitor

The group with low power and low interest consists of equipment suppliers, that can make/deliver a new prototype. The master of bulk carriers that dock at the EMO terminal are only interested if the ship is damaged, how well the hold is cleaned, and if the crew is disturbed. Local residents have complained in the past about dust and noise nuisances, this is their interest in the project. For the EMO stevedores and other personnel are mostly only remotely connected to the project and have a low level of interest. This group of people should be monitored.

Inform

The stevedore shift managers have earlier been involved with a similar project and are very interested in the result of the project. Some of these people will also actively work with a new solution so this can have a large influence on their work process. This group of people should be kept informed.

2.6. Conclusion

The question that this chapter has answered is the following: What is the problem with the current unloading process at EMO and what is available in the literature?. It has been shown that after a large grab has almost emptied the hold, some bulk material is stuck against the walls of the hold. To gain access, first the stairs have to be cleaned manually. After that, an excavator with a steel brush is used to remove the material from the walls, but this can cause damage. This whole process can be dangerous for the people involved, and it is time-intensive.

No specific literature has been found regarding the cleaning of the hold of bulk carriers, but other relevant topics have been analyzed containing information about the properties of bulk materials, silo discharge aids, and bulk material conveying methods. This showed material-related hazards, why not all material is free-flowing, how it can be made to flow, and how it could be transported from a hold.

3

State of the art of cleaning

This chapter will investigate what commercial solutions are available and what kind of equipment has already been tried at EMO.

3.1. Available cleaning products

This section will look at the commercially available products that are designed to be used, or could potentially be used, to clean bulk carrier holds.

3.1.1. Water gun

A long-distance water gun on a tripod is a commercially available solution, see Figure 3.1. It is built from stainless steel and is fastened to a swivel connection on a tripod [54, 55]. It uses the normal suppression pump on the fireline, and working airline on board. The recommended water pressure is 6 bar, the recommended air pressure is 7 bar. The estimated water consumption is 454 l/m and the estimated air consumption is 33 l/s, this is a very high volume solution. The water hose size is 51mm and the air hose size is 20 mm. The weight is 14.5 kg. At the maximum working distance of 30 meters, the force of the water on the surface being cleaned is around 10 kg. The air valve is adjusted in such a way to produce a tight hard jet of water. Too much air will cause the jet of water to break and spread.

This type of product is also available from other manufacturers [56, 57]

Figure 3.1: Wilhelmsen Unitor Tornado 3 cargo hold cleaning jet [54]

3.1.2. Water lance

A way to get closer to the surface is to use a dedicated pump and a long lance, see Figure 3.2a and 3.2b respectively. The pump has a heavy-duty stainless steel frame for protection and it enables lifting [58]. The machine is designed for 24 hours operations. The electrically driven 3-cylinder inline plunger pump runs 1720 rpm. This makes it relatively quiet. The pump system can go pressureless by going into standby operation by closing the trigger gun. It has a filter to protect the pump from dirty water. It weighs 154 kg. The feed water pressure can be between 2 and 8 bar using a hose of minimal 20 mm. The water flow rate is 17 l/m and the working pressure is 500 bar.

There are multiple lance kits for different size ships available, but the maximum height is 20m [59]. According to the manufacturer it is designed for cargo hold cleaning and removal of stains in high areas. It is made of aluminum so it is lightweight. It includes rope and pulleys so it can be attached to the deck of the ship and lifted or lowered that way.

(a) Wilhelmsen Unitor HPC Extreme 520 pump [58]

(b) Wilhelmsen Unitor HPCE Anaconda lance kit [59]

Figure 3.2: Products from Wilhelmsen for cleaning holds

This type of product is also available from other manufacturers [60–62]. A different style of lance is available where it rides on the wall with wheels without being lifted by ropes, see figure 3.3.

Figure 3.3: Products from Navadan for cleaning holds [60]

3.1.3. Wall riding robot

A new product is a robot that uses magnetic treads to stick to the wall surface and ride on it, see Figure 3.4. Four high-pressure nozzles are attached to it each applying 190 bars with 12 l/min per nozzle [63, 64]. The arm to which the nozzles are attached can also be rotated to the side of the robot. The robot is connected to a high-pressure pump that is placed on the deck, which in turn is connected to the remote control in the hands of the operator in the cargo hold. It is functional for vertical surfaces with an angle up to 60° from vertical (150° from horizontal). It fits between the side shell frames and other large flat surfaces. It is not possible to use the robot on stairs. The problem with this device is that the surface on which it rides needs to be clean, so that it has enough grip and does not fall off. It is also secured by a cable so that if it loses contact with the wall surface, it does not fall to the ground.

(a) Cliin robot [65]

(b) Cliin robot on the wall [63]

Figure 3.4: Robot from Cliin for cleaning holds

This product is also offered in different implementations [66, 67], see Figure 3.5. One model for example uses wheels instead of treads, the nozzles are not angled forward, but they are also mounted onto a swiveling arm and it can also ride on surfaces of up to 60°. It weighs 75 kg and can clean a width of 1.2 m.

(a) Vertidrive robot on the ground

(b) Vertidrive robot on the wall [63]

Figure 3.5: Robot from Vertidrive for cleaning holds [66]

3.1.4. Pneumatic ship unloader

Another possible option is a pneumatic ship unloader, see Figure 3.6 [68]. The unloading capacity is up to 230 tons per hour. It is possible to have all the equipment for unloading and discharging on one road-mobile semi-trailer. However, it is available in different types: road-mobile, dock-mobile, barge-mounted, gantry-mounted and stationary. The suction arm has 4 sections for good reach in the hold. This system would have trouble accessing partly enclosed stairs and it could be a challenge to steer the suction arm to the sides of the hold so suck the coal from the walls. Cohesive coal is also a difficult material to transport pneumatically.

(a) Trailer emptying a hold

(b) Road-mobile trailer

Figure 3.6: Pneumatic road-mobile ship unloader from Van Aalst [68]

This type of product is also available from other manufacturers [69–71]. These include machines that can be placed on deck with a footprint of 2.5m, see Figure 3.7 [72].

Figure 3.7: Vigan pneumatic unloader [72]

3.1.5. Excavator with high-pressure air/water gun

A small company has developed a high-pressure washer system that is mounted on an excavator that has two 500 l water tanks, see Figure 3.8 [73]. A low-pressure water pump is used for dust suppression and a high-pressure water pump is used for cleaning. It uses a mixture of air and water for cleaning, so that less water is used. For this, an air compressor of 25 m^3/min is also present. It also pulsates the water/air output and supports different nozzle configurations. Depending on the arm of the excavator, it can go up to heights of 24 m. It can use an Autec remote control mode so that the operator does not need to be in the cabin.

(a) [74]

(b) [73]

Figure 3.8: High-pressure jet from The Big Smile B.V.

The following products are not designed for the cleaning of a bulk carrier hold, but are still included for their principle and possible alteration and implementation.

3.1.6. Explosive cleaning

Explosives are used to clean boilers, smelters, and other tanks [75]. This is done by using a lance to place explosive charges in the boiler, see Figure 3.9. These are then detonated in a controlled way, so that residue is removed. This is not normally used for (relatively) open spaces such as a bulk carrier hold, it is unknown if this would work in this situation.

Figure 3.9: Explosive cleaning [76]

3.1.7. Air cannon

Air cannons or air jets are often used as a discharge aid in silos, and they are available from many manufacturers [77–82]. They consist of a high-pressure tank pressurized up to 10 bar, a quick-opening valve, and a fill line, see also Figure 3.10. Some advertise high discharge strength from the high-velocity output with low air volume, while others say that large volumes of air with a lower peak force work better at dislodging material. A high peak force would be beneficial when the buildup is very hard, so that it can be blasted away. For softer materials however, the high peak force can penetrate through the material leaving a hole behind while not removing much buildup. It is also possible to mount different nozzle types that have different flow types. Some have a concentrated blast while others cover a larger area with less force.

(a) Air cannon product photo

(b) Air cannons installed

Figure 3.10: An air cannon used for silos [77]

3.1.8. Vibrator

Many different types of vibrators are available [83–87]. However most (if not all) of these vibrators are designed for use on hoppers, trucks, or railcars, see for example Figure 3.11a and they are meant to be mechanically fixed to the surface that needs to be vibrated. Since this is not possible for cleaning holds and they can not be just pushed against the wall, there are 2 other options. Temporarily fix the vibrator to the wall with for example electromagnets, or use vibrators that are not meant to be fixed to the surface that needs to be vibrated, for example a hydraulic compactor for soil compaction, see Figure 3.11b.

(a) [83] (b) [88]

Figure 3.11: Electric and hydraulic vibrators

3.1.9. Ultra-high-pressure water jetting

High-pressure washers are widely available in different configurations [89–92]. These can be run on electricity and by diesel engine, see Figure 3.12, are mobile or stationary, can use different nozzles, and have a wide range of operating pressures and flow volumes. These can be operated by hand or mounted to a machine.

Figure 3.12: Electric and diesel engine driven high-pressure water blasters [91]

3.2. Previous tests at EMO

This section outlines the previous experiments that have been done by EMO to investigate better methods and equipment to clean a hold.

3.2.1. Hydraulic hammer

An excavator with a hydraulic hammer that is normally used to break concrete was outfitted with a flat plate instead of a chisel. This is then placed against the walls and vibrated to loosen the coal. The noise level was so high that noise complaints were made in Oostvoorne, a neighboring residential area. Also, sounding pipes and stairs came loose and dents were made in the walls. However, this was a very fast method and was easy to use.

3.2.2. Vibration plate tamper

A plate tamper that is used to compact soil is mounted on an excavator. A rubber mat is fastened to the surface to prevent damage to the ship which mostly worked. However, the use of the machine in the rearmost hold next to the engine room resulted in damage to the instruments present there. And since the machine is made to operate horizontally and it was used vertically, the lubrication of the engine did not work correctly. This necessitated breaks in operation otherwise the engine would run dry and fail. Also, the rubber mat got too warm during use, which caused it to fail. The speed was reasonable, but not fast enough for the operator. This caused them to angle the tamper so that the bare metal edge of the vibration plate contacted the hold wall. This was done because this metal-on-metal contact improved the speed of cleaning. However, this also damaged the internal rubber of the machine and the wall.

3.2.3. Vibration needles

Vibrating needles that are normally used to remove air bubbles from poured concrete are mounted on an excavator, see Figure 3.13. This did not damage the ship, only if the needles were placed directly against a sounding pipe if the coal was very sticky. They are relatively fragile and broke when people did not place them only in the coal, but also pushed them against the wall of the ship. This was done since this caused the cleaning to go quicker, because the vibration is sent into the wall. It worked well for stairs and inspection ladders, but less for the shell frames.

Figure 3.13: Vibrating needles

3.2.4. Air cannon

The details are not clear, but it worked by releasing compressed air. The pressure wave of this caused the window of the machine in the hold to break. It was also not good at cleaning the coal. The noise level was very high and it caused a lot of dust to be airborne.

3.2.5. Water hose

It has been tried to use a water hose from an articulated aerial lift. This used the standard water line pressure of around 7 bar and a hose of 50 mm. This used too much water causing the coal to get too contaminated with water, very roughly 50 m^3/hour

3.2.6. Narrow excavator bucket

Two types of narrow buckets have been used to clean the walls, see Figure 3.14a and 3.14b. This worked reasonably well, but there was residue that remained. Also, the operators used the bucket to hit the walls so the vibration caused the coal to fall, which causes damage to the ship. This was not suitable for cleaning stairs. For some areas in the corner another tool was necessary, see Figure 3.14c. This was able to tilt so that it could be used to scrape the material off the plates.

(a) A narrow excavator bucket

(b) A scraper with a different shape but the same width

(c) A rotating scraper for corners

Figure 3.14: Various metal scrapers

3.3. Conclusion

The question that this chapter has answered is the following: What is the state of the art regarding cleaning in general and at EMO? Cleaning equipment consisting of low and high-pressure water systems, which are used from far away or very close, high-pressure air systems, pneumatic unloaders, and vibrators have been shown.

Further, the tests of EMO have been shown which include vibrations by using a hydraulic hammer, a plate tamper, and vibrating needles. Also, an air cannon, low-pressure water hose, and various mechanical buckets and scrapers have been tested.

4
System analysis

In this chapter, the system in which the solution operates will be analyzed. Then the functions that the new solution should fulfill are investigated. Finally, from this follow the functional specifications and the design requirements that will be used to determine the best concepts.

4.1. Conditions

The conditions of the system are explained here. This includes the standard of cleaning, damage levels, safety aspects, and the speed of cleaning.

4.1.1. Cleaning standard

There are multiple standards for cleaning holds, these are listed below [93, 94].

- Hospital clean
- Grain clean
- Normal clean
- Shovel clean
- Load on top

Hospital clean is the highest standard, it requires the paint of all surfaces to be intact and all surfaces to be clean.

Grain clean is a very common requirement, the hold should be clean, swept, and washed with fresh water. It should also be free of insects, odor, and any loose material or paint.

Normal clean only requires the holds to be swept and free from residue from the previous cargo. Washing the hold is optional and depends on the requirements.

Shovel clean means that a shovel (hand shovel or front loader) is used to remove the material and possibly a rough sweep is done. No washing is required and material may remain.

Load on top is described by the name, new cargo is loaded on the old cargo. No cleaning is necessary.

The regulations for vessels that EMO has defined their cleaning process as “bulldozer clean holds” with added “EMO is not obliged to remove cargo residues or sweeping the holds”. This corresponds mostly to the “shovel clean” standard defined above, except for the action of sweeping the hold.

The new cleaning method should be at least shovel clean by removing most material from the walls. Since EMO has not expressed plans about increasing the cleaning standard, removing all residue of the previous cargo is optional. However, it has happened in the past that the crew of the vessel continued cleaning a hold after EMO was done so that later a front loader needed to be lifted back into the hold to remove the extra removed cargo. If the walls are cleaned to such a degree that the crew using a hand shovel is not necessary, it will have time and image benefits for EMO.

4.1.2. Damage costs

There are many cases where damage has been done to the ship during unloading and cleaning. The incidents where significant damage has been done to the ship between 1-1-2020 and 1-7-2021 have been analyzed. This was 127 cases total, where 71 were caused by grab movement and 56 by the CAT 966 front loader or the CAT 329 excavator. In some cases it is not clear if the damage is caused by the grab or by the machines in the hold, in these cases an educated guess is made. The damages caused by the front loader and excavator were further categorized. This results in 36 cases of damage to stairs or ladders, 16 cases where sounding pipes are damaged, 2 cases of scratches on the walls and/or floor in the hold, 5 cases of dents in the walls and/or floor in the hold, and 16 cases of other assorted damage. This is illustrated in Figure 4.1. It should be noted that these numbers include damage done by the front loader which is not responsible for cleaning the walls of the hold, only the floor, because these were impossible to separate.

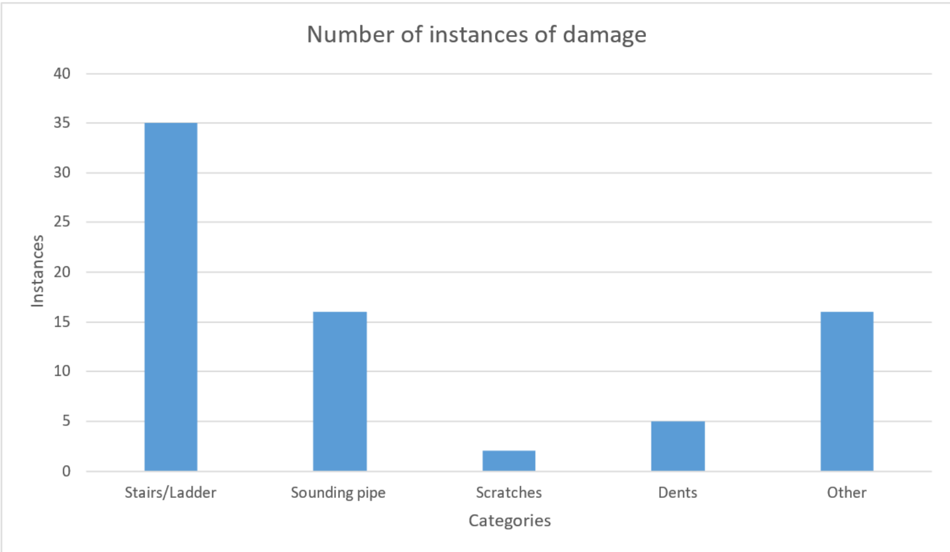


Figure 4.1: Number of instances of damage in different categories

The costs of these damages are shown in Table 4.1. The total costs are all the costs associated with these damages, the reserved costs are costs that have only been reserved but these are not the final paid price. The paid costs are the costs that have actually been paid. It can be seen that most of the incurred damages are caused by the grab movements and not the CAT machines.

	Machines	Grab
Total costs	€68,282.00	€381,297.00
Reserved costs	€31,650.00	€160,074.00
Paid costs	€36,632.00	€221,223.00

Table 4.1: The costs of the damages to ships by the machines in the hold and by the grab

It would be financially attractive and better for the reputation of EMO if less damage was done to ships. In at least one case the master of the ship has asked to stop using the excavator for cleaning the side shell frames because of damage done to the ship. Internally at EMO it is known that most damages are caused by the carelessness and attitude of the stevedores. The brush used on the excavator is also improperly used. This consists of beating the hold with the brush and using it too long such that the steel brush wires are almost completely gone.

The amount of damage caused is lower for larger unloading volumes. This matches what is said by EMO personnel, that it is more difficult to unload smaller ships because the grabs that EMO uses are very large and thus come into contact with the side of the hold more often. There is also a shift in the size of the ships that dock at EMO for unloading, see Table 4.2 and Figure 4.2. The number of Capesize vessels has dropped sharply from around 200 to 50. The number of Panamax vessels is not very constant but it shows a trend that is increasing. The other categories have relatively few ships that dock every year, but the number of Handysize ships also seems to be increasing. This trend towards smaller ships is part of the reason that it is necessary to reduce the damage done to ships during unloading.

Year	Capesize	Panamax	Handymax	Handysize	Coaster	Total
2011	250	50	4	3	0	307
2012	180	99	3	2	0	284
2013	204	108	3	7	3	322
2014	194	108	1	11	0	314
2015	188	119	1	7	0	315
2016	157	97	1	2	0	257
2017	117	155	3	1	0	276
2018	94	178	10	10	7	292
2019	73	168	11	14	7	266
2020	47	130	3	14	0	194

Table 4.2: The number of ships that have docked at EMO for unloading every year

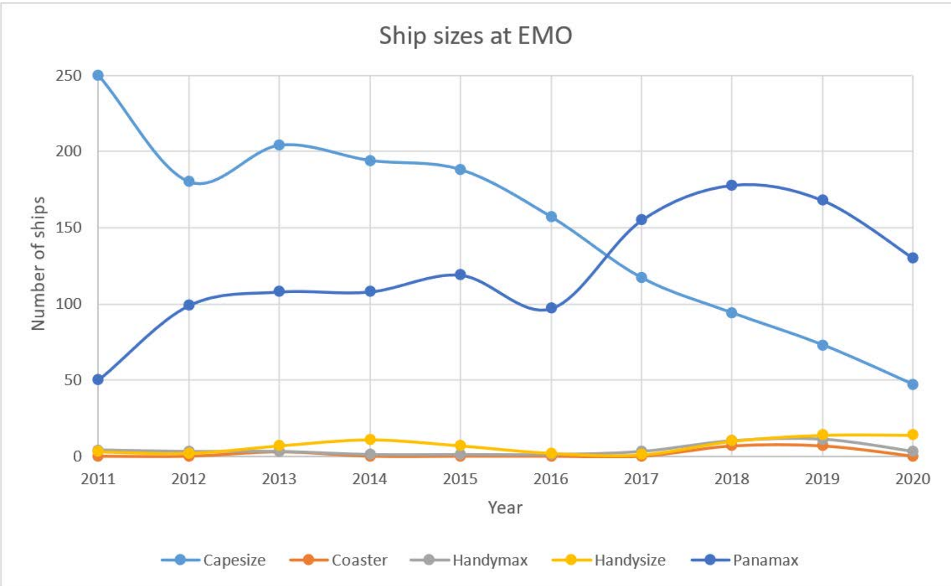


Figure 4.2: The number of ships of different sizes that have docked at EMO for unloading every year

Figure 4.3 is a graph is that shows how many tonnes are unloaded at the EMO quay every year, this is expressed in million tonnes. This data is overlaid on the number of ships that dock at the EMO quay in Figure 4.4. It can be seen that the data seems consistent.

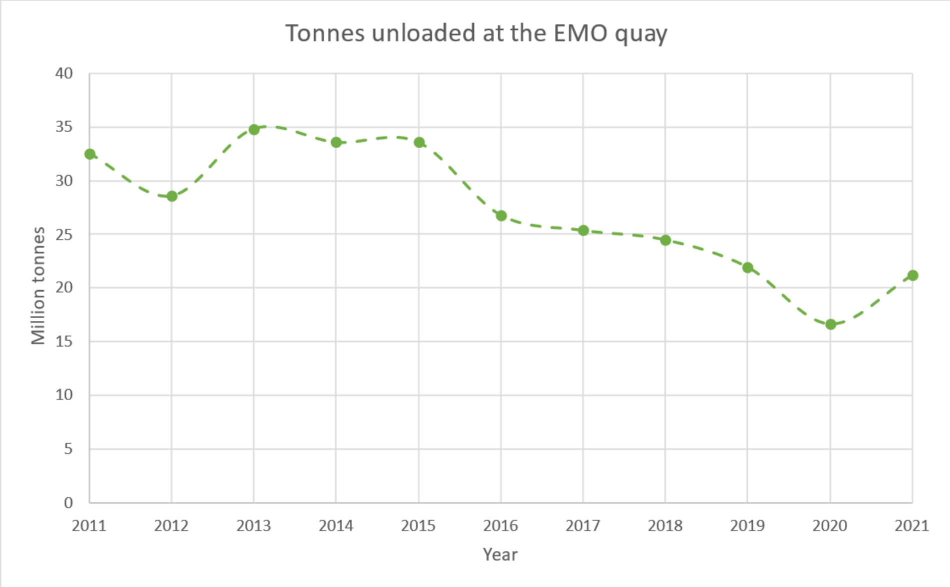


Figure 4.3: The number of tonnes that is unloaded at the EMO quay every year

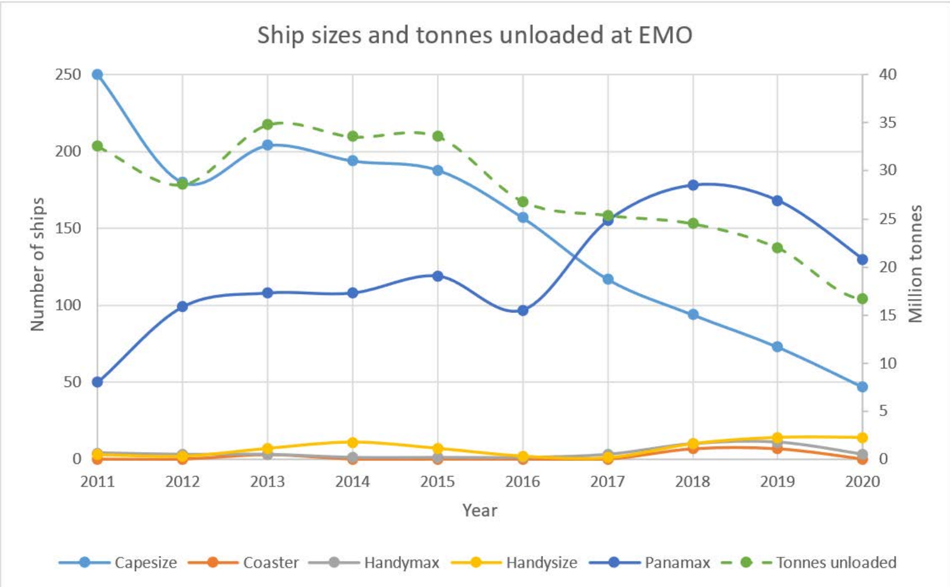


Figure 4.4: The number of ships and the number of tonnes unloaded at the EMO quay every year

4.1.3. Safety incidents

To improve the safety of the unloading process and measure the difference, a reference needs to be established. To that end are in Table 4.3 the reported safety incidents at EMO between 1-1-2020 and 1-7-2021 with regards to unloading ships. They are divided into two categories, solvable and not directly solvable by a new solution. The number of occurrences is listed and each type of incident is given a severity score from 1 to 5. 1 corresponds to very mild potential harm, and 5 is very serious probable harm. The number of occurrences is multiplied by the severity to create a danger score. When these are added together it is clear that most incidents could be prevented. This can be done by not needing hand tools, not descending into the hold, and the remote operation of front loaders in the hold.

A new solution can not be instantly be measured to be safer, but if certain incidents can not happen anymore, there is an improvement.

	# of occurrences	Severity (1-5)	Danger score
Solvable			
Bad stairs/ladder in hold	2	3	6
Hit in the face by a reek in hold	1	2	2
Hit occupied front loader with grab	2	5	10
Handtool not fastened to front loader during lifting	1	2	2
Crane not put in safe mode for lifting front loader	2	3	6
Front loader not secured for lifting	1	4	4
			30
Not directly solvable			
Fall on board (deck)	1	2	2
Open hatch in the kway on deck	1	4	4
Crane in auto dragged hose coupling against person	1	2	2
			8

Table 4.3: The safety incidents during the cleaning procedure

4.1.4. Hold cleaning speed

As discussed in Section 2.1 a CAT 329 excavator is used to clear the sides of the hold and a CAT 966 front loader is used to move the cargo on the floor to a central location such that the grab can unload it. In Figure 4.5 the number of emptied holds per month is plotted. This is done from November 2019 to November 2020 for the 2 different machines types, the different startpoints and endpoints are present because this was the data available at EMO. It can be seen that the excavator is used in fewer holds than the front loader. This is because the excavator is not needed for every hold, since there are cargo types that are free-flowing so the walls do not need to be cleaned.

In Figure 4.6 the run hours per hold of the previously discussed machines are plotted. It can be seen that April and August seem to be outliers, for the rest of the data points the run hours are comparable between machines types. The average number of run hours per hold is 3.0 for the front loader and 2.5 hours for the excavator.

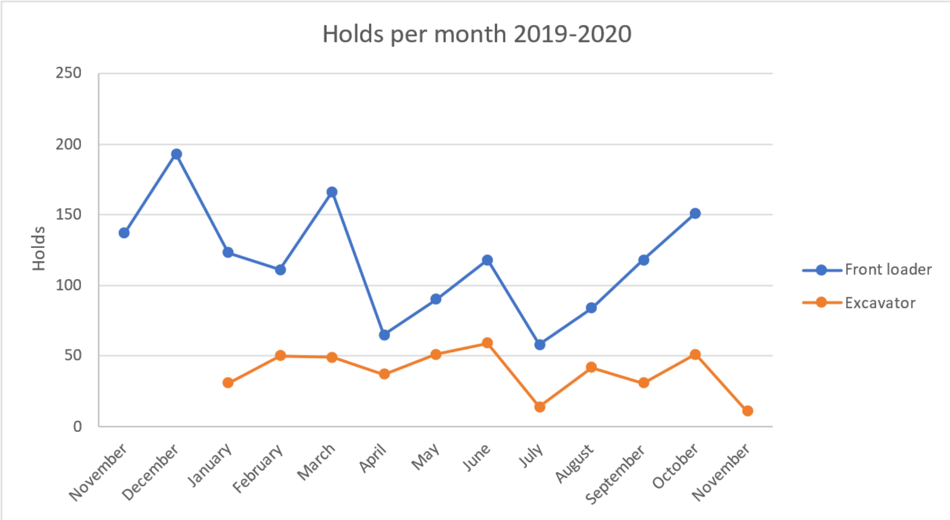


Figure 4.5: Holds emptied per month by front loaders and excavators from 2019 till 2020

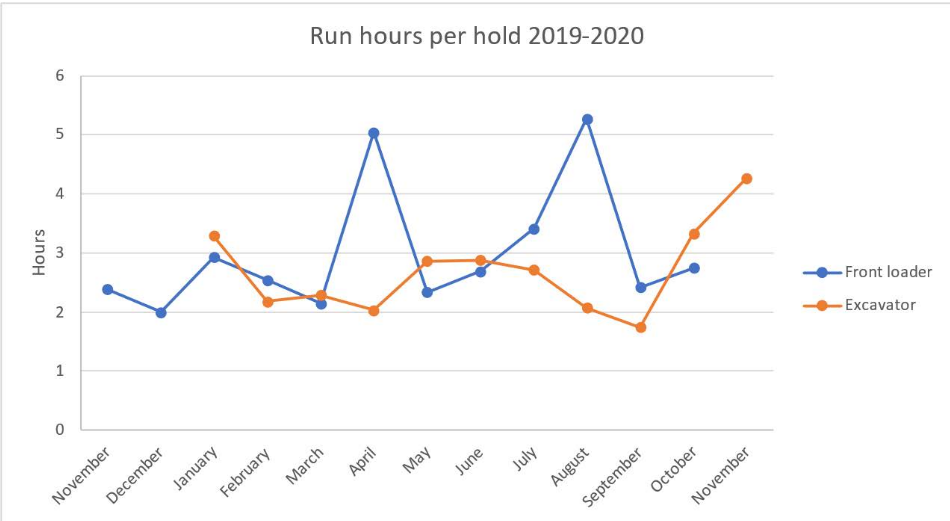
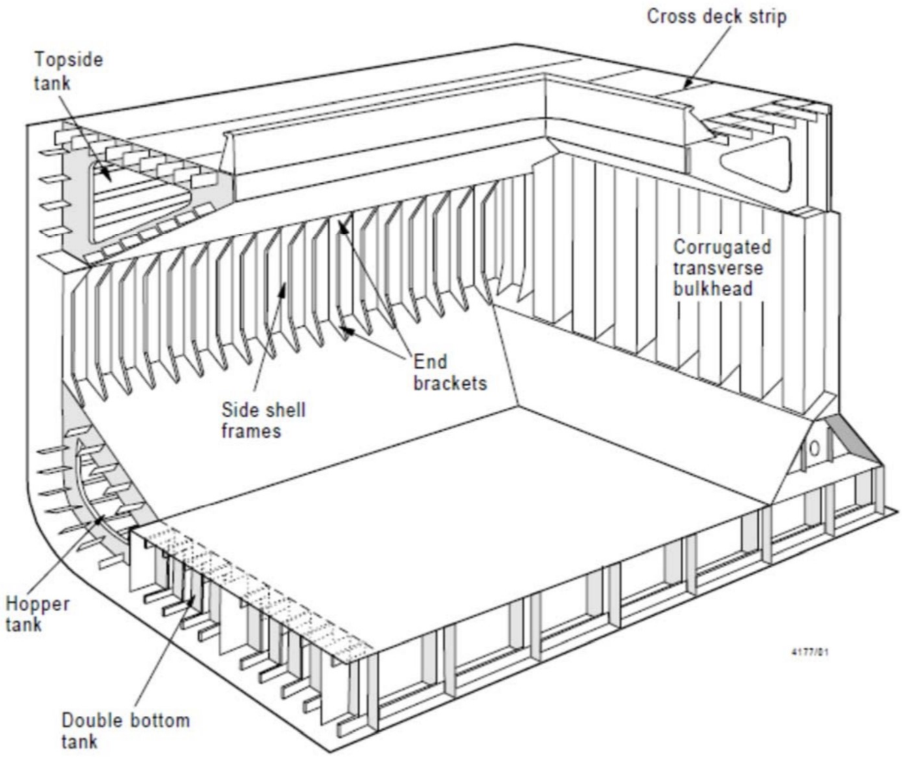


Figure 4.6: Run hours of front loaders and excavators per hold averaged per month from 2019 till 2020

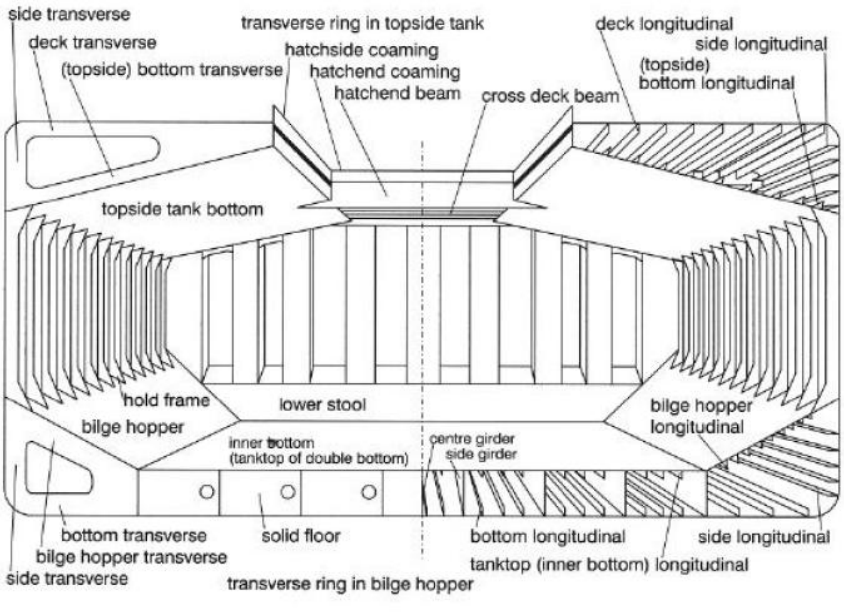
It would be good if the new solution is faster than the current way of operations, so 2.5 hours for the cleaning equipment. However, this can not be an exact comparison for a few reasons. The run hours do not denote the time that the machine is actually used, it can also just be turned on but stationary. Also, the process of cleaning the stairs with water hoses sometimes starts when the grab is still halfway in the hold and is finished when the hold is nearly empty. Other times the stairs are cleaned when the hold is already nearly empty, so that not all operations run in parallel which means longer cleaning times. The most important note is that not all cargo is the same. Some cargo is free-flowing and the final stage of emptying takes just 30 minutes according to stevedores at EMO, but when it is very sticky it can take 6 to 8 hours.

4.1.5. Physical constraints

The physical boundaries and space of the system are important aspects of a possible solution, so that is analyzed in this section. See Figure 4.7 for a schematic image of the inside of a hold.



(a) Isometric hold schematic [15]



(b) Cross-section hold schematic [95]

Figure 4.7: Schematic image of a cargo hold

The required reach in the hold of a generic Capesize vessel is shown in Figure 4.8 (the truck is for illustrative purposes only). There are also smaller vessels that dock at the EMO terminal, but the solution should be able to service the largest ships. These have a hold that is approximately 25 m high and 45 m wide.

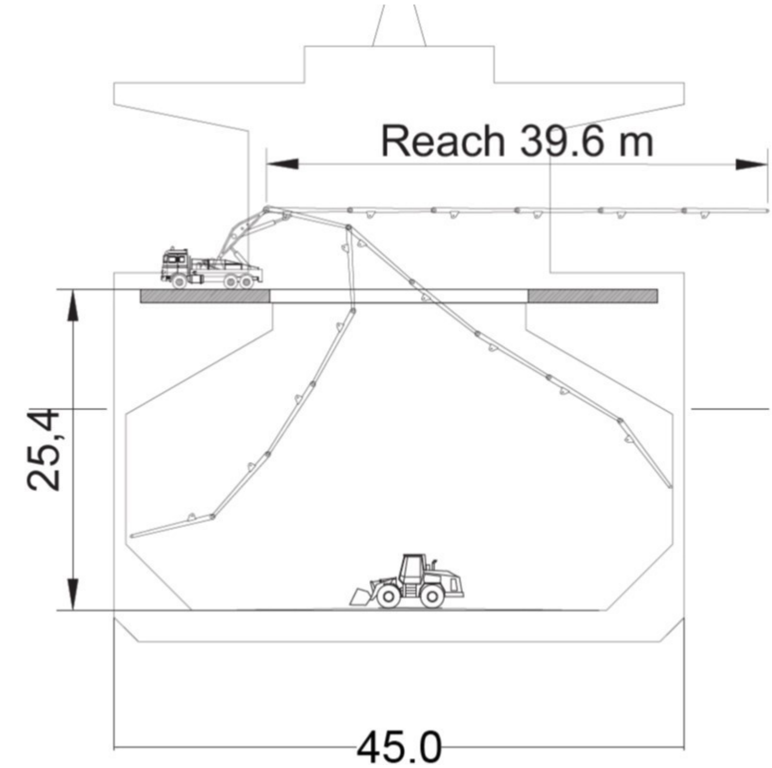


Figure 4.8: The hold dimensions of a general Capesize bulk carrier [17]

The maximum air draft from the water level to the top of the hatch cover is 19.5 m, this is the height that the grab can clear. The distance between the bottom of the grab and the hopper where the material is deposited is 7.1 m, this is the space where equipment is lifted attached to the grab from quay to ship and vice versa. However, if the grab is decoupled, this space is increased significantly. The hatch size of ships differs, but for a Capesize vessel a typical hatch is around 15 m x 15 m [96]. A Panamax vessel has hatches that are 16 m x 13 m and a Handymax 17 m x 17 m. Figure 4.9 shows a schematic of a typical ship.

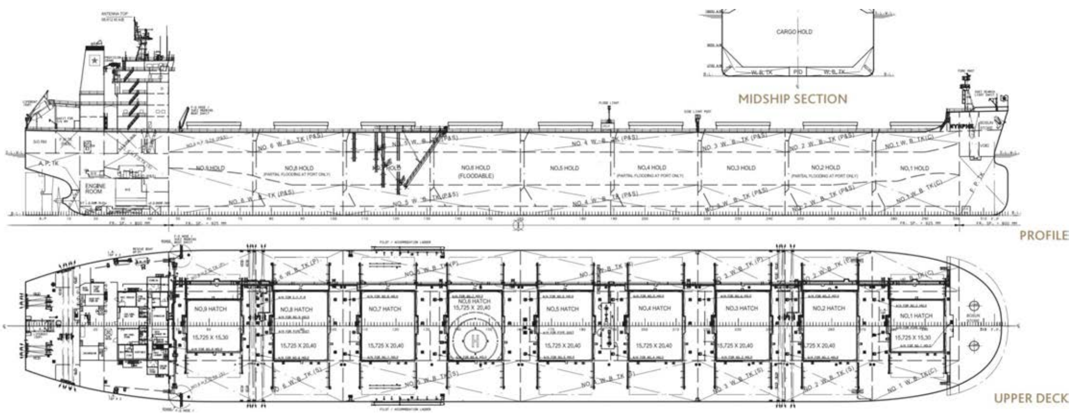
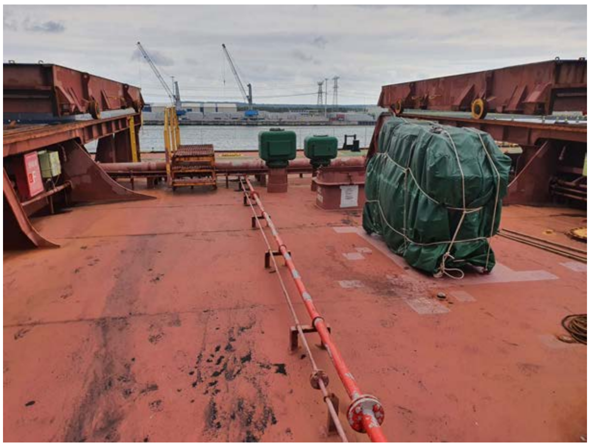
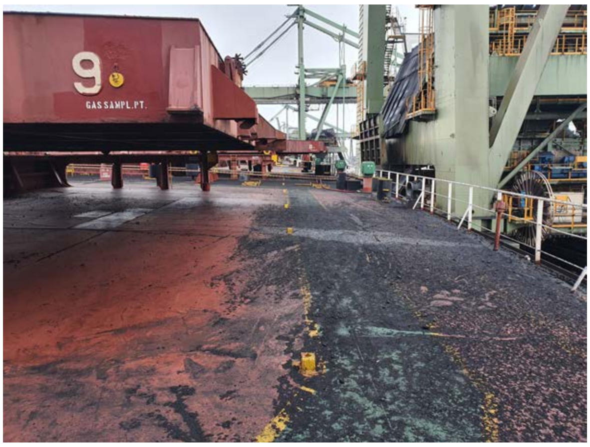


Figure 4.9: The schematic of a Capesize bulk carrier and its hatches [96]

The space on deck is limited, in Figure 4.10a and Figure 4.10b the space between holds can be seen. The distance between holds is a few meters, but there are often various parts of the ship present on deck so there is little free space. In Figure 4.10c the space between the holds and the side of the ship is visible, here are a few meters of width available and approximately double that in length. In Figure 4.10d the space on the quay is shown. There is very little space between the quay edge and the crane that rides on the tracks. Behind the tracks are four belt conveyors, behind those is a material storage area, and behind that are the other tracks for the crane. The distance from the quay edge to the material storage area behind the conveyors is approximately 15 m.


(a) Space on the deck of a bulk carrier between holds


(b) Space on the deck of a bulk carrier between holds



(c) Space on the deck of a bulk carrier between the hold and the railing


(d) Space on the quay

Figure 4.10: Space for equipment at various locations

4.2. Functional specifications

The solution needs to be able to be placed in the correct location for operation, and reach the places in the hold where cleaning is required. It of course also needs to be able to clean the hold by removing the material from every possible location in the hold. This can mean that the material falls onto the floor of the hold and is moved together by a front loader so the grab can transport it out of the hold. These are the functions that the solution needs to fulfill, the conditions for which have been explained earlier in this chapter. These functions are represented in the following functional specifications. They are split into a required section, a recommended section, and an optional section.

Requirements

- No excessive noise
- No internal damage to the ship by vibration
- No excessive damage to the hold
- No dust generation above the limit
- No excessive contamination by water
- Works on all ships
- Cleans every location in the hold e.g. stairs, corners, behind pipes, and high places
- Safe to use
- As fast as current cleaning process
- Possible to automate

Recommended

- No damage to the hold
- Not impeding crane riding action
- Not impeding crane unloading action
- Faster than current cleaning process
- Cleans the hold such that ship personnel do not “after-clean” the hold
- No personnel needed to clean stairs
- No personnel in the hold to operate machines
- Not quickly damaged by (improper) use

Optional

- No people needed in the hold
- Not needed for personnel to haul/handle heavy equipment
- Quick to learn how to use
- Not expensive

4.3. Design requirements

The functional requirements of the last section are used to directly create the following design guidelines. These guidelines are more practical and where possible have been given a numeric value so they can be used directly in the design process in Chapter 5. The same required, recommended and optional sections are used again.

Required

- The noise level of the equipment and cleaning process needs to be below 100 dB.
- (if applicable) Vibration levels such that other parts of the ship do not undergo damage.
- No scratches/dents/other damage to the hold due to hard contact between the ship and cleaning equipment such that financial compensation is necessary.
- (if applicable) An airflow rate below 5 m^3/min at 10 bar minimizing dust generation.
- (if applicable) A waterflow rate below 30 l/min to minimize contamination of the cargo and increase running time using a water tank.
- The size and function of the equipment are such that the equipment can be placed at a location (e.g. in the hold, on deck) where it is functional in cleaning the hold (for every ship).
- A reach of 20 m vertically and 3m horizontally to reach the entire hold with the cleaning equipment inside the hold. A reach of 25 m vertically and 35 m horizontally to reach the entire hold with the cleaning equipment on deck. If the equipment is outside and further away, this distance needs to be added to the distance needed if the equipment is on deck.
- The equipment does not create dangerous situations for personnel.
- Able to clean a hold in 3 hours on average.
- Can be automated such that no people have to be in the hold.

Recommended

- No scratches/dents/other damage to the hold and ship at all.
- The equipment is located such that crane operations such as riding and unloading are not hindered.
- The cleaning method is quick, able to clean a hold in 2 hours or less on average.
- Cleaning removes all material from the walls (follows “normal clean” standard).
- Can clean the stairs completely.
- Completely remote-controlled (or automated), no people needed at all in the hold.
- The equipment is very (physically) robust.

Optional

- Remote controlled equipment, (if applicable) remotely detachable.
- (if applicable) No water/air/power/etc connection to shore, everything is attached to the equipment.
- The equipment is simple, with not many complicated components.
- The initial cost is low, less than €20.000,-.

4.4. Conclusion

The question that this chapter has answered is the following: What is the system and its conditions in which the solution operates? The cleaning standard has been defined, as well as the damage costs of cleaning holds. The safety incidents associated with the cleaning have been analyzed, and the current speed of cleaning and physical constraints are detailed.

After that, the functional specifications of the concepts have been shown, and from this the design requirements were created, which are all split into requirements, recommendations, and optional points. The points include requirements among other things for noise, damage, size, speed, and safety.

5 Design

In this chapter, the different design concept components will be scored to determine the best ones. These will be further analyzed so that one complete final concept remains with the most potential. Finally, a rudimentary design will be made and the steps towards automation are detailed.

5.1. Concept scoring

From all the information in the previous chapters several concepts for cleaning (and known equipment) are selected for scoring using a multi-criteria analysis, see Figure 5.1. This includes using low-pressure water, high-pressure water, high-pressure air, and a combination of high-pressure air and water. Vibration needles and a vibration plate are also included. An air cannon, sound horn, aeration nozzles, explosives, and pneumatic and hydraulic transport are also scored. Finally, a large type of brush is also included.

These options are scored in 3 categories: Safety & environment, damage, and costs & speed. The first category includes the noise level, the risk they impose on the people nearby, the possible caused dust pollution by the cargo. The second includes the damage done to the hold, the damage done to the rest of the ship, and the pollution of the cargo by water. The last category includes the initial cost, the robustness of the solution, the cleaning performance, the cleaning speed, and how feasible the solution is. These are all given a weight depending on their importance. The concepts are scored from 1 to 5, where 5 is the best score. The category score is multiplied by the category weight and all the points for a concept are added, giving a ranking. Three people have independently given their own ranking, this is shown in the last columns denoted by the 2 initial letters of their names. The people are the author of this thesis, the EMO supervisor, and a senior stevedore. These people are selected to have a variety of experience and different insights.

	Safety & Environment			Damage			Costs & Speed					Scores			
	Noise level	Risk	Dust pollution	Hold damage	Ship damage	Cargo pollution	Initial cost	Robustness	Cleaning perf.	Speed	Feasible	GV	YO	FL	Average
Score weight (1-5)	2	5	3	4	4	3	4	4	5	4	5				
Low pressure washer	3.7	4.7	5.0	5.0	5.0	2.3	4.0	3.7	3.3	2.7	4.3	176	175	166	172
High pressure washer	3.0	3.3	5.0	5.0	5.0	3.3	4.0	3.0	5.0	4.0	4.7	179	187	174	180
Air compressor	3.3	3.7	2.0	5.0	5.0	4.0	3.7	3.0	2.7	3.0	4.3	161	162	147	157
Air/water HP combi	2.7	3.7	4.3	5.0	5.0	3.7	4.0	3.0	4.3	4.0	4.7	179	185	166	177
Vibration needles	3.3	4.3	3.3	3.7	4.3	5.0	3.0	2.7	2.3	2.7	4.7	153	159	149	154
Vibration plate	1.0	3.0	3.0	3.0	3.0	5.0	3.3	3.0	3.7	4.7	4.0	153	161	128	147
Air cannon	1.0	2.0	1.7	4.0	4.0	5.0	3.0	3.7	3.0	3.0	3.0	143	143	112	133
Sound horn	1.0	1.7	3.0	4.7	4.7	5.0	2.7	2.7	3.3	3.7	2.7	132	145	136	138
Aeration nozzle	3.7	3.3	2.7	5.0	5.0	5.0	3.0	2.3	2.7	2.3	2.3	130	140	158	143
Explosives	1.0	1.0	1.7	3.3	3.3	3.3	3.3	3.3	3.3	3.3	2.0	115	121	110	115
Pneumatic transport	2.7	3.0	4.3	3.7	4.3	5.0	2.0	2.0	2.3	1.7	1.3	118	120	126	121
Hydraulic transport	3.7	2.7	4.7	3.7	4.3	3.7	2.0	2.0	2.3	1.7	1.3	114	114	128	119
Large brush	4.3	3.3	4.0	3.0	4.3	4.7	3.3	2.3	3.0	2.7	4.3	160	165	127	151

Figure 5.1: Scores of the different cleaning concepts

The concepts for the reaching function include fixing it to the quay crane, a pump truck used for concrete on the quay, an extra ship with a crane and fixing it to that, using a CAT329 in the hold, putting a platform lift in the hold, using a magnetic wall riding vehicle, hanging it from (a machine on) the ship deck, handheld, and an all-terrain vehicle that is constantly riding next to the wall as the hold is being dug out.

For the concepts of the reaching function, see Figure 5.2 a very similar scoring procedure is done, the difference is only in the scoring categories. These are: Reach & control, operations, and costs & speed. The first category includes how far it can reach in the hold, the ease of reaching into the hold, and the ease of control of the equipment. The second includes the impedance posed to the crane and if it would be easy to be made remote controlled. The last category includes the initial cost, the robustness of the solution, the cleaning and positioning speed, and how feasible the solution is.

	Reach & Control			Operations		Costs & Speed				Scores			
	Reach in hold	Ease of reach	Ease of control	Crane impedance	Remote control	Initial cost	Robustness	Speed	Feasible	GV	YO	FL	Average
Score weight (1-5)	5	3	2	4	4	4	4	3	5				
Fixed to crane	4.0	3.0	3.0	1.3	4.3	3.7	4.0	4.0	2.7	108	117	116	114
Concrete pump truck shore	3.0	1.3	2.7	2.7	4.7	3.3	3.7	3.3	2.3	110	89	111	103
Crane on extra ship	4.0	2.3	2.3	3.3	3.7	2.3	4.3	3.0	2.3	96	95	130	107
CAT329	4.0	4.7	4.3	3.0	4.0	4.0	3.7	4.0	4.7	140	146	124	137
Platform lift	4.3	4.3	4.3	3.7	3.0	3.3	3.3	4.3	4.0	111	124	154	130
Magnetic wall vehicle	2.3	4.0	3.7	4.3	5.0	3.0	2.0	3.3	3.7	122	119	109	117
Hang from (machine on) deck	2.7	4.0	3.7	3.0	3.7	3.0	4.0	3.3	2.7	104	122	106	111
Handheld	2.3	2.7	3.0	4.3	1.0	5.0	2.7	3.0	3.0	98	92	115	102
All terrain vehicle in hold	2.7	3.0	3.0	3.0	4.3	3.3	3.0	3.7	3.7	125	137	75	112

Figure 5.2: Scores of the different reaching concepts

5.2. Final concept selection

The concepts with the highest scores in the previous section are a low-pressure washer, air compressor, a high-pressure air/water combination, and a high-pressure washer. For the reach function, the highest-scoring concepts are the CAT 329 excavator and a platform (scissor) lift. These concepts will be analyzed further to choose the best for the final design.

At the moment EMO already uses a low-pressure washer. This is a water line that runs along the quay at a pressure of around 7 bar. Hoses are connected to this pipe and run to the deck of the bulk carrier so they can be used to manually hose down the stairs to the hold, also mentioned in section2.1. The process of cleaning one set of stairs takes about an hour and in this time 50 m^3 water is used according to EMO personnel. This amount of water can already be problematic if it is not distributed over a large amount of cargo because then it is too wet. A very conservative estimate about how much water cleaning the entire hold this way would take, based on the estimated volume of cargo on the stairs and the rest of the walls, is 500 m^3 of water. This volume is simply too large to maintain the quality of the cargo, so this concept can not be used.

Air compressors are used for small-scale, light cleaning, but no applications of heavy-duty cleaning were found. Abrasives are added to deliver more impact and remove surface contaminants. Very abrasive methods use metal shot, or sand [97]. Fairly abrasive methods use glass beads, plastic or organic material such as walnut shells. Mildly abrasive methods use baking soda and dry ice. However, all these methods use an extra material that would contaminate the cargo if used in a hold, which is not acceptable. It might be possible to use the cargo (at least a very similar material) as the abrasive so that no contamination occurs, but this requires further study. A typical worksite compressor can deliver 20 m^3/min at 14 bar [98], which is probably not powerful enough to blast away coal at a distance. The high airflow also creates much dust which would have to be captured by using water mist from fine nozzles. As shown earlier in section 3.1 a device exists which uses mostly high pressure pulsing air, to improve the impact and thus the cleaning, with some water mixed in [73]. However, from a video clip it seems that the working distance from nozzle to material is not very large, less than a meter, and it took multiple years to create the pulsing mechanism. So the concept of using an air compressor does not seem very effective and is thus not used further.

The advantages of using both water and air under high pressure in a system that combines them and shoots it out of a nozzle, are that it uses less water than a pure water system. This has the effect that with the same volume of water, the cleaning time and surface area are increased. It also means that less water will be mixed into the cargo which is good. However, an exhaustive search for available commercial products that combine high-pressure water and airflow did not turn up any options. Also in the literature there were not any results found of this application. There is also a lot of variability in how the waterflow and airflow can be combined before ejection from the nozzle. The way this combination of flow happens and the geometry from the combination point to the nozzle probably has a large influence on the characteristics of the resulting jet. For example the ratio of water to air, the jet shape, the size of air bubbles in the water, the size of water droplets in the air. If such a system is to be designed, since it does not seem to exist yet, this requires thorough study that is beyond the scope of this assignment. For these reasons it is decided that this concept will not be used for the final concept design. However, it has potential and should be investigated.

A high-pressure water jet is similar to a low-pressure water system with some differences. It also uses water, but only around 15-25 l/min, which is around 1 m^3 of water per hour instead of 50. It can work with less water since the pressure is much higher and a nozzle is used to create a concentrated water jet. The high pressure is created by a high-pressure pump that can easily create pressures of 250 bar and higher is also possible. It is possible to experiment with the water pressure and the nozzle type to find the combination that works best at removing coal. High-pressure cleaning is a well-established technique and so parts and equipment are widely available. The disadvantages are that a high-pressure pump is loud, but not above the allowed noise levels. Also, there is a possibility of damaging the paint on the walls due to a too powerful water jet. However, this can be prevented by testing what a safe distance/pressure/nozzle combination is so that no damage is done.

A scissor lift has a personnel basket at the end since it is made to place people at a certain height. Since the goal is to make an automated system, a person doing the cleaning from a scissor lift is not going to happen. Instead a jet system, if that is air, low-pressure water or high-pressure water does not really matter, needs to be mounted to the basket. This basket is not designed for maneuverability, so a system would need to be designed that can direct the jet at different places on the wall in the hold. It can also lift only a few hundred kilograms which could be a problem if heavy equipment would be needed such as a compressor, pump, or water tank. The wheels are rather small and would be difficult to drive over the remaining material on the floor, so the hold floor would need to be quite clean before emptying the side shell frames, which would again deposit material on the floor. To automate this type of machine a lot of work would be required. There are some scissor lifts that are remote-controlled, but this system would need to be unified with the movement system of the jet.

The CAT 329 excavators that EMO already uses to clean holds are the other option. The end of the arm has large maneuverability and can reach every part of the wall in the hold. So if the jet system is mounted to the end this would be ready to go regarding movement. It rides on large tracks so there is no problem with driving over some remaining cargo on the floor. It has ballast on the back which could be replaced by the required heavy equipment, and since it is designed to dig and undergo large forces, some reaction force from a jet on the end of the arm is not a problem. Regarding automation, there are remote-controlled excavators available, and the only other part that needs to be controlled would be the cleaning system.

A low-pressure water system uses too much water, a high-pressure air systems has not enough power. A system that combines water and air has potential but requires more study, so the best cleaning option at this moment is a high-pressure water system.

The mobility, availability, and the more easy way of automation of the excavator with respect to the scissor lift make this the final choice.

5.3. Final concept design

In this section a conceptual design will be shown of the chosen solution. It contains specification guidelines and steps towards making an automated design.

5.3.1. Schematic design & specifications

The design includes a high-pressure pump of at least 200 bar, this can be adjusted according to the results of the experiments. For now, a pump unit is shown that has a working pressure of 1000 bar [91]. It has its own water tank of 50 L and weighs approximately 750 Kg. A water tank of at least 1 m^3 is also present. In Figure 5.3 various views of the design are shown, including 2 water tanks of 1 m^3 to show the size. This could be 1 tank of a custom size. The width of the CAT 329 is a little over 3 m [99], the water tanks 1 x 1 m, and the pump (L x W x H) 1.5 x 1 x 1.2 m so the design is roughly to scale. The tank and pump are mounted on the back of the excavator.

(a) Top view. Original image from [99]

(b) Left side view. Note: Pictured is not the exact same type of excavator. Original image from [100]

(c) Right side view. Note 1: To obtain a right side view, the left side view image of the excavator is mirrored. Note 2: Pictured is not the exact same type of excavator. Original image from [100]

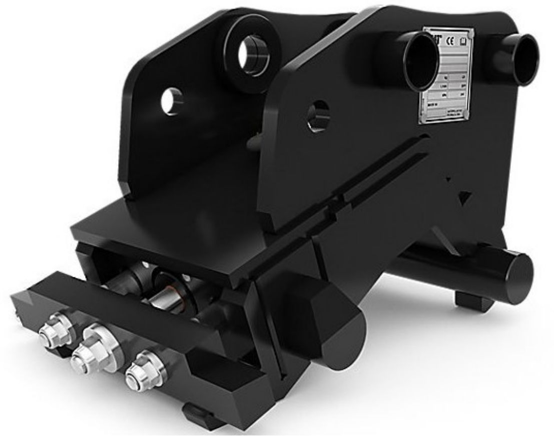
Figure 5.3: Views of the design of an excavator with water tank and high-pressure pump equipment

The tank and pump can be placed here by removing the counterweight that is normally present on the machine, see Figure 5.4. In its place a platform is constructed that can hold the tank and pump. The counterweight of a similar excavator weighs 4600 kg [99]. So a maximum weight of 2 tonnes of water, a pump of 800 kg, and a supporting frame of roughly 200 kg is only 3 tonnes, a significantly lower weight. This further decreases when the water tank is empty, then only 1 tonne will be present. This can be supplemented by adding extra material to increase the weight, however the cleaning attachment should not experience large loads so such a large counterweight might not be necessary.

Figure 5.4: Removal of the counterweight on an excavator [101]

Hoses are run from the water tank to the pump and from there to the boom, arm, and finally to the attachment. Also, a discharge valve is mounted to start and stop the flow. Filters are placed between the tank and pump so that if the “working water” of EMO is used, the particles are prevented from entering the pump system so that no clogs and/or damage is caused.

Coupling mechanism
There are multiple coupling mechanisms for attaching attachments. The mechanism that EMO uses on its machines can be seen in Figure 5.5. Figure 5.5a shows the coupler that is mounted on the arm of the excavator and Figure 5.5b shows a bracket that has the correct shape for the coupling. The coupler uses a hydraulic wedge to lock the bracket in place. Figure 5.5c shows a tilt coupler. That type of coupler can also tilt the attachment, which could be useful while cleaning a hold. This negates the need for making a system that moves only the nozzles, because the whole attachment can also rotate sideways.



(a) CAT CW type coupler [102]

(b) CAT CW type bracket [103]

(c) CAT tilt coupler. Note: this is another type of coupling mechanism not compatible with the other images [104]

Figure 5.5: Coupling interface used by EMO on their CAT equipment and a hydraulic tilt coupler

Cleaning attachment
The attachment is a piece of steel on which at least 1 nozzle is mounted that is connected to the pump, see Figure 5.6 for a prototype design. The pipe and nozzles are placed on the underside of an HEB 200 wide flange beam so that when it is used in a hold and large pieces of bulk material fall, the water pipe and nozzle are not damaged. Also, when it is set on the ground, the geometry prevents contact between the nozzle and the ground so that it will not be damaged. At the tip of the attachment the pipe bifurcates so that multiple nozzles can be mounted. The other end is only a steel plate for now, so that a coupling mechanism can be attached to it.

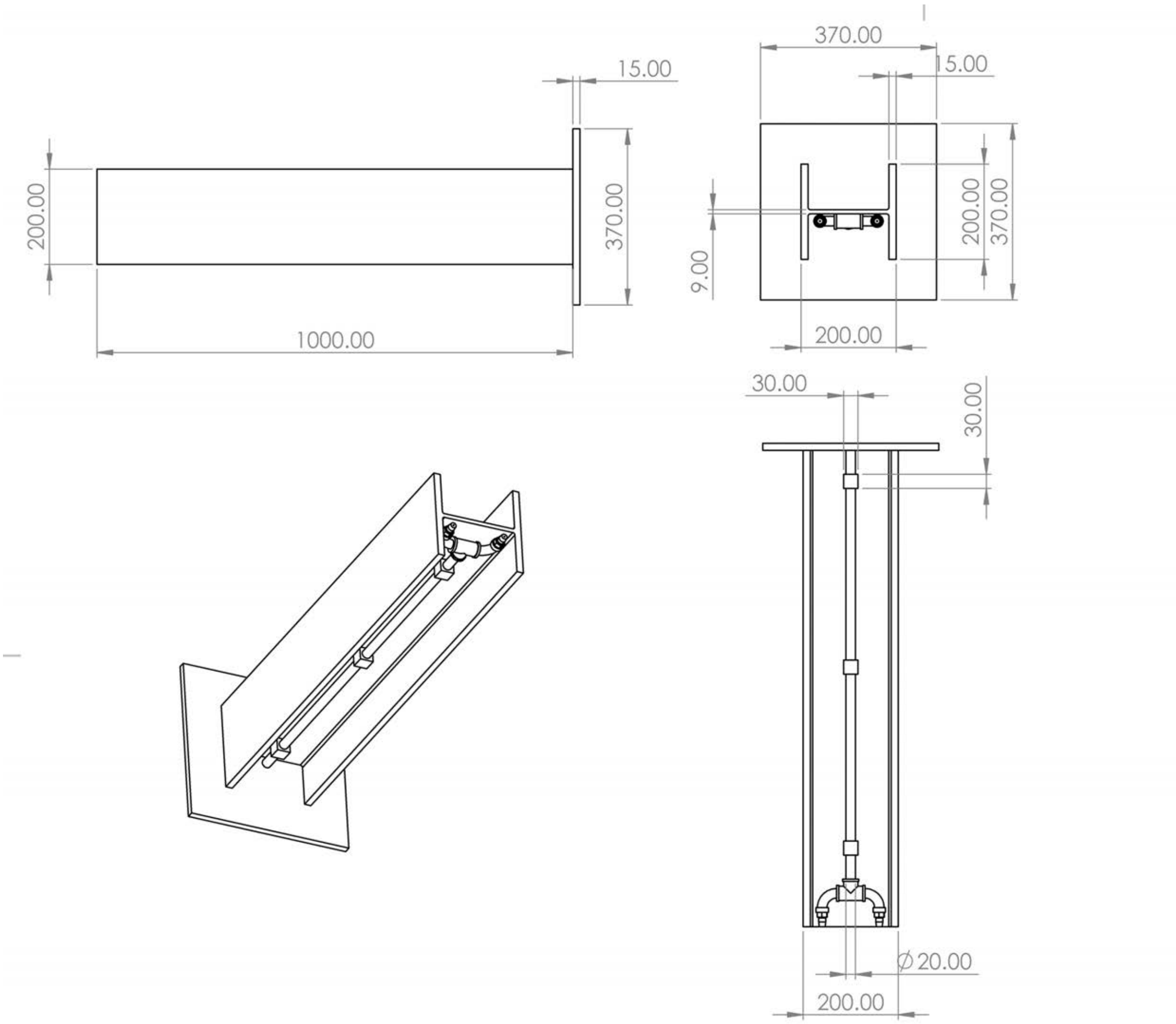


Figure 5.6: Drawing of a concept design of the cleaning attachment

Water hammer
Water hammer is a pressure spike that can occur in many systems that has abrupt changes in the flow, often caused by pump starts and stops, or the opening and closing of valves [105]. These pressure spikes cause the flowing water column to undergo a sudden momentum change. This produces a shock wave that can cause physical damage to the system. This is why in large systems with high water pressures, it is procedure to start the pump while the discharge valve is closed. When the pump is at full speed, slowly the valve is opened starting the flow. Before the pump is stopped, the valve is closed. Starting and stopping a pump against a closed discharge valve and opening & closing it slowly will curb water hammer. Variable frequency drive (VFD) control is nowadays also used to stop water hammer. This is done by using the VFD control to slowly start and stop the motor and thus the pump. An alternative is to install water hammer arrestors. These are air-filled cylinders that absorb the shock of a sharp water pressure increase.

Added air
Adding air to a water jet has not been found to be in use beyond what was discussed in Chapter 3 regarding a system that uses a combination of a pulsating air and water jet [73]. Air is also used with a water gun on the floor of a hold that uses standard pressure water lines. The air pressure helps reach the high parts of the hold. However, in the current design a high-pressure pump is present, so using extra air is not necessary. Such a system also uses a large volume of water, so the air does not appear to save water. This is why adding air to the water is not investigated at this time. There are also many variables when designing and testing such a system, however it presents possibilities for further research.

5.3.2. Steps towards automation

This section will discuss how the equipment can be automated so that no people are directly involved with cleaning a hold. There are multiple steps towards automating the cleaning solution, these will be detailed next.

First step

At the moment the excavator needs to be manually decoupled from its lifting harness, which is used to lift it into the hold by the shore crane, so a person is needed in the hold. That means that one set of stairs needs to have been cleared and cleaned so the hold is accessible. If this is the case, it would not be troublesome to have a person in the cabin operating the machine. The controls of the pump would need to be routed to and mounted in the cabin, including start/stop, pressure control, status information, water level, and discharge valve control. At this step, the difference with the current operations is the way of cleaning, the damage done to the ship, and the speed of cleaning, since only the cleaning equipment is changed.

Second step

If a remote (de)coupling mechanism in the lifting harness is used to lift the excavator, e.g. similar to how automatic container cranes work, there are more options. See Figure 5.7 for a spreader that locks and unlocks automatically via a mechanical system when lifting and setting down a container. Fully electric spreaders with batteries are also available [106]. Such a system could be adapted to work with the CAT 329 excavator that is in use now at EMO, which at the moment has its own custom lifting frame. This way an excavator can be decoupled automatically (or remotely) without the need for people at the decoupling location.

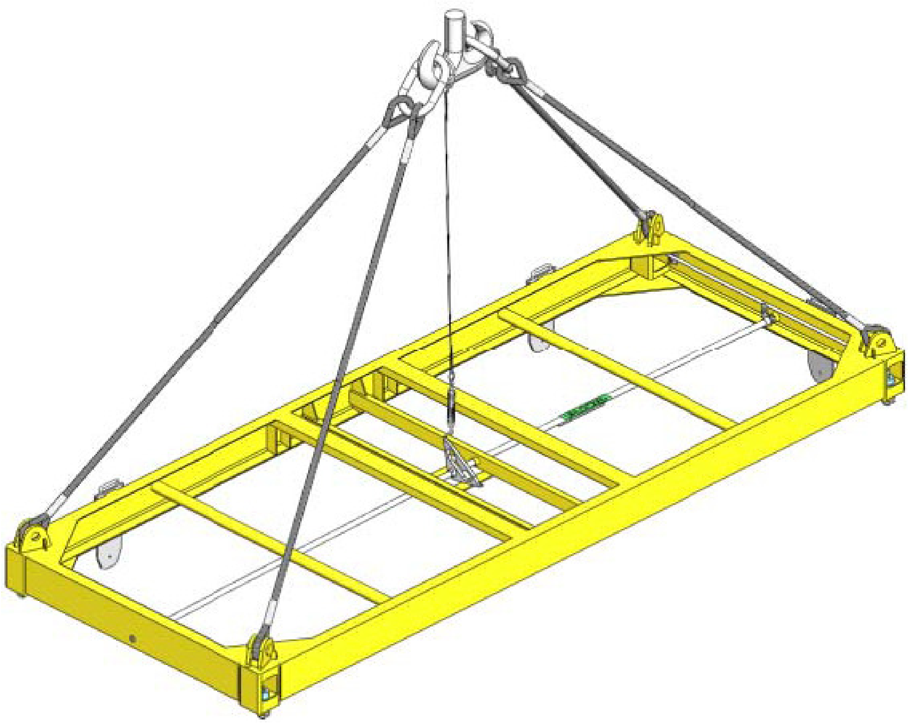


Figure 5.7: Mechanical automatic spreader [107]

This means that no personnel needs to be in the hold and thus that no stairs have to be cleaned. To operate the excavator the operator could be operating using a “command console” from the manufacturer on the deck of the bulk carrier so he has a direct line of sight, see Figure 5.8 [108]. This way, the goal of removing personnel from the hold can be achieved.

Figure 5.8: Remote control for excavators [108]

Such a remote control system has a range of up to 400 meters but does not require any on-site communications infrastructure. The drive-by-wire technology replaces mechanical inputs by an electrical system. So, the controls are fully integrated with machine electronics so the control and response time is the same if one is in the cab. The machine status information including engine rpm, fuel level, hydraulic temperature, engine temperature, and machine warnings are available through a display on the controller. If the controller is angled more than 45°, because the operator has fallen, the machine shuts down as a safety measure. This remote control system is available for select models of excavators and the control system can be retro-installed on certain existing machines.

Another option is to have a “command station” at a remote location, see Figure 5.9 [108]. It enables the operator to work remotely in a seated “virtual cab”. It can be located in a command center onsite or far away. The inputs are sent directly to the machine electronics via a dedicated radio transmitter/receiver, resulting in real-time control. It is claimed that such a system delivers the same response time as in the cab. Video delivers a clear view of the work area. It is available for select models of excavators and the control system can be retro-installed on certain existing machines. Other companies are also developing remote control technology for their machines including microphones to record machine sounds [109–111].

Figure 5.9: Remote control station for excavators [108]

Third step
The final step makes the equipment autonomous. It includes the setup of the previous steps: The cleaning equipment mounted on the excavator, an automatic spreader, and a remote control system for the excavator and pump system. The equipment can still be controlled directly, but for the cleaning of the hold no human input is necessary since a computer generates the control input necessary for operation.

If the system is automated this will have influences on multiple operational aspects such as speed, damage, and safety. The speed of the cleaning process depends very much on how the automation is implemented. It is possible that a computer is more efficient than a human with its movement and spray technique thanks to its controller. But it could also be that a human is quicker due to experience and insight that is difficult to program.

The damage done to a hold due to accidental contact is likely to be reduced, if the sensors and controller are robust and implemented correctly, because then the equipment will not touch the walls of the hold. However as discussed earlier the stevedores (mis)use the equipment so that the time spent cleaning a hold is minimized, even though this causes damage to the equipment and the hold. This would not happen with a controller that operates with strict parameters which set a minimum distance so no contact is made.

Automation also has the potential to increase the safety of the stevedores. This is achieved by not needing personnel in the hold to operate the excavator. However, the cleaning process of a hold uses two machines: An excavator and a front loader. If the front loader is operated by a person in the cabin, this has risks due to the interaction of the vehicles. A similar situation can occur if a person needs to be in the hold while the automated excavator is running, then the excavator can harm the person. This can be avoided by implementing robust safety features. These can consist of using the sensors on the excavator to avoid obstacles such as other machines and/or people for example. Another feature is an emergency stop that shuts the excavator down and can at any time be operated by someone.

Determining what part of the hold needs to be cleaned and what part does not, is not easy. Ground-penetrating radar is possible to use to determine where the cargo ends and where the hold wall begins. However, this is would only be usable with coal and not for iron ore since that is a conductive material which is a limitation of ground-penetrating radar. Optical object recognition might work, but has difficulties such as water in the air, dirty cameras, camera angles, lighting conditions, and surfaces that are difficult to differentiate.

Scanning a hold to determine where the walls are, seems to be an easier solution. This can only be done when a hold is completely empty, so the ship first needs to be emptied. Then a 3D scan can be made of the hold and the scan be cleaned up, because there are probably errors in the model. EMO filters out bad data using algorithms using for example the angle of repose of a material and the fact that there can not be empty space underneath measured points when scanning the cargo in a hold. This process would need to be done for every single ship, because the geometry in a hold is different in almost every ship. Then the next time that the ship docks at EMO the scan of the empty hold can be used to determine where the machine should aim the jet and where there is no bulk material. This would be done by combining the scan data with positional data from the excavator. This all means that a ship can only be cleaned on autopilot the second time that it docks, which translates to a long startup period for an automation process.

Radar is being used underground to accurately position equipment in the mining industry, so that could be used to position an excavator in a hold [112].

RTK base stations can be used to improve the accuracy offered by a GNSS. It is used to provide real-time corrections to achieve centimeter-level accuracy. In the middle of a hold the visible section of the sky is limited, which makes getting line-of-sight to satellites more difficult. However there are a large number of satellites nowadays, so this might not be a problem [113].

Local positioning systems are also used in places where GNSS systems do not reach such as inside. This system uses beacons with a limited range of which the position is known exactly. Then another device uses these beacons to determine its own position. This relative position combined with the global location of the beacons provides accurate location information. Such as system could be placed around the opening into the hold to improve the positioning information.

There are problems to be overcome in the automation process. The movement in the machine itself, since it and its connection to the ground are not infinitely stiff, should be accounted for in the programming. There is also the possibility of wet coal and water splashing back towards the machine because of the water jet. This material will get onto the windscreen of the cabin and sensors impeding visibility, the degree depending on the type of sensor used. Integrating a wiper system is possible, but would add complexity.

5.4. Conclusion

The question that this chapter has answered is the following: What is the new concept design? To choose the design a multi-criteria analysis was done where a selection of the best concepts was made. From these the final prototype concept was chosen, an excavator with a water tank and high-pressure pump mounted on the back and a nozzle at the end of an attachment. This attachment is attached via a coupling to the excavator's arm. Also, the steps towards an automated design are detailed, including automatic (de)coupling, remote control, and autonomous operation.

6
Concept testing

In this chapter, the chosen concept will be tested. This includes the testing motivation and methodology. After that, the results of the tests are shown and interpreted.

6.1. Test motivation

Until this point all the research and design towards a solution has been theoretical. Now we want to know the practical performance of using high-pressure water jetting for cleaning holds. There are multiple things that are interesting to know before continuing towards a practical implementation. These are the impact of the water jet, if the water jet does damage to a hold, how fast it cleans, and how it is influenced by the pressure, standoff distance, and nozzle type. These things will be measured in 3 series of tests which are outlined in the following section. The impact test is a quick way to determine what the influence is of pressure, standoff distance, and nozzle type on the imparted force on the material that needs to be removed. The damage test is necessary to see if this method of cleaning damages the hold. If that is the case, a cost-benefit analysis can be done to determine if the concept is a net positive. Lastly, the cleaning speed test will show how well the different variations of the concept clean the material. It is not possible to use an actual hold, due to the operational schedule, to test the real-world cleaning performance. So this test will only give an indication towards that, and furthermore provide information on the influence on performance by variables such as standoff distance and nozzle type. And while the tests will be done with a CAT 329 excavator, there will be no real test to evaluate the “reaching” function of the concept, instead focussing on the “cleaning” function.

6.2. Test setup

This section will show the test setup and methodology that is used. This includes the general parts of the test and all the specifics of the 3 test categories.

6.2.1. General setup

In Figure 6.1a the excavator attachment is shown. Apart from the standard geometry so that it can be attached to an excavator, its shape is not important for this test. A rigid pipe is mounted to it which can be connected to a standard 3/8” high-pressure hose. On the other end different nozzles can be attached. The setup is not identical to the concept design as shown in Chapter 5, however the function during the tests is the same. So the choice was made to use a simple setup for testing with minimal construction complexity. In Figure 6.1b the excavator with attachment is shown. In Figure 6.1c the high-pressure pump with its water tank is shown. The capacity is approximately 100 l and is filled with tap water and not the “working water” that EMO often uses. If it would be filled with the “working water” filters would be needed since this water is quite dirty and can cause congestion or damage to the pump. The pump unit is located on a trailer so that it can be placed nearby. It connects with a hose to the pipe on the attachment. In Figure 6.1d the pressure gauge of the pump is shown. The pressure is regulated by opening and closing the throttle of the diesel engine that drives the pump.

(a) Excavator attachment with a nozzle

(b) CAT 329 excavator used for testing

(c) High-pressure diesel pump

(d) Pressure gauge on the pump

Figure 6.1: The general components of the testing setup

A standoff distance of 1, 2, and 3 m was initially the plan, so that also the rear side of a spiral staircase can be cleaned without having to maneuver the nozzle between the railings. However, before the start of testing it became apparent that at that distance the water jet has lost a lot of its power. Also, the arm of the excavator could not be positioned vertically and still have a distance of more than 1.5 m. Since typical standoff distances when high-pressure cleaning are also smaller, the choice was made to test at 0.5, 1, and 1.5 m distance.

Another thing that was changed from the original test plan is the pressure. This was planned to be tested at working pressures of 150, 200, and 250 bar. The pump that was available however could, depending on the nozzle, only produce a pressure of 180 bar. So the pressures at which the test was done, were changed to 100, 140, and 180 bar.

There are 3 different nozzle types used. Nozzle 1, see Figure 6.2a, is just a round hole that generates a tight round jet of water. It has an opening of 1.52 mm. In Figures 6.2b and 6.2c the nozzle can be seen in action. It hits a small surface, but it seems that little of the water is blown away in the wind.

(a) Nozzle close-up

(b) Nozzle in action side view

(c) Nozzle in action top view

Figure 6.2: Nozzle 1 detail and jet shape

Nozzle 2, see Figure 6.3a, is also a round hole, but the exit has a sort of slit. That generates a planar jet of water that has an internal angle of 15°. It has an opening of 2.05 mm. In Figures 6.3b and 6.2c the nozzle can be seen in action. It hits a wider surface, but it also seems that some of the water is not in the core water jet and loses its energy.

(a) Nozzle close-up

(b) Nozzle in action side view

(c) Nozzle in action top view

Figure 6.3: Nozzle 2 detail and jet shape

Nozzle 3, see Figure 6.4a, is a special nozzle that a ball with a hole in it that rotates when water flows through it. This generates a cone of water that has an internal angle of 20°. The opening diameter when measured is 1.7 mm. In Figures 6.4b and 6.4c the nozzle can be seen in action. It hits a wide surface, but it also seems that the water is more of a mist than a jet, and that it loses much of its energy.

(a) Nozzle close-up

(b) Nozzle in action side view

(c) Nozzle in action top view

Figure 6.4: Nozzle 3 detail and jet shape

The experimental plan included a flow meter in the water line, so that it could be measured directly, but this is not available. However, there is a datasheet that gives the maximum volume flow for various pressures for the different nozzles. This data is plotted in Figure 6.5. For nozzles 1 and 2 all the visible data points are directly from the manufacturer, however for nozzle 3 only the volume flow at 200 bar is available. Since the shape of the curve for nozzles 1 and 2 are very similar, the choice is made to give nozzle 3 a similar curve. This is done by using the relative position of the single data point of nozzle 3 at 200 bar, between the data points of nozzles 1 and 2 at that same pressure. Then generating data points for every other pressure at the same relative position (at 34% of the vertical distance between nozzle 1 and nozzle 2) for nozzle 3. The trendline function in Excel is used to generate a formula for the curves of the nozzles, with a fit quality of $R^2 > 0.99$. This formula is then used to generate data points at 180 bar, since the data only specifies 175 and 200 bar. The same power value of the formulas confirms the similarity of the curves of nozzles 1 and 2.

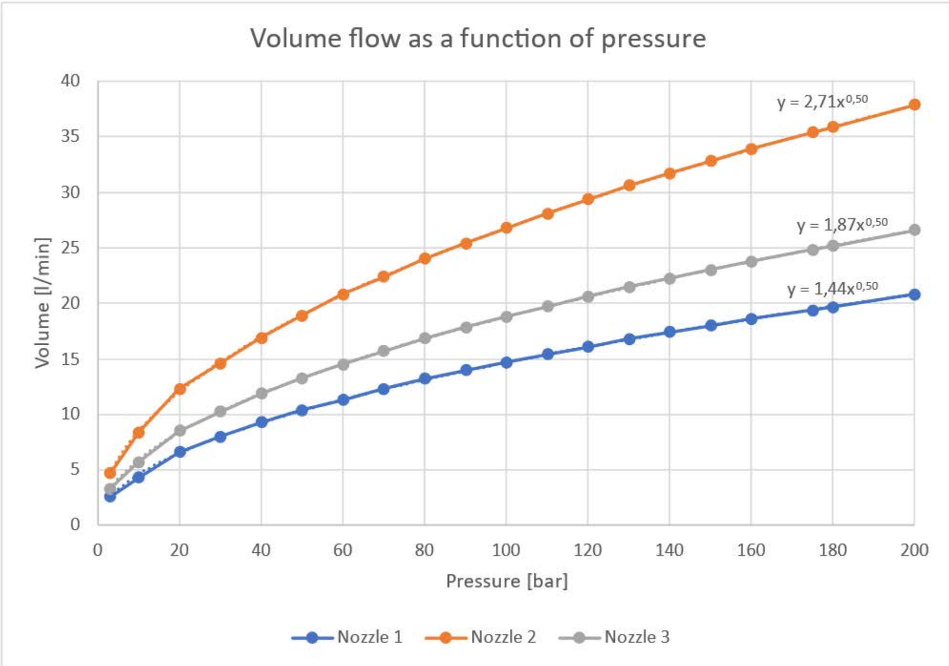


Figure 6.5: The volume flow through the different nozzles at different pressures. Nozzle 3 is extrapolated data.

6.2.2. Impact test

To measure the impact of the water spray, the following setup is used as seen in Figure 6.6. In Figure 6.6a on the left is the force sensor, in the middle is the analog signal conditioner and on the right is the data acquisition device (DAQ). Not shown is the laptop that is connected to receive the digital signal from the DAQ via USB. The signal conditioner also needs to be connected to mains electricity, which was not available on location, so a large diesel generator is used that supplies 230 V power. The force sensor is a Phidgets CZL301 S type load cell [114], which has a maximum capacity of 500 kg, but has been calibrated up to 1000 N or 100 kg by the measuring department of the 3ME faculty of the TU Delft. According to this department the accuracy of the load cell is one-thousandth of its measuring range, which with this calibration means 1 N. The ADC is a National Instruments USB-6002 [115], and the signal conditioner is a Scaime CPJ [116].

In Figures 6.6b and 6.6c the test setup is shown. The load cell is mounted to a steel table with W x L x H dimensions of 1000 x 1100 x 550 mm with an M12 bolt. On top of the load cell a 580 x 580 x 2 mm steel interface plate is mounted also with an M12 bolt.

(a) Measuring electronics

(b) Load cell mounted between a table and a plate

(c) Table with the force measuring plate

Figure 6.6: Impact measuring setup

The 3 nozzles are tested at a distance of 0.5 m, 1 m, and 1.5 m. This distance is determined with a measuring tape. The tests are done at pressures of 100, 140, and 180 bar for nozzles 1 & 2. The pump could only create a pressure of 170 bar when using nozzle 3, so a pressure of 100, 140, and 170 bar is used in this case.

The excavator attachment is lifted vertically above the plate that is mounted to the load cell, and the water jet is centered on the plate by eye. The water jet is maintained for approximately but at least 10 seconds during which the load cell output is measured. Every 100 ms a data point is saved, resulting in 110 to 140 data points. To zero the data later, 10 seconds of data is gathered of only the weight of the plate without a water jet. The average value of this measurement can then be subtracted from the data that is measured during jetting, giving the net impact force.

(a) Testing with nozzle 1 (b) Testing with nozzle 2 (c) Testing with nozzle 3

Figure 6.7: Jetting on the measuring plate during impact testing

6.2.3. Damage test

This test is meant to evaluate the damage done by a water jet to the paint of a hold. This is done by using a water jet on a painted surface and measuring the thickness of that paint layer. Before the jetting, the control thickness of the layer of paint is measured. This is done with an ultrasonic thickness gauge as seen in Figure 6.8a. The measuring of the layer is done in 3 locations, to give an average value.

The water jet is aimed at a painted steel plate that lies on the ground, see Figure 6.8b, the paint is a typical heavy-duty outdoor type paint that is used at EMO. The 3 nozzles are tested at a distance of 0.5 m, 1 m, and 1.5 m. This distance is determined with a measuring tape. The test is done only at 180 bar (170 bar for nozzle 3), since that would be most likely to damage the paint. If there is negligible damage at that pressure, lower pressures should also be fine. If there is significant damage, then it can be considered to use a lower pressure, although that might make the cleaning a longer process.

During 10 seconds the plate is subjected to the water jet, after which the layer thickness is measured again to see if the layer is thinner. Then the distance is decreased from 1.5 m to 1 m, to increase the chance of damage. The thickness is measured again and the distance is decreased a final time to 0.5 m and the layer thickness is measured a final time. This process is repeated for every nozzle, which are all tested on a new and identical plate.

(a) Positector 6000 ultrasonic layer thickness gauge [117]

(b) Jetting on the painted plate during damage testing

Figure 6.8: Damage testing setup

6.2.4. Speed test

This test is done to see the relative speed of cleaning using different nozzles and distances. The 3 nozzles are tested at a distance of 0.5 m, 1 m, and 1.5 m. This distance is determined with a measuring tape. The test is done only at 180 bar (170 bar for nozzle 3), because that pressure would most likely give the shortest cleaning times.

Doing the test in an actual hold in a docked bulk carrier is not possible due to tight scheduling at EMO, so an alternative is used. On the EMO terrain there is a low sheet pile wall with roughly the same shape as the separating wall between holds, see Figure 6.9a. The filled sections of the sheet pile wall have L x H x W dimensions of 800 x 800 x 300 mm approximately. They are filled with a mixture of coal and iron ore. This is material that has accumulated over time and seems to have been quite compacted. Every pressure & nozzle combination is used to clean one section of the sheet pile wall, the time this takes is measured. The excavator (and its attachment) is moved by an operator so that the whole section is hit with the water jet. However not every section is filled identically which is a problem regarding the reliability of the results.

(a) Filled sheet pile wall section

(b) Excavator using the jet attachment to clean a sheet pile wall section

Figure 6.9: Speed testing setup

In Figure 6.10 the tests using nozzle 1 are shown, in Figure 6.11 the tests using nozzle 2 are shown, and in Figure 6.12 those of nozzle 3 are shown.


(a) 0.5 m distance


(b) 1 m distance


(c) 1.5 m distance

Figure 6.10: Speed tests using nozzle 1 at various distances


(a) 0.5 m distance


(b) 1 m distance


(c) 1.5 m distance

Figure 6.11: Speed tests using nozzle 2 at various distances


(a) 0.5 m distance


(b) 1 m distance


(c) 1.5 m distance

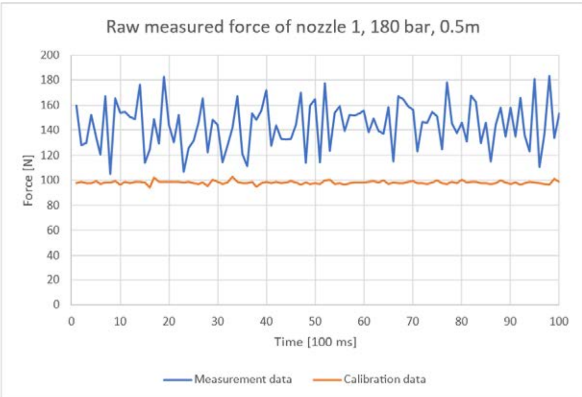
Figure 6.12: Speed tests using nozzle 3 at various distances

6.3. Test results

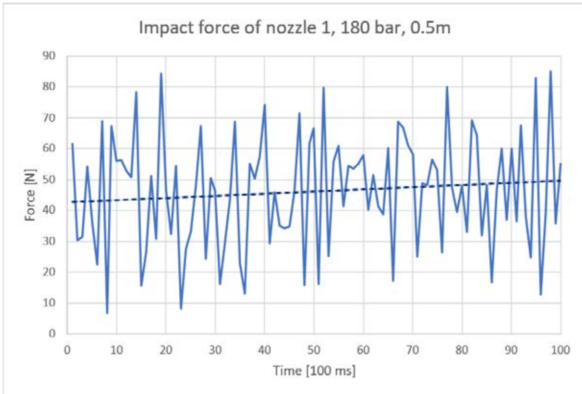
In this section the results of the tests are shown. Also, the results will be discussed and a calculation done for the cleaning time of an entire hold.

6.3.1. Impact test results

In Figure 6.13a the measured impact force over time of nozzle 1 at a pressure of 180 bar at 0.5 m distance is plotted. In the same figure is the calibration measurement of the setup plotted, this is only the weight of the test setup without any water. It can be seen that the calibration signal has much less variance than the measurement using water, so the variance is a physical property of the interaction of the water jet with the interface plate. In Figure 6.13b the actual impact force, which is the measured forces minus the average calibration value, is plotted. Here the relative size of the variation becomes much larger, however because it seems to be a characteristic of the physical system, this should not be a problem.



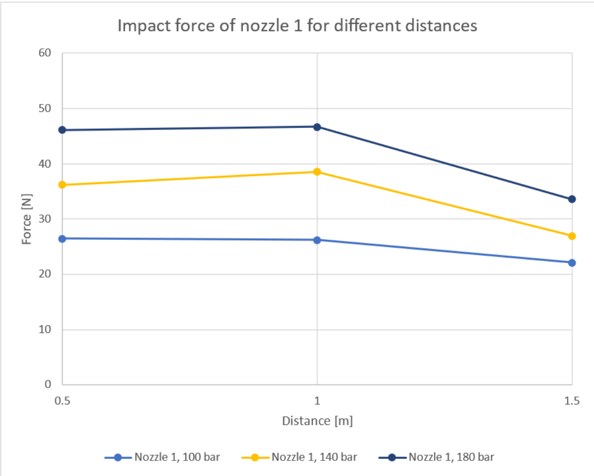
(a) The raw measured impact force over time of nozzle 1, 180 bar at 0.5 meter.



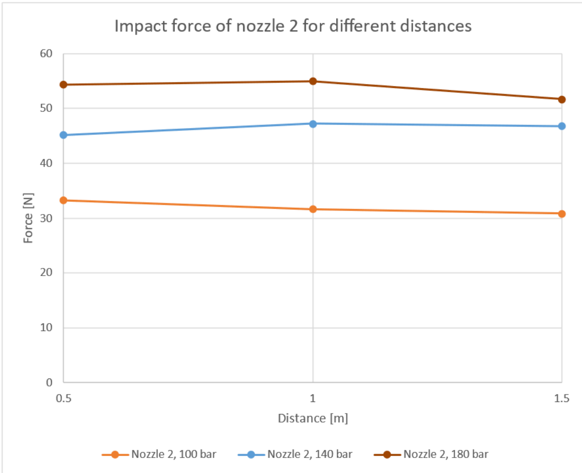
(b) The impact force over time of nozzle 1, 180 bar at 0.5 meter corrected for the weight of the setup. The trendline is also plotted

Figure 6.13: The measured impact force and the net impact force. The time between measurement points is 100 ms, the total measured time is 10 s.

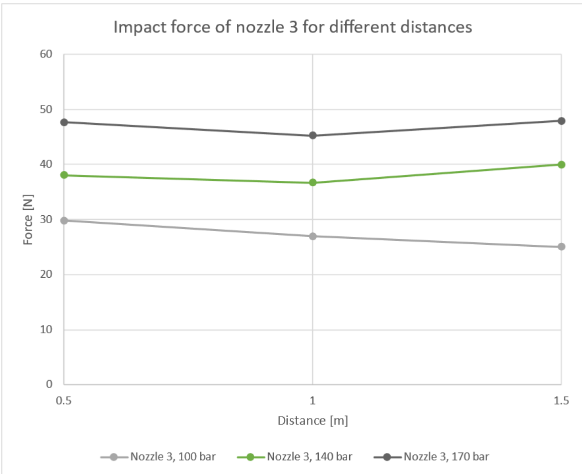
In Figure 6.14 the average impact force is plotted against the standoff distance. This is done for nozzles 1, 2, and 3. It can be seen in Figure 6.14a that there is very little difference in the force between 0.5 m and 1 m using nozzle 1. However, at 1.5 m the force decreases, more so for 140 and 180 bar. In Figure 6.14b there is a slight downward trend for increasing distance when using nozzle 2, but at 140 bar the maximum force is at 1 m. In Figure 6.14c when using nozzle 3 at 140 and 170 bar there is a minimum at 1 m. However, at 100 bar the data trends only downwards for increasing distance.



(a) Average impact force when using nozzle 1 at various standoff distances



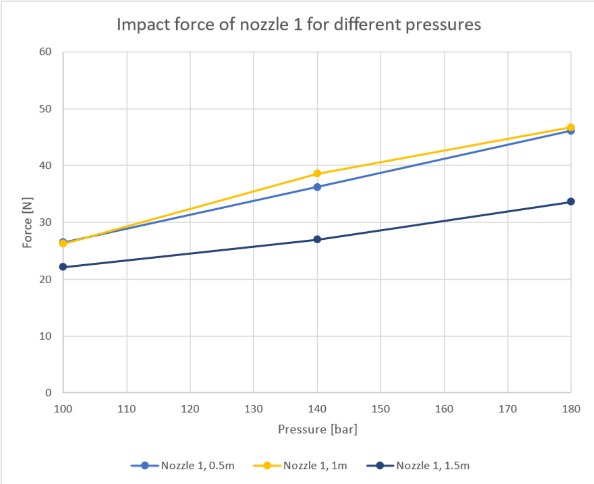
(b) Average impact force when using nozzle 2 at various standoff distances



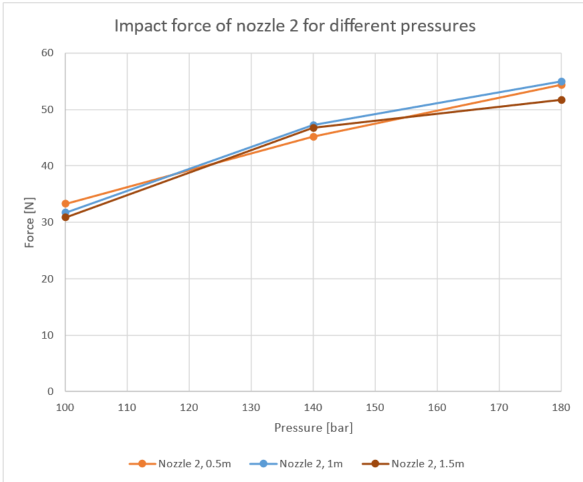
(c) Average impact force when using nozzle 3 at various standoff distances

Figure 6.14: The average impact force for the different nozzles plotted against the standoff distance

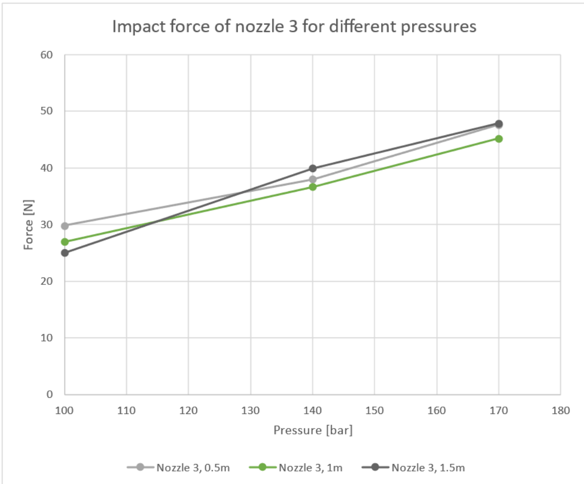
In Figure 6.14 the average impact force is plotted against the working pressure. This is done for nozzles 1, 2, and 3. In Figure 6.15a, 6.15b and 6.15c the impact force always trends upwards for increasing pressure. In most cases this seems pretty linear, so the force increases almost proportionally with the working pressure, lagging a little bit. The line of nozzle 2 flattens a bit between 140 and 180 bar, indicating a deviation from this linear relationship.



(a) Average impact force when using nozzle 1 at various pressures



(b) Average impact force when using nozzle 2 at various pressures

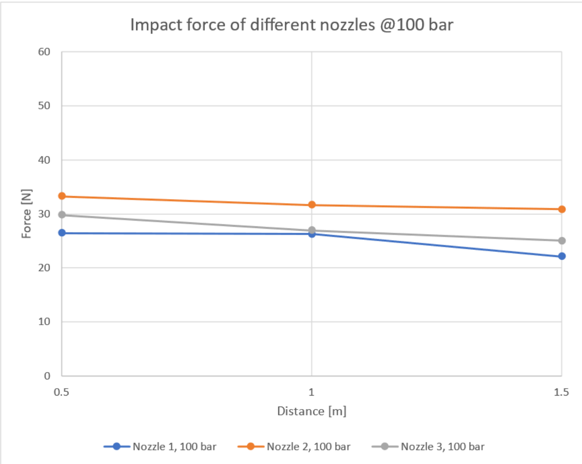


(c) Average impact force when using nozzle 3 at various pressures

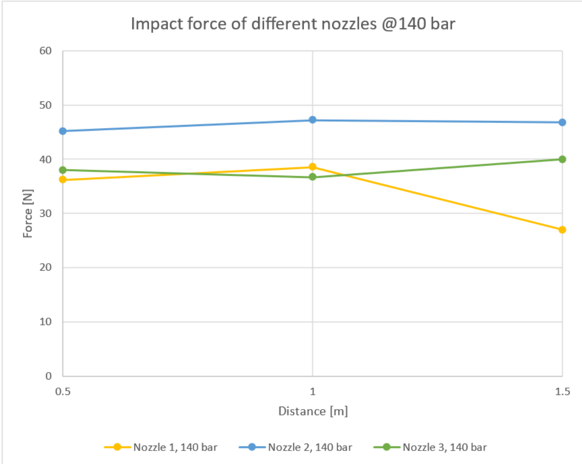
Figure 6.15: The average impact force for the different nozzles plotted against the pressure

In Figure 6.16 the differences in impact force between the different nozzles are shown. In Figure 6.16a, 6.16b and 6.16c this is done by plotting against the distance at a certain pressure.

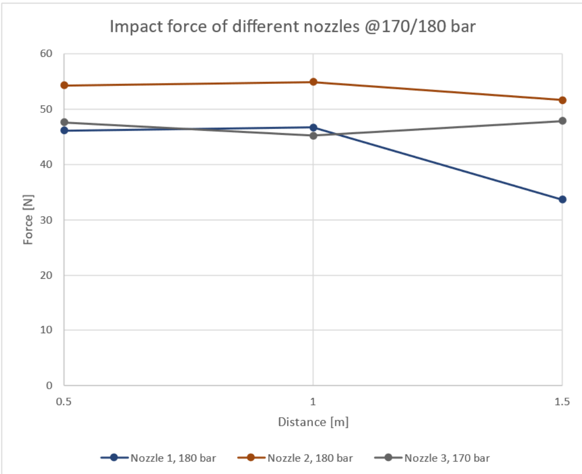
In Figure 6.16a it can be seen that nozzle 2 has the largest force at all distances at 100 bar, with nozzles 1 and 3 having similar results. In Figure 6.16b nozzle 2 again has the largest force at all distances at 140 bar. At 0.5 m and 1 m nozzles 1 and 3 are also again very similar, but at 1.5 m the force of nozzle 1 drops sharply. In Figure 6.16c at 170/180 bar the results are very similar to the last figure.



(a) Average impact force when using different nozzles at 100 bar



(b) Average impact force when using different nozzles at 140 bar

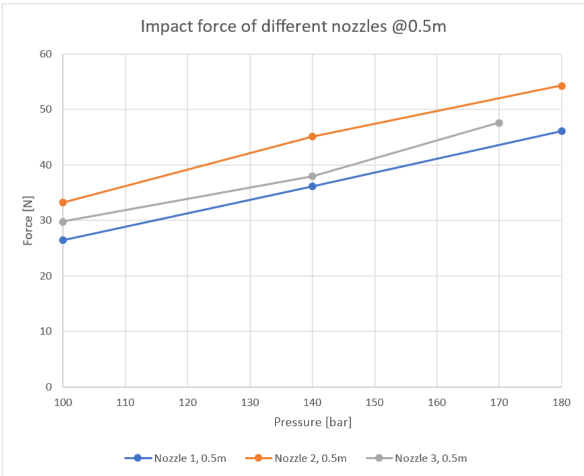


(c) Average impact force when using different nozzles at 170/180 bar

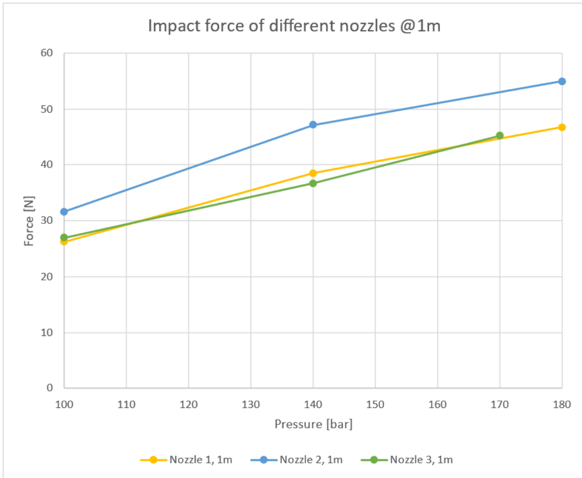
Figure 6.16: The average impact force for the different nozzles plotted against the distance

In Figure 6.17 the differences in impact force between the different nozzles are shown. In 6.17a, 6.17b and 6.17c this is done by plotting against the pressure at a certain distance. See also Appendix B for the combined complete graphs of the impact force.

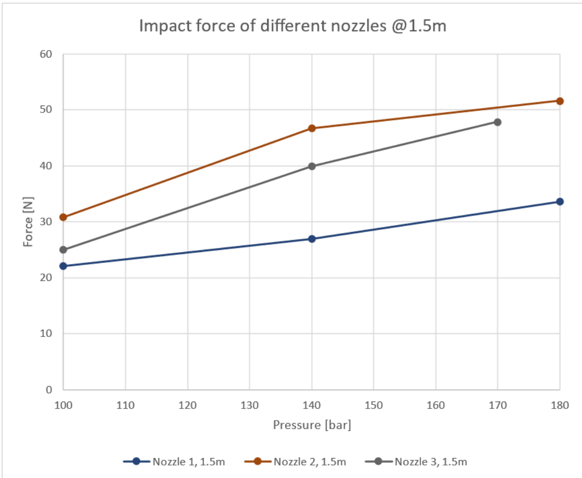
In Figure 6.17a nozzle 2 again generates the largest force at 0.5 m. Nozzles 1 and 3 are close together, but nozzle 3 does have larger measured force. In Figure 6.17b nozzle 2 has the largest force again, with nozzles 1 and 3 very close together. And lastly in Figure 6.17c nozzle 2 has the largest force, with nozzle 3 a close second and nozzle 1 with the smallest force.



(a) Average impact force when using different nozzles at 0.5 meter



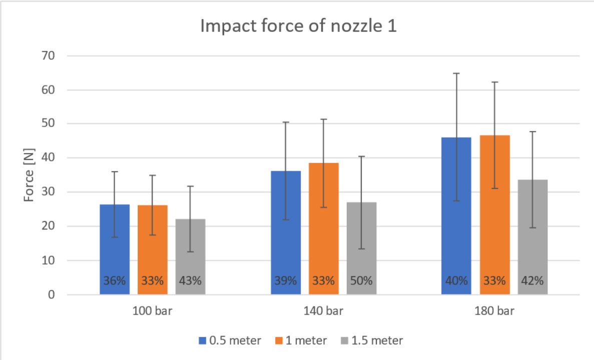
(b) Average impact force when using nozzle 2 at 1 meter



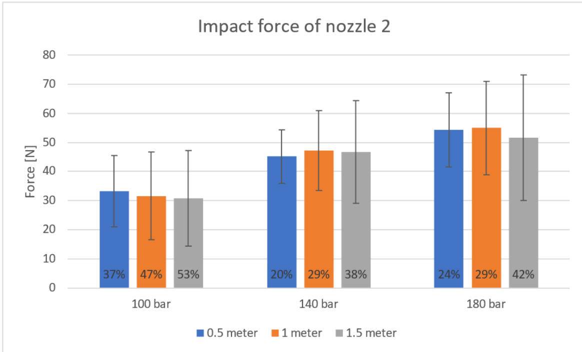
(c) Average impact force when using nozzle 3 at 1.5 meter

Figure 6.17: The average impact force for the different nozzles plotted against the pressure

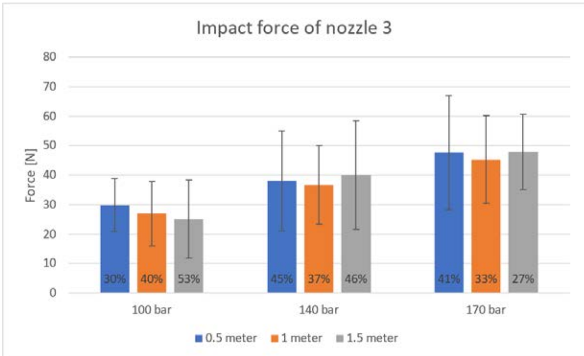
In Figure 6.13 was visible how the measured force fluctuated, this fluctuation will now be quantified. In Figure 6.18 the standard deviation of a sample set of data is plotted using the “n-1” method. It can be seen that there is a large degree of uncertainty, especially since many measured values are relatively close together. Further, at higher pressures the standard deviation generally increases, but not as a percentage of the average value. That percentage does often increase for larger standoff distances.



(a) Average impact force when using nozzle 1 at various standoff distances



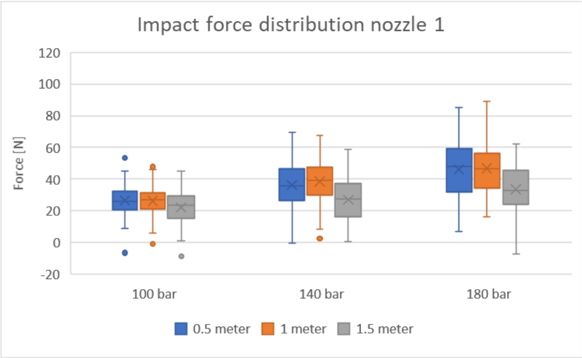
(b) Average impact force when using nozzle 2 at various standoff distances



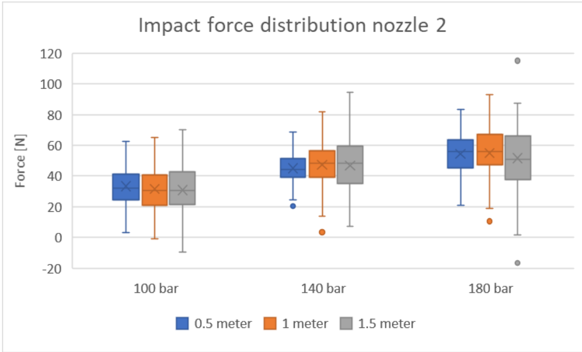
(c) Average impact force when using nozzle 3 at various standoff distances

Figure 6.18: The average impact force and standard deviation of a sample for the different nozzles. Also shown is the percentage of the average value that the standard deviation is

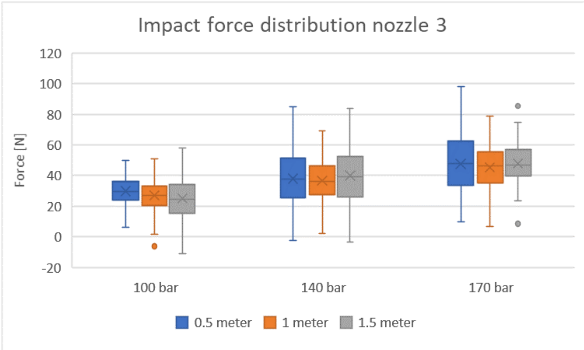
In Figure 6.19 Box and Whisker plots are shown. These further detail the distribution of the data points. They show the median, lower and upper quartiles, extremes, and outliers of the data.



(a) Distribution of the force data of nozzle 1 at various standoff distances



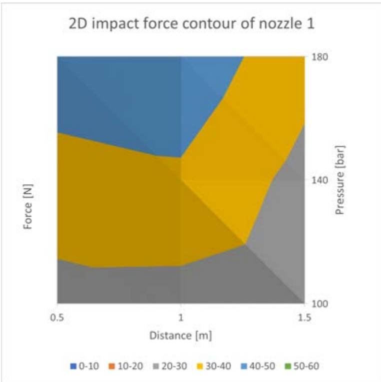
(b) Distribution of the force data of nozzle 2 at various standoff distances



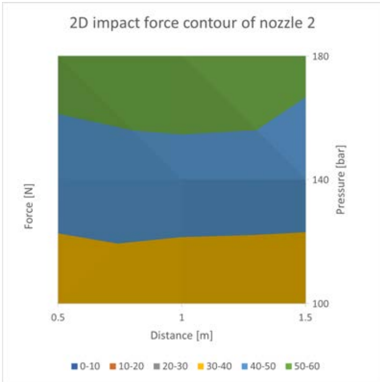
(c) Distribution of the force data of nozzle 3 at various standoff distances

Figure 6.19: Box and Whisker plot of the force measurements showing the distribution of the data. It shows the median, quartiles, extremes, and outliers. n1=nozzle 1, p100=100 bar, x0.5=0.5 meter, etc

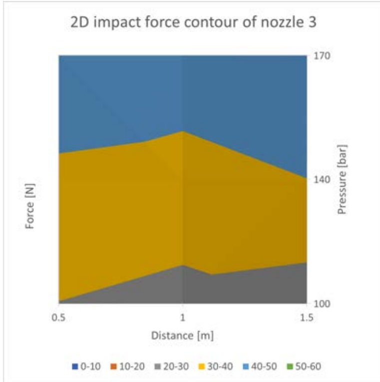
The testing was done as a full factorial experiment, where multiple factors that have possible values, are tested in all possible combinations of all these values. Response surfaces can be plotted to explore the relationship between the factors or variables, and can show optimal outcomes for specific variable values. In this case the relationship is between the distance, working pressure, and the nozzle type, resulting in the largest impact force. In Figure 6.20 3D response surfaces, and the corresponding 2D contours, of the nozzles are plotted. The two variables are the distance and the working pressure. It can be seen that the maxima are on the edges and corners. This indicates that higher forces can be generated by expanding the range of the variables, the standoff distance, and the pressure. Further, there does not seem to be a definite relationship between the distance and the pressure. At 0.5 m, 1 m, and at 1.5 m the relative increase in the impact force is the same. The distance seems to have a steeper slope at higher working pressures using nozzle 1. This means that at 180 bar the relative difference in impact force between 0.5 m and 1.5 is larger than at 140 bar. This does not hold for nozzles 2 and 3.



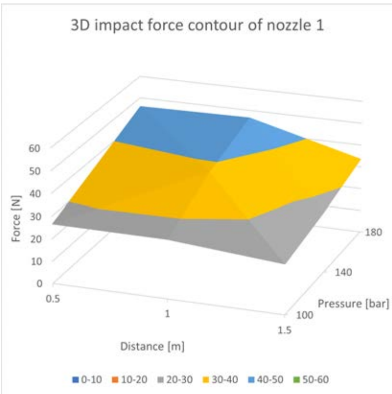
(a) 2D impact force contour of nozzle 1



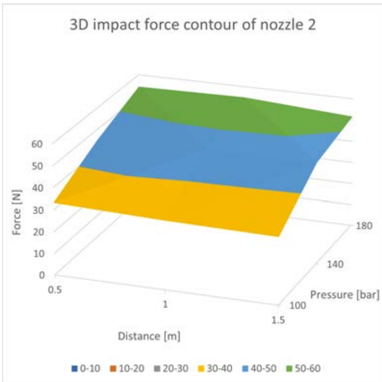
(b) 2D impact force contour of nozzle 2



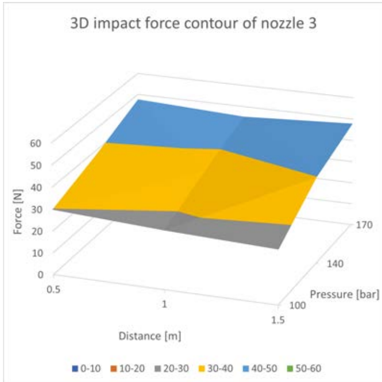
(c) 2D impact force contour of nozzle 3



(d) 3D impact force contour of nozzle 1



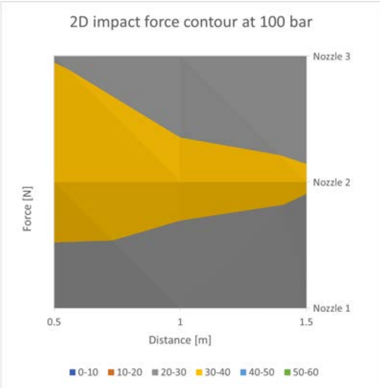
(e) 3D impact force contour of nozzle 2



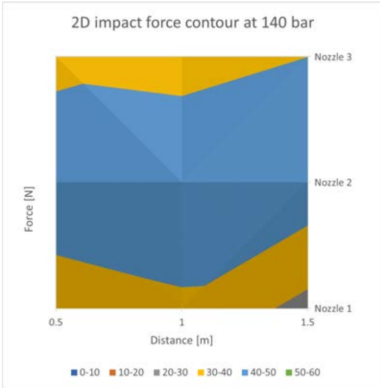
(f) 3D impact force contour of nozzle 2

Figure 6.20: Impact force contours of the nozzles based on the distance and pressure

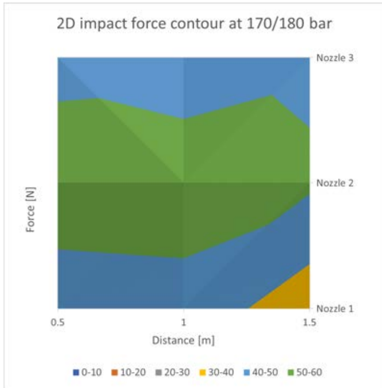
Figure 6.21 shows the contours at a certain pressure, with the variables being the nozzle type and the standoff distance. At 1.5 m only nozzle 1 has a relatively sharp unexplained drop, but further there seems no connection between the nozzle type and the distance on the force. The impact force slope caused by the distance has the same angle for every nozzle.



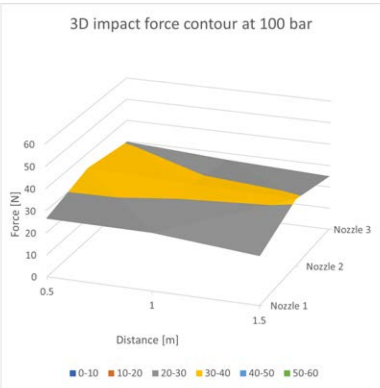
(a) 2D impact force contour at 100 bar



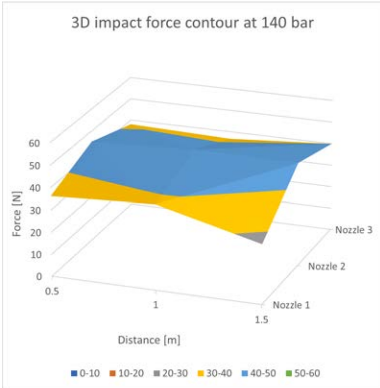
(b) 2D impact force contour at 140 bar



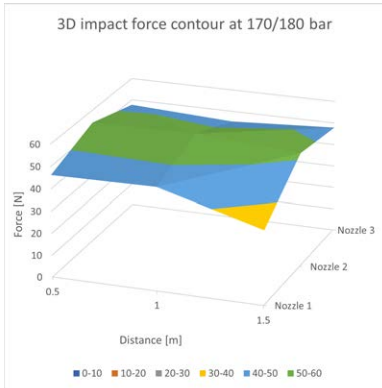
(c) 2D impact force contour at 170/180 bar



(d) 3D impact force contour at 100 bar



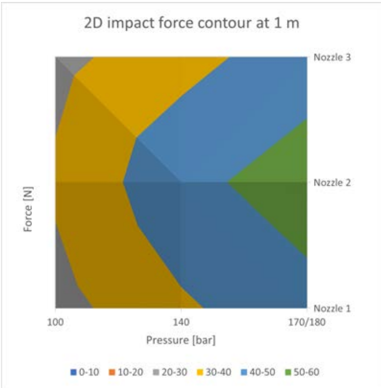
(e) 3D impact force contour at 140 bar



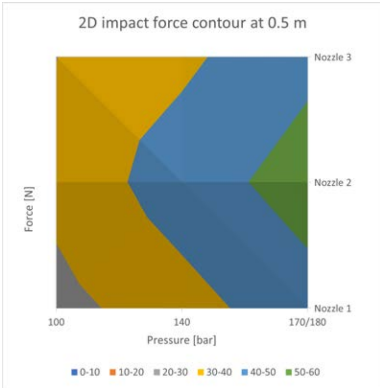
(f) 3D impact force contour at 170/180 bar

Figure 6.21: Impact force contours at a certain pressure based on the nozzle type and distance

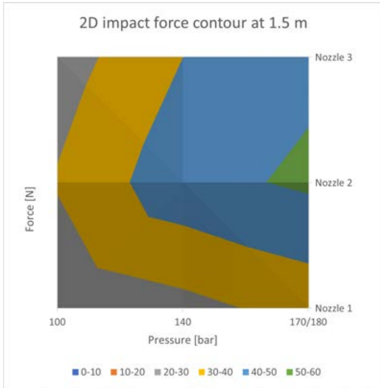
Figure 6.22 shows the contours at a pressure, with the variables being the nozzle type and the distance. Also here seems to be no connection between the nozzle type and the pressure. The relative difference of the impact force between working pressures is the same for every nozzle. This means that an increase of the working pressure has the same effect on the impact force for every nozzle. Also, there is no clear effect of the working pressure on the relative difference of the impact force between the nozzles. So, the relative difference in impact force between the nozzles is the same at every working pressure.



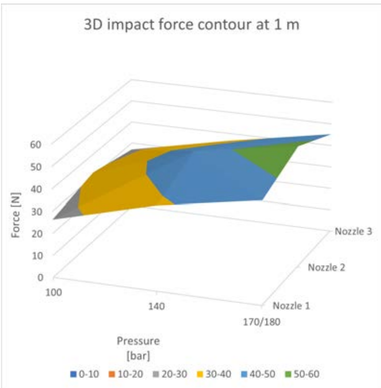
(a) 2D impact force contour at 0.5 m



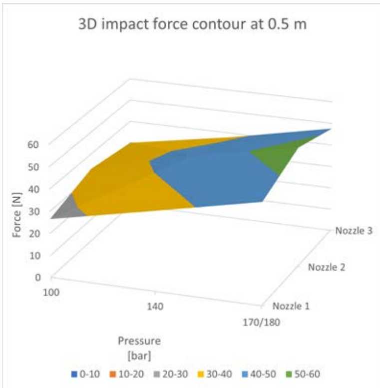
(b) 2D impact force contour at 1 m



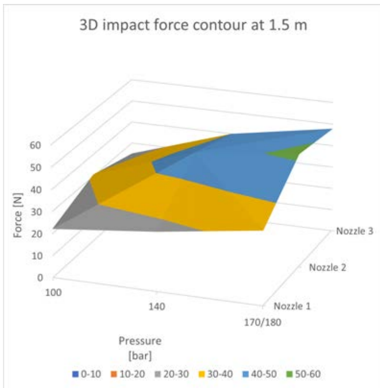
(c) 2D impact force contour at 1.5 m



(d) 3D impact force contour at 0.5 m



(e) 3D impact force contour at 1 m



(f) 3D impact force contour at 1.5 m

Figure 6.22: Impact force contours at a certain distance based on the nozzle type and pressure

Impact pressure

Only looking at the impact force does not paint a complete picture. When a greater standoff distance is used, the force seems to largely remain the same. This force is however spread over a larger area due to the internal angle of the water jet and the angle of the spray pattern. This means that the pressure of this impact, the force divided by the area, decreases. To calculate the impact pressure of the water the impact force and the impact area are necessary. The force is already known, the area will be calculated now.

The internal angle α of the jet from nozzle 1 has been measured digitally from a photo to be 1°. This same angle is used for the core water jet of nozzles 2 and 3 to determine the width of the jet at a certain distance x. The angle β is the internal angle of the spray pattern of nozzles 2 and 3. The nozzle diameter is d, and the diameter of the jet at impact is D. The length and diameter of the pattern of nozzle 2 and 3 respectively is L.

- $d_i = nozzle\ diameter = 1.52\ mm/2.05\ mm/1.70\ mm$
- $D_i = jet\ diameter$
- $L_i = jet\ impact\ pattern\ length/diameter$
- $\alpha = jet\ angle = 1°$
- $\beta_j = jet\ pattern\ angle = 15°/20°$
- $x = standoff\ distance = 0.5\ m/1.0\ m/1.5\ m$

Equation 6.1 is used to calculate the diameter of the jet at impact. This is illustrated in Figure 6.23. The index i is used to denote the nozzle number. Equations 6.2, 6.3 and 6.4 are specific for the various nozzles.

$$\tan\left(\frac{\alpha}{2}\right) = \frac{\frac{D_i}{2} - \frac{d_i}{2}}{x} \Rightarrow x\tan\left(\frac{\alpha}{2}\right) = \frac{1}{2}(D_i - d_i) \Rightarrow D_i = 2x\tan\left(\frac{\alpha}{2}\right) + d_i\ for\ i = 1,2,3 \tag{6.1}$$

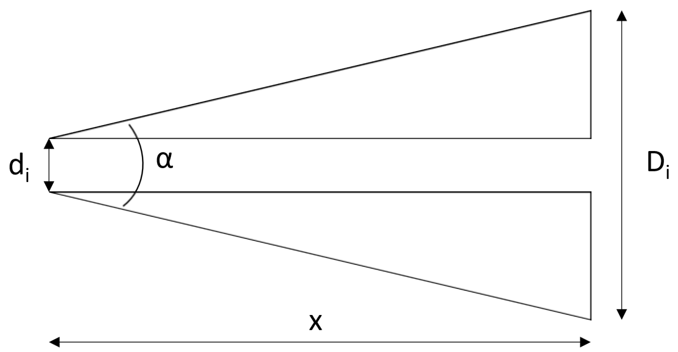


Figure 6.23: The core water jet profile. Note: Figure is not to scale

$$D_1 = 2x\tan\left(\frac{\alpha}{2}\right) + d_1 \tag{6.2}$$

$$D_2 = 2x\tan\left(\frac{\alpha}{2}\right) + d_2 \tag{6.3}$$

$$D_3 = 2x\tan\left(\frac{\alpha}{2}\right) + d_3 \tag{6.4}$$

The impact area of nozzle 1, which is a simple circle, is described by equation 6.5. This is also illustrated in Figure 6.24.

$$A_1 = \frac{1}{4}\pi D_1^2 \tag{6.5}$$

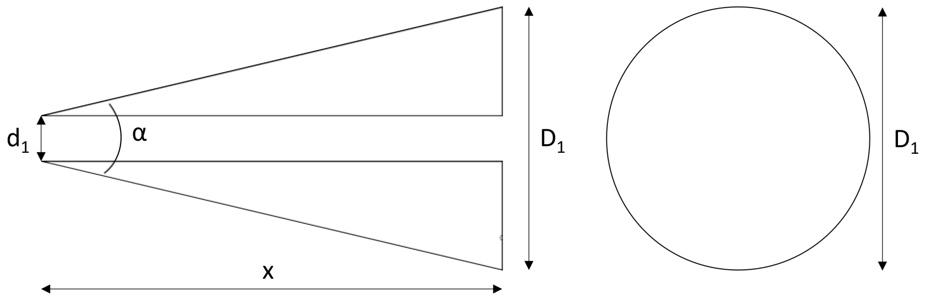


Figure 6.24: The impact pattern of nozzle 1. Note: Figure is not to scale

This impact pattern of nozzle 2 is illustrated in Figure 6.25. This is a rectangular impact pattern, where the width is the jet diameter D_2 and the length is calculated from the jet pattern angle. Equation 6.6 describes the length of the line pattern of nozzle 2 (and the outer diameter of the circle of nozzle 3). For nozzles 2 and 3 this translates to equations 6.7 and 6.8 respectively.

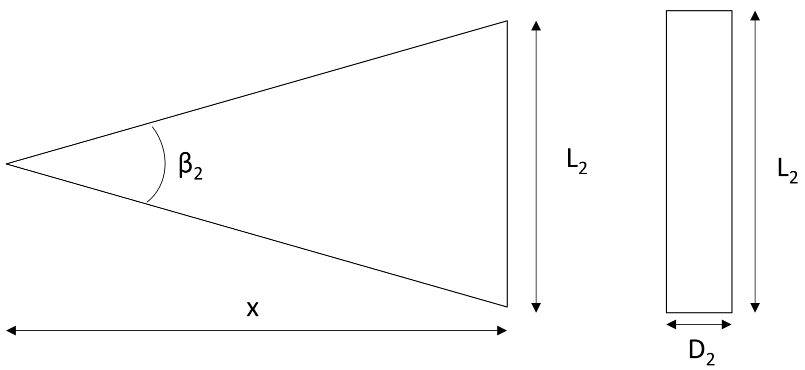


Figure 6.25: The impact pattern of nozzle 2. Note: Figure is not to scale

$$\tan\left(\frac{\beta_j}{2}\right) = \frac{\frac{L_i}{2}}{x} \Rightarrow L_i = 2x\tan\left(\frac{\beta_j}{2}\right) \; for \; i = 2,3 \; and \; j = 2,3 \tag{6.6}$$

$$L_2 = 2x\tan\left(\frac{\beta_2}{2}\right) \tag{6.7}$$

$$L_3 = 2x\tan\left(\frac{\beta_3}{2}\right) \tag{6.8}$$

The area of the impact pattern of nozzle 2 is then given by equation 6.9.

$$A_2 = D_2 * L_2 = \left(2x\tan\left(\frac{\alpha}{2}\right) + d_2\right) * 2x\tan\left(\frac{\beta_2}{2}\right) \tag{6.9}$$

The area of the impact pattern of nozzle 3 has the shape of a ring since the core water jet rotates so that a cone shape is created, illustrated in Figure 6.26. The area of a ring is described by equation 6.10. The inner diameter $L_{3,inner}$ of the ring of the spray pattern is given by equation 6.11, while the outer diameter was calculated with equation 6.8. Then finally, the area of the ring of nozzle 3 is given by equation 6.12.

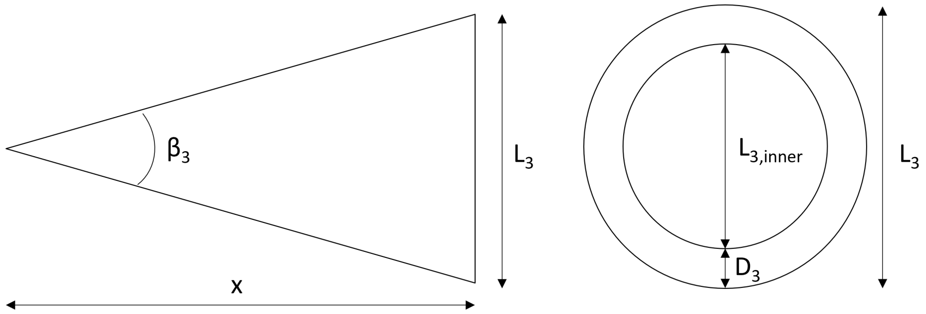


Figure 6.26: The impact pattern of nozzle 3. Note: Figure is not to scale

$$A_{circle} = \frac{1}{4}\pi\left(D_2^2 - D_1^2\right) \tag{6.10}$$

$$L_{3,inner} = L_3 - 2 * D_3 \tag{6.11}$$

$$A_3 = \frac{1}{4}\pi\left(L_3^2 - (L_3 - 2 * D_3)^2\right) \tag{6.12}$$

Figure 6.27 shows the calculated impact area of the nozzles. It can be seen that nozzle 1 has by far the smallest area, then nozzle 2, and finally nozzle 3 has the largest area. Also, the increase of the area for increasing distance is visible. The y-axis has a logarithmic scale to better display the differences between the data points.

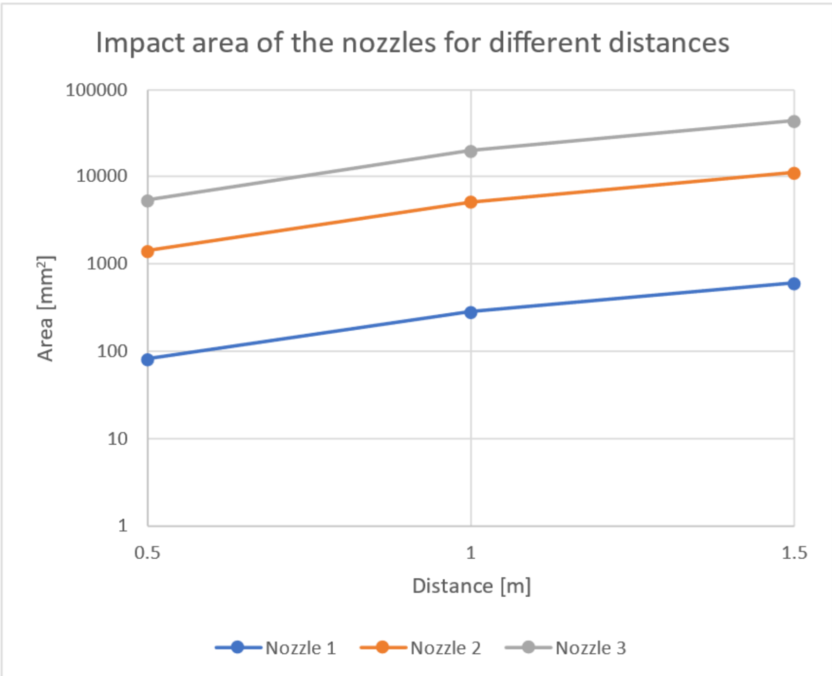
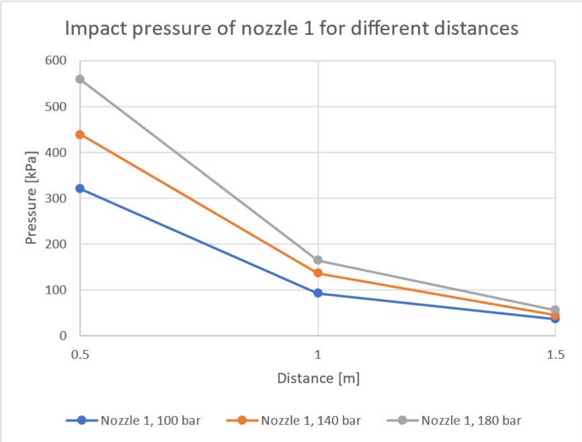
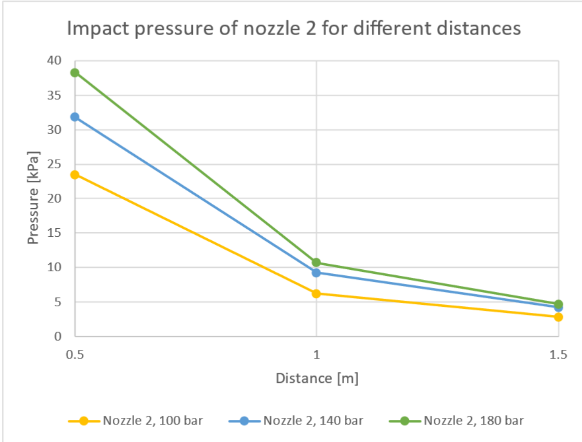


Figure 6.27: The impact area of the various nozzles plotted against the standoff distance. Note: The y-axis is logarithmic for better visibility.

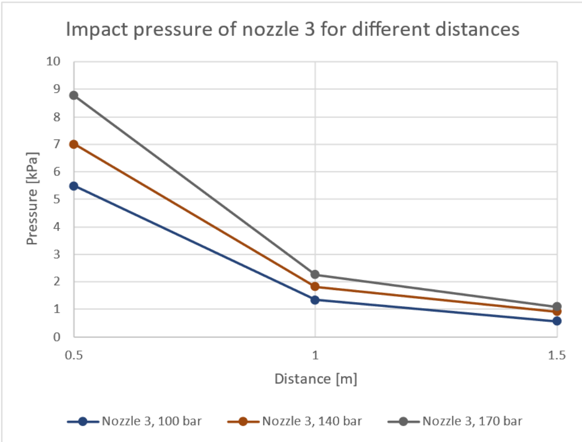
In Figure 6.28 the impact pressure of the different nozzles is plotted against the standoff distance. It can be seen that nozzle 1 has the highest pressures, then nozzle 2 and lastly nozzle 3. This is logical, since this is also the order of increasing impact area, and thus lower pressures. Also, for increasing distance the absolute difference between the impact pressure decrease, while the relative difference in impact pressure stays the same.



(a) Average impact pressure when using nozzle 1 at different distances



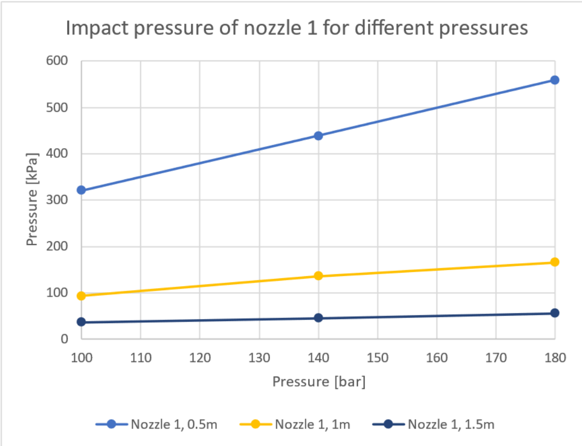
(b) Average impact pressure when using nozzle 2 at different distances



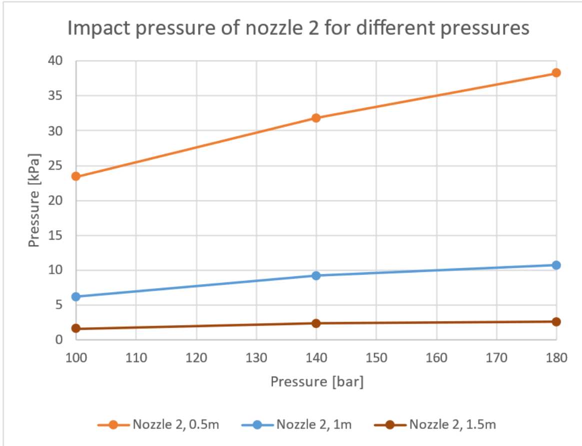
(c) Average impact pressure when using nozzle 3 at different distances

Figure 6.28: Average impact pressure for the different nozzles against the standoff distance

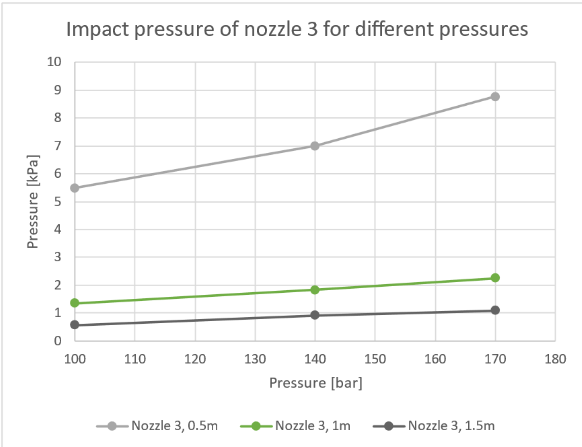
In Figure 6.29 the impact pressure of the different nozzles is plotted against the working pressure. It can be seen that increasing working pressure causes increasing impact pressure at the same distance. This is consistent with earlier data, since it was shown that increasing working pressure caused increasing impact force. Also as seen before, at larger distances, the slope of the impact pressure is flatter.



(a) Average impact pressure when using nozzle 1 at different pressures



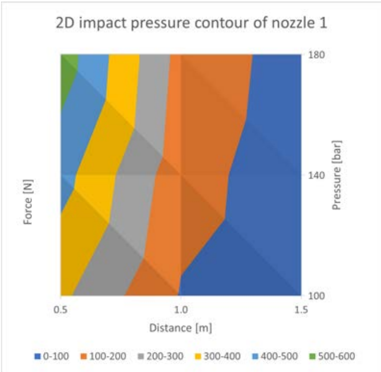
(b) Average impact pressure when using nozzle 2 at different pressures



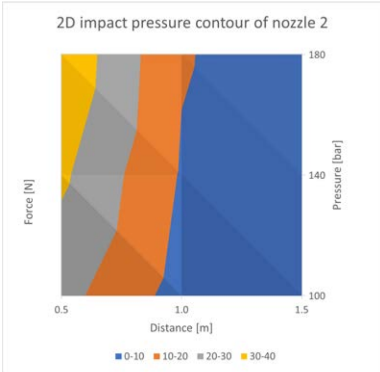
(c) Average impact pressure when using nozzle 3 at different pressures

Figure 6.29: Average impact pressure for the different nozzles against the pressure

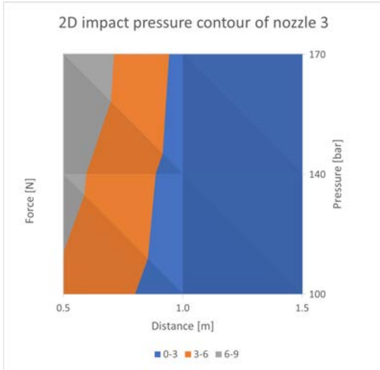
Earlier the surface response was plotted for the impact force, now it is done for the impact pressure to see if links exist between the variables. Figure 6.30 shows the impact pressure contours of the various nozzles. The distance is plotted against the working pressure. For smaller standoff distances, the slope for increasing pressure is steeper. This means that at 0.5 m an increase of the working pressure of 40 bar results in a larger change in the impact pressure, than at 1 m. This can also be seen in Figure 6.29. Also, at a higher working pressure, the distance has a larger effect on the impact pressure. This means that at 140 bar the decrease in impact pressure from 0.5 m to 1 m is larger than at 100 bar. This can also be seen in Figure 6.28.



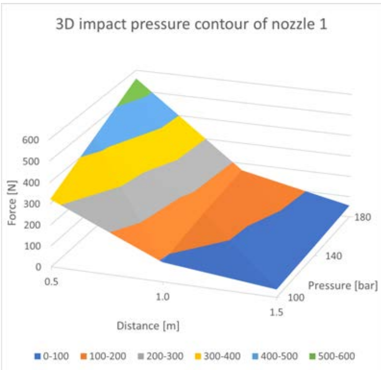
(a) 2D impact pressure contour of nozzle 1



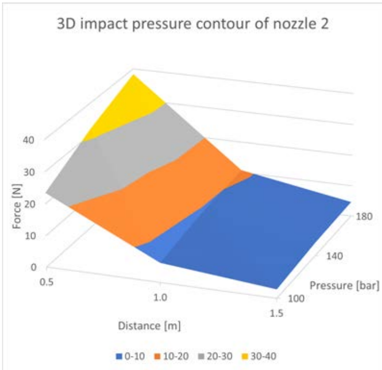
(b) 2D impact pressure contour of nozzle 2



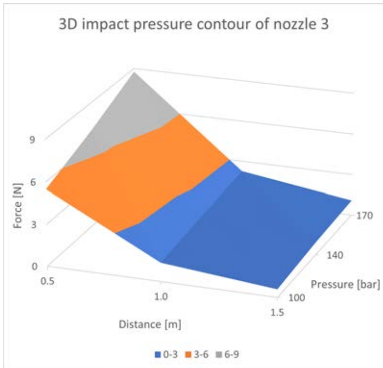
(c) 2D impact pressure contour of nozzle 3



(d) 3D impact pressure contour of nozzle 1



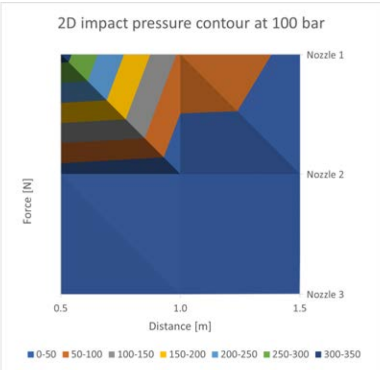
(e) 3D impact pressure contour of nozzle 2



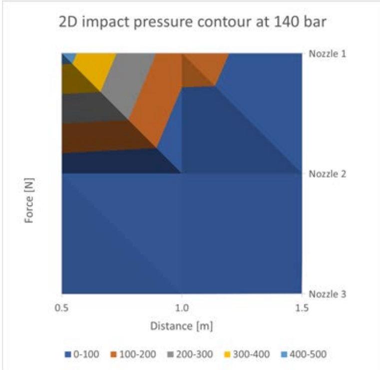
(f) 3D impact pressure contour of nozzle 2

Figure 6.30: Impact pressure contours of the nozzles based on the distance and pressure

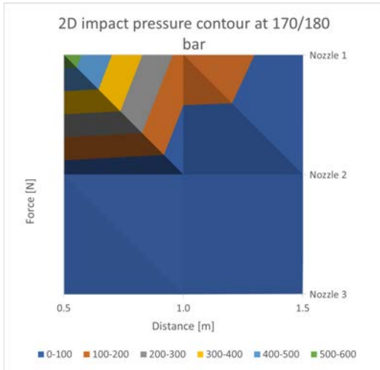
Figure 6.31 shows the impact pressure contours at a certain working pressure. The distance is plotted against the nozzle type. There is a large difference between the nozzles, but all the nozzles seem to have about the same pressure response to the distance. Nozzle 1 has a slightly steeper impact pressure response to the distance than the other 2 nozzles, meaning that at increasing distance, the impact pressure falls slightly quicker. Also, at every distance, the difference between the nozzles is about the same coefficient on average. So at 0.5 m, 100 bar, nozzle 1 has 13 times the impact pressure of nozzle 2, approximately the same as at 1 m and 1.5 m.



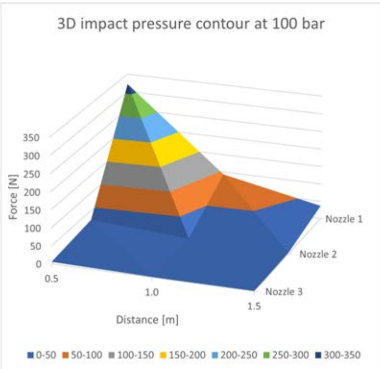
(a) 2D impact pressure contour at 100 bar



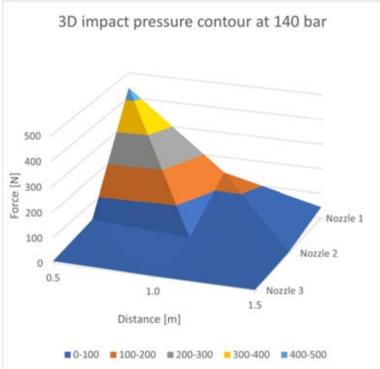
(b) 2D impact pressure contour at 140 bar



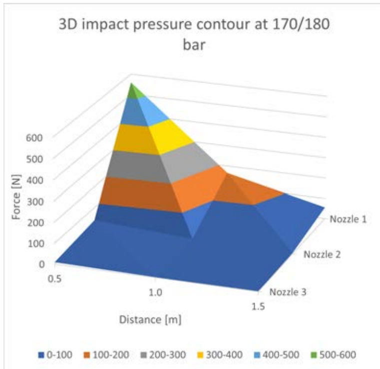
(c) 2D impact pressure contour at 170/180 bar



(d) 3D impact pressure contour at 100 bar



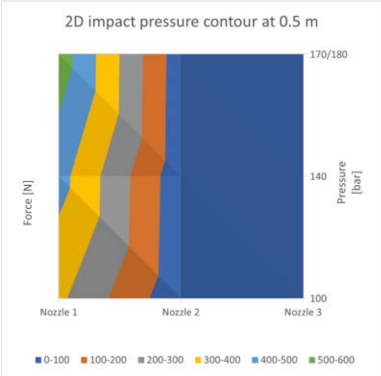
(e) 3D impact pressure contour at 140 bar



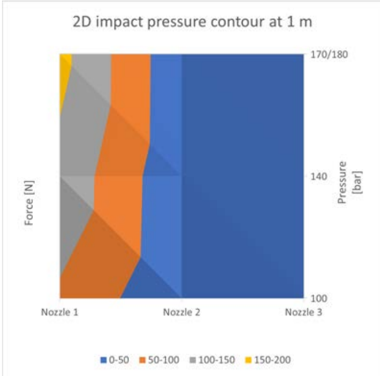
(f) 3D impact pressure contour at 170/180 bar

Figure 6.31: Impact pressure contours at a certain pressure based on the nozzle type and distance

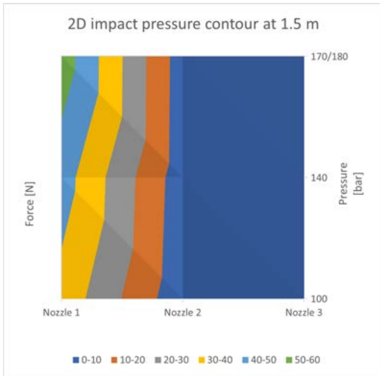
Figure 6.32 shows the impact pressure contours at a certain standoff distance. The working pressure is plotted against the nozzle type. Again there is a large difference between the nozzles, but there seems to be no connection between the nozzle type and the working pressure. At every working pressure the relative difference between the nozzles is about the same. Also, at every distance, the relative difference between the nozzles is approximately the same.



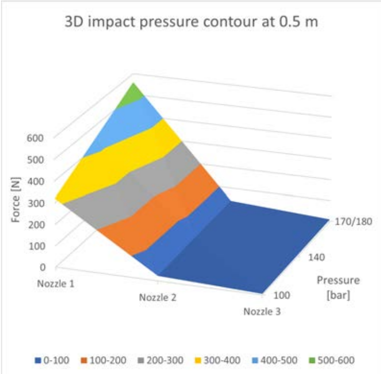
(a) 2D impact pressure contour at 0.5 m



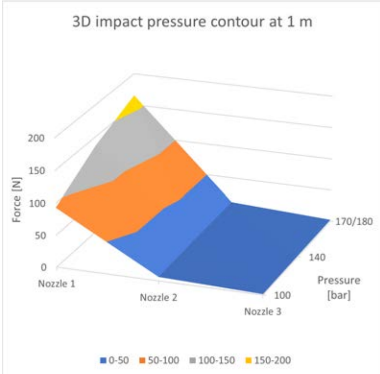
(b) 2D impact pressure contour at 1 m



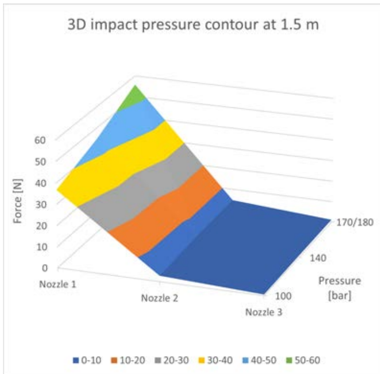
(c) 2D impact pressure contour at 1.5 m



(d) 3D impact pressure contour at 0.5 m



(e) 3D impact pressure contour at 1 m



(f) 3D impact pressure contour at 1.5 m

Figure 6.32: Impact pressure contours at a certain distance based on the nozzle type and pressure

6.3.2. Damage test results

Figure 6.33 shows the measured average layer thickness during the damage tests. The order of tests of a painted steel plate is from left to right. First, the reference is measured, then after water jetting at 1.5 m, then at 1 m, and finally at 0.5 m. Also shown is the standard deviation of the sample values measured. While there is some variation in the layer thickness between measurements, there is no significant decrease in layer thickness for every nozzle, and thus no damage to the paint.

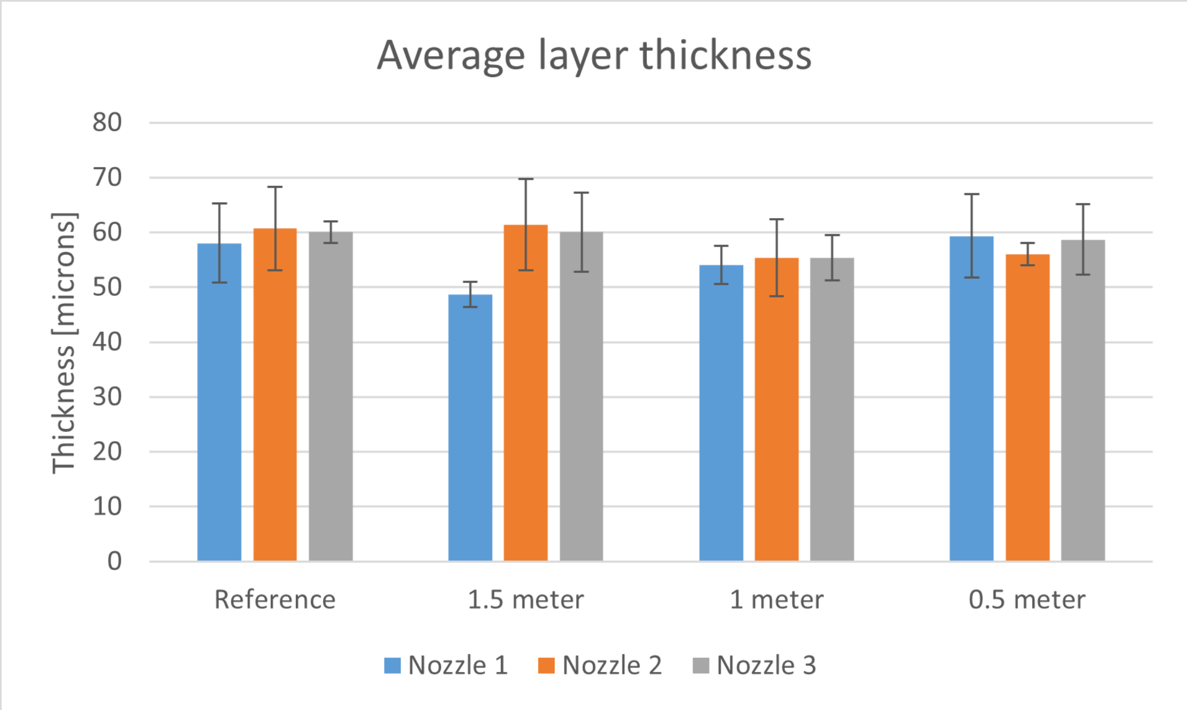


Figure 6.33: Average paint layer thickness after water jetting at decreasing distances

6.3.3. Speed test results

In Figure 6.34 the cleaning times of all the nozzles and distances are shown. Nozzle 1 was effective in cleaning the section. It can be seen in Figure 6.35b and 6.35a that it is a very narrow jet that sometimes creates holes in the material. This means it will punch through, but not remove a lot of material. A larger standoff distance caused the cleaning time to increase for nozzle 1 from just above 60 seconds to over 3 minutes.

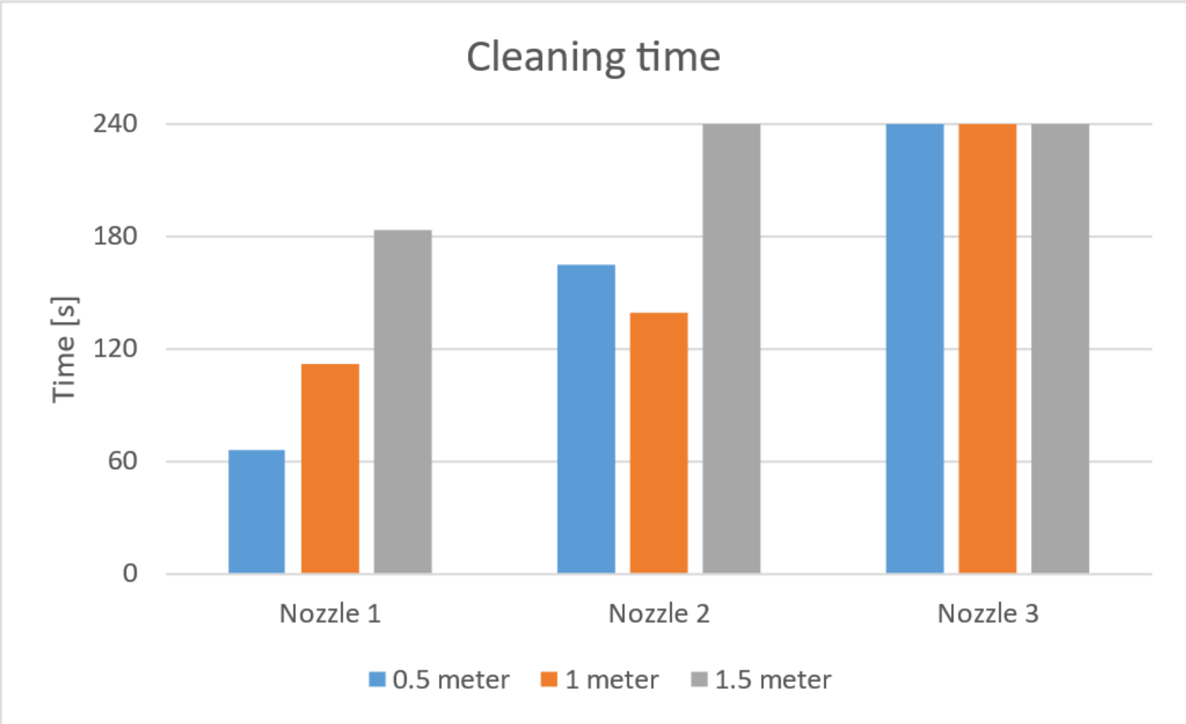


Figure 6.34: The time it takes to clean a section of sheet pile wall. Results of 240 s are at the cutoff time of measuring.

The cleaning times of nozzle 2 are a lot higher than those of nozzle 1. In Figure 6.36a is the section depicted after cleaning at 0.5 m. It can seem from the photo that there is still quite a bit of material left, but during jetting it was visible that the material was very loose and only remained in the section because it laid on the ground. At 1.5 m distance the nozzle was not able to clean the section completely, see Figure 6.36b for the section after 240 s. During testing it was clear that the water jet had very little impact on the material shown.

It is unexpected that the cleaning time at 1 m is shorter than at 0.5 m. The material subjected to nozzle 2 at a distance of 1 m seemed quite soft during the test, this could explain the shorter time for this measurement. The material in the other section seems harder, this could be due to material differences of the influence of water and/or temperature. The tests were started in the morning when the outside temperature was just below freezing, continuing into the afternoon with the temperature climbing to around 5°C. This means that the material was (partially) frozen for the first tests and was thawing for later tests.

The cleaning times of nozzle 3 are for every standoff distance 240 s, because it could not clean the sections of sheet pile wall. Figure 6.37a and 6.37b show the results after jetting for 4 minutes. At 0.5 m some material has been removed, but at the other distances very little difference is seen. During testing, the water jet seemed to have very little to no impact on the material. This lack of performance at larger standoff distances could be caused by a loss of coherence of the water jet and thus the velocity [118]. This is caused by the jet diffusing in the air by the process of air entrainment [119]

(a) Nozzle 1, 0.5 m

(b) Nozzle 1, 1 m

Figure 6.35: A cleaned section of sheet pile wall using nozzle 1

(a) Nozzle 2, 0.5 m

(b) Nozzle 2, 1.5 m (not cleaned completely)

Figure 6.36: A cleaned section of sheet pile wall using nozzle 2

(a) Nozzle 3, 0.5 m

(b) Nozzle 3, 1 m

Figure 6.37: Section of sheet pile wall using nozzle 3 (not cleaned completely)

Minimum necessary impact pressure

It is probable that the impact pressure determines how quickly the material is cleaned, and that there is a certain lower limit to this pressure, also mentioned in [118]. The lower limit of this where there is still cleaning performance, is extracted from the speed tests in combination with the earlier calculated impact pressure. This is done so a prediction can be made regarding the necessary working pressure to achieve adequate cleaning performance at a certain distance with a certain nozzle.

The test with the highest impact pressure where the section was not cleaned completely is nozzle 3 at 0.5 m, producing 8.8 kPa. The test with the lowest impact pressure where the section was cleaned completely is nozzle 2 at 1 m, producing 10.7 kPa. But as said earlier, the material in this section seemed softer than in the others giving an explanation for an outlier result. With these factors in mind, the estimated minimum impact pressure where adequate cleaning is possible is taken as 20 kPa.

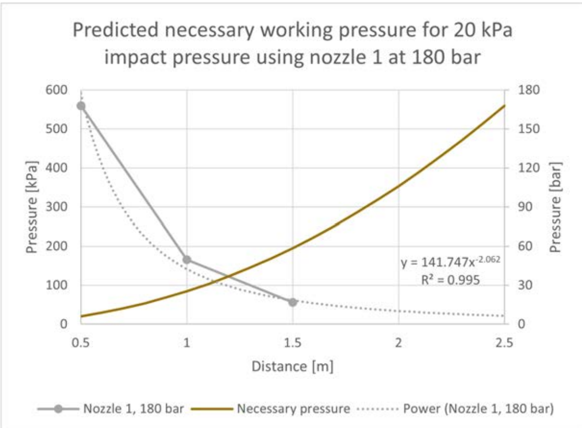
Excel is used to generate an equation of the impact pressure response curve for the speed tests. This equation gives the predicted impact pressure for larger distances. The impact pressure scales almost linearly with the working pressure, lagging behind only 3% on average. This lag is disregarded in this approximation, and this linear relationship is used to generate equation 6.13. Here $q_{w,predicted}$ is the predicted working pressure to generate the minimum impact pressure $q_{i,minimum}$ of 20 kPa. The predicted impact pressure is $q_{i,predicted}$, from the excel equation, and $q_{w,nozzle}$ is the working pressure of the nozzle, either 180 bar or 170 bar depending on the unit.

$$q_{w,predicted} = \frac{q_{i,minimum}}{q_{i,predicted}} * q_{w,nozzle} \tag{6.13}$$

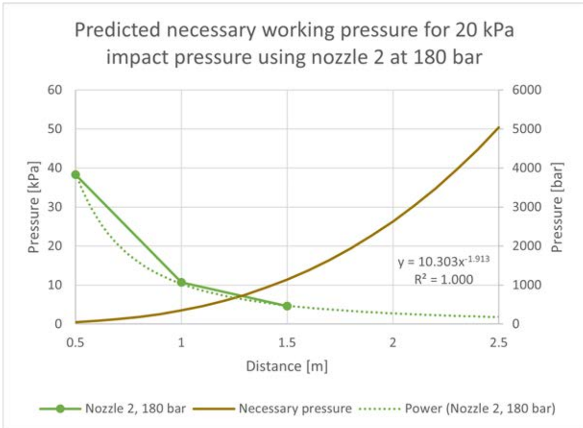
The performance of the nozzles during the speed test, the fitted equation, and the predicted necessary working pressure are plotted in Figure 6.38. The necessary working pressure scales quadratically with the distance, which makes sense since the impact area and thus the impact pressure, scales approximately with the quadratic inverse of the distance. Some notable data points are the following. Nozzle 1 produces 20 kPa at 2.58 m, and still produces 21.4 kPa at 2.5 m. Nozzle 2 produces 20 kPa at 79 cm, and produces only 3.2 kPa at 1.5 m, so the necessary pressure to produce 20 kPa at that distance is 1138 bar. At 2 m, this is 2632 bar. Nozzle 3 does not produce 20 kPa at distances of 50 cm and larger. Nozzle 3 produces only 1.1 kPa at 1.5 m, so the necessary pressure to produce 20 kPa at that distance is 3174 bar. At 2 m, this is 5488 bar.

It is clear that to use a standoff distance of 1.5 m or more with nozzle 2 or 3 unfeasible high working pressures are necessary to achieve good cleaning performance. This would seem to necessitate a short standoff distance for these nozzles. Nozzle 1 even reaches the minimum impact pressure at distances up to 2.58 m using 180 bar working pressure.

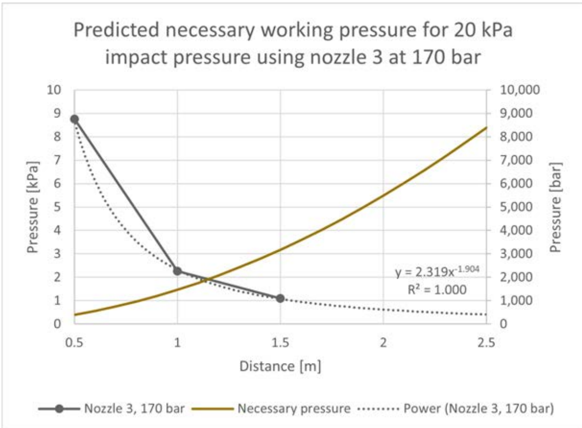
The minimum working pressure needed to generate an impact pressure of 20 kPa at 0.5 m is 6 bar for nozzle 1, 93 bar for nozzle 2 and 392 bar for nozzle 3. This means that nozzles 1 and 2 could use a lower working pressure and use less water to still achieve adequate cleaning performance. This not apply to nozzle 3. At 1 m, nozzle 1 only needs 25 bar, but nozzle 2 needs 349 bar. At 1.5 m nozzle 1 still only needs 59 bar, and at 2 m 106 bar. If nozzles 1 and/or 2 are used, a worthwhile consideration is to lower the working pressure and reduce the water consumption. However, the influence on the cleaning speed would need to be tested beforehand to know for certain there are no adverse effects.



(a) The predicted impact and working pressure of nozzle 1



(b) The predicted impact and working pressure of nozzle 2



(c) The predicted impact and working pressure of nozzle 2

Figure 6.38: The predicted impact pressure and the calculated working pressure necessary to achieve 20 kPa impact pressure at a certain distance.

Hold cleaning time estimation
The speed test did not directly give any information about the cleaning time of a hold, so some simple approximate calculations are done to get a rough idea of how long it would to take clean an entire hold with the concept. This is done by calculating the speed for a given volume of material from the speed test, and then calculating the volume that needs to be cleaned in a hold. These two are combined, giving the cleaning time for a hold. This is done to produce an estimation of the time for EMO, for when they continue with the project.

From the speed test the approximate cleaning time per volume can be calculated in equation 6.14.

$$Volume\ speed\ test : 0.8m * 0.8m * 0.3m = 0.192m^3 \tag{6.14}$$

The best recorded cleaning time was 66s, giving the speed in equation 6.15.

$$Speed = \frac{Time}{Volume} = \frac{60s}{0.192m^3} = 343.75\frac{s}{m^3} \tag{6.15}$$

The used dimensions are for a Capesize bulk carrier and are as follows:

- Hold width: 45 m
- Hold length: 30 m
- Hold height: 25 m
- Knee height: 3 m
- Bulkhead depth: 1 m
- Side shell frame depth: 0.3 m

There is an angle change in the wall, this is a place where all the material in a section of the wall rests on. So if the material in this section is blasted away, then the material above it will fall since there is no material to rest on. This behavior propagates upwards, often causing the entire column of material to fall, see also Figure 6.39. This section is also called the “knee”. The length (height) of the knee is thus the section that needs to be cleaned. Figures 4.7 and 4.8 also illustrate the structure of a hold.

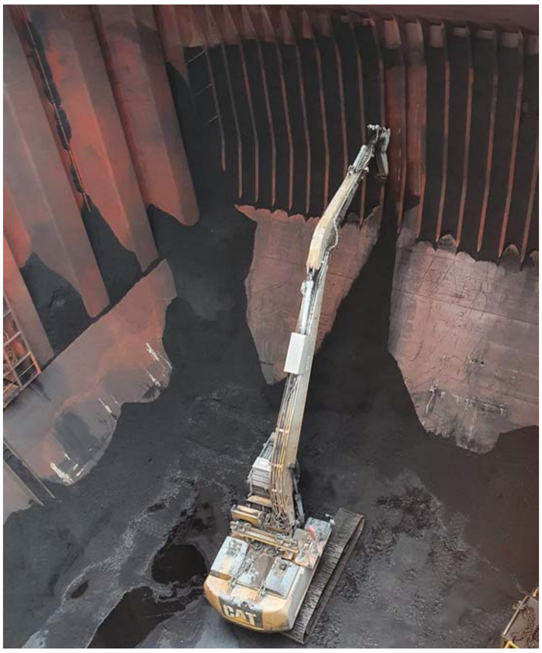


Figure 6.39: A CAT 329 cleaning a side shell frame

The volume that needs to be cleaned consists of the sides and the ends of the hold. For the sides, the area where the material is, is taken as the entire length of the hold, since the width of the shell frames is narrow. The volume of the side shell frames of the hold is calculated in equation 6.16.

$$Volume\ sides : knee\ height * frame\ depth * hold\ length = 3m * 0.3m * 30m = 27m^3 \tag{6.16}$$

The transverse bulkhead is corrugated, so half of it is concave, and the other half is convex. Thus only half of the hold width is filled with material and then the volume of the ends of the hold is given by equation 6.17.

$$Volume\ ends : 0.5 * knee\ height * bulkhead\ depth * hold\ width = 0.5 * 3m * 1m * 45m = 67.5m^3 \tag{6.17}$$

The total volume to be cleaned in the hold is described in equation 6.18.

$$Total\ volume : 2 * (volume\ side + volume\ bulkhead) = 2 * (27m^3 + 67.5m^3) = 189m^3 \tag{6.18}$$

Then the cleaning time for a hold is given by equation 6.19.

$$Time = Speed * Volume = 343.75 \frac{s}{m^3} * 189m^3 = 18.0\ hours \tag{6.19}$$

If the knee height is taken as only 2 m (it might be, it is difficult to say), then the volume will be 2/3, and thus the cleaning time also, giving 12.0 hours. If the height is just 1 m, then the time will be further reduced to 6.0 hours. Still, this is much longer than it takes to clean a hold now. If this is the actual time it takes, without some very large improvement the concept would be much worse than the current cleaning method since time is a very important factor at EMO. However, in the speed test the material was very compact, frozen, and on a horizontal surface. These are about the worst possible circumstances, so the expectation is that the cleaning time of a hold would be significantly less.

Nozzle 1 at 180 bar uses 19.7 l/m, which is 1.18 m^3/h. This corresponds with a run time of 102 minutes if 2 m^3 of water is present in the tanks. A 6 hour run time would use 7.1 m^3 of water. Nozzle 2 at 180 bar uses 35.9 l/m, which is 2.15 m^3/h. This corresponds with a run time of 56 minutes. A 6 hour run time would use 12.9 m^3 of water. Nozzle 3 at 170 bar uses 24.4 l/m, which is 1.46 m^3/h. This corresponds with a run time of 82 minutes. A 6 hour run time would use 8.8 m^3 of water.

Water volumes over 4 m^3, when the hold is almost empty, are problematic since a large volume of coal-water slurry will be created. If there is more material left in the hold, this water can be split over more material making it only somewhat wetter. This problem has multiple possible solutions. The first is to reduce the water consumption per hour, this could be done by lowering the pressure, but this would probably extend the cleaning time. It is also possible to keep the pressure the same, but reduce the nozzle so the volume flow decreases. Another option is to begin the hold cleaning earlier, when the hold is not yet emptied by the grab, so there is more material to absorb the water. The final option is to reduce the cleaning time with some sort of optimization to the water jetting.

6.4. Conclusion

The question that this chapter has answered is the following: Does the prototype satisfy the requirements & wishes? If the prototype satisfies the requirements can mostly be answered.

- The noise level of the equipment has not been measured but it did sound like it was below 100 dB.
- The equipment does not damage the hold.
- The water flow rate was below 30 l/min for most scenarios.
- A schematic design shows that the equipment can be placed in the hold where it is functional in cleaning the hold (for every ship).
- The equipment has a reach of more than 20 m vertically and 3m horizontally to reach the entire hold with the cleaning equipment inside the hold.
- The equipment has not been observed to create dangerous situations for personnel.
- It is not known if the concept will be able to clean a hold in 3 hours on average since this was not tested. Some rough calculations suggest it is doubtful.
- The equipment can be automated such that no people have to be in the hold, however this will take a lot of work.

If the prototype satisfies the wishes can also mostly be answered.

- No damage whatsoever was observed in the damage test.
- The crane operation is not hindered because there is nothing on the quay.
- As mentioned before, the cleaning time of a hold is unknown, but 2 hours is doubtful.
- The water jet can remove all material from the wall so the ”normal clean” standard can be attained.
- Cleaning straight stairs should not be a problem, but spiral staircases could be problematic as it has been shown that at larger standoff distances the cleaning performance greatly diminishes.
- The fragile nozzle is relatively enclosed in the designed attachment, so the concept is quite robust. The testing prototype however is damaged very quickly.

7 Discussion

This chapter will discuss some of the shortcomings of this study and other notes.

The scores of the multi-criteria analysis are based on developing a first prototype, so a high initial cost can decrease in the future if for example more units are made after the design is complete. So one could argue that if it is likely that more units will be made, the initial cost is less important than assumed in this report.

The testing done was limited by the time available. There were two testing days possible which were fully utilized. If there had been more time, more extensive tests could have been executed.

Since the water jet in the impact test was aimed downward, gravity was acting in the jet's favor. This means that when jetting horizontally or even upwards, there might be a more significant difference in the impact force at larger distances. Also, there was some sort of oscillation during the impact test, because while positive outliers are not very unexpected, there were also negative values recorded.

Since the measured values in the damage test had quite a large variance under the same conditions, the averaged values of the three measurements still have a large standard deviation and there was no correlation visible between tests. So a larger number of measurements, or a more even paint application, is beneficial.

The speed test has various limitations. The movement of the attachment, and the nozzle, was done by an operator, so the movement will not be identical between tests. It was also inexact to determine when a section was completely cleaned. The material composition between sections was also possibly not identical, since it was material that naturally accumulated, causing differences in material properties. Also, since the night before it was freezing and later in the day the temperature climbed, this caused the material to transition from frozen to thawed, changing the properties between tests. The speed test is also very limited in its contribution to understanding how fast the concept would clean a hold, due to a small and non-representative area.

8

Conclusion & Recommendations

The main research question was: Is it possible to clean the hold of a coal bulk carrier by machine, and have the hold be cleaned faster and with less damage? To answer this, other questions have been posed at the beginning and have been answered.

It has been shown that some bulk material is stuck against the walls of the hold. To gain access to the hold, first the stairs have to be cleaned manually. After that, an excavator with a steel brush is used to remove the material from the walls, but this can cause damage. This whole process can be dangerous for the people involved, and it is time-intensive. No specific literature has been found regarding the cleaning of the hold of bulk carriers, but other relevant topics have been analyzed containing information about the properties of bulk materials, silo discharge aids, and bulk material conveying methods.

Cleaning equipment consisting of low and high-pressure water systems, which are used from far away or very close, high-pressure air systems, pneumatic unloaders, and vibrators have been shown. Further, the tests of EMO have been shown which include vibrations by using a hydraulic hammer, a plate tamper, and vibrating needles. Also an air cannon, low-pressure water hose and various mechanical buckets and scrapers have been tested in the past.

The cleaning standard has been defined, as well as the damage costs of cleaning holds. The safety incidents associated with the cleaning have been analyzed, and the current speed of cleaning and physical constraints are detailed. After that, the functional specifications of the concepts have been shown, and from this the design requirements were created, which are all split into requirements, recommendations, and optional points.

From many ideas a final prototype concept was chosen, an excavator with a water tank and high-pressure pump mounted on the back and a nozzle at the end of an attachment. This attachment is attached via a coupling to the excavator's arm. Also, the steps towards an automated design are detailed, including automatic (de)coupling, remote control and autonomous operation.

Regarding satisfying the design requirements, the noise level did not seem too high, no damage was observed, the water flow rate was moderate, the prototype can be used for cleaning the entire hold, the equipment has not been observed to create dangerous situations for personnel, the time to clean a hold is still only a rough estimate, and the equipment can be automated such that no people have to be in the hold. Further, regarding the wishes, the crane operation is not hindered, the "normal clean" standard can be attained, spiral staircases could be problematic at larger standoff distances due to the cleaning performance diminishing, and the designed attachment is robust and encloses the fragile nozzle.

However, the main research question is difficult to answer completely based on this report. Firstly, from the testing it was evident that the water jet does not damage a paint layer. This means that a hold can be cleaned with the prototype with no damage at all to the hold from the water jet. So the objective to cause less damage has been amply achieved.

Secondly, the speed test gave valuable information about the relative performance of the nozzles and standoff distances. However, the material conditions during the speed test are not comparable to an actual dirty hold, so the data it generated and that was used in calculating the cleaning time of an actual hold, is inexact. The actual cleaning time of a hold can most easily be tested by cleaning a (section of a) hold. And while the impact force did not drop much at increasing standoff distance, the impact pressure does, and this effect was also visible in the speed test results where a greater distance resulted in longer cleaning times. So it is uncertain how well the concept would perform on spiral stairs in the hold where the standoff distance could be as much as 2-3 m. It was however also shown what working pressure is needed to maintain the minimum impact pressure needed for cleaning.

Lastly, for there to be no need for people in the hold, a remote (de)coupling system needs to be in place for the excavator. Similar systems as used for shipping containers are very common, so this can probably be relatively easily implemented. Also, a remote control system for the excavator itself is necessary, but such systems are commercially available on new models so this is also possible. The automation of the cleaning process will be difficult, but parts of this problem have already been tackled by the mining industry, and EMO has experience in this field so it is certainly possible.

The process of cleaning the stairs in a hold takes a lot of time and can be dangerous so a new concept can be a safer way to deal with the problem. The current machines used in the hold are not always usable in difficult-to-reach areas e.g. stairs. The use of these machines also can result in damage to a ship resulting in extra costs, while also damaging the reputation of EMO. The high docking costs and potential demurrage costs, of bulk carriers also create a large financial incentive to reduce the cleaning time. So if the concept performs well in a hold time-wise, large savings can be realized, and potentially not only for EMO. Also, the new method is better at cleaning the difficult-to-reach last bits of material, so a higher cleaning standard can be attained, which is good for the reputation of EMO. Since no specific research has been done about the cleaning of large quantities of stuck material in bulk carrier holds, this topic of study is very relevant for EMO and on a global scale and worth further investigation.

Further, the following recommendations for further research and development at EMO are proposed:

- Further research into oscillating flow, since the initial transient pressure is very large relative to the steady-state impact pressure [120, 121].
- Can air be added to the jet to decrease the water usage without losing too much impact force?
- Are moveable nozzles better than always having to move the entire excavator boom & arm.
- Design in detail the physical systems needed for an excavator with a water jet to be untethered and operational.
- Further testing:
  - Testing more nozzle types. One nozzle shape produces a larger impact pressure than another [120].
  - Testing more nozzle sizes. Is a bigger nozzle better? Or is too much water used? Or is a smaller nozzle at a higher pressure better?
  - Test with a more powerful pump at higher pressures, since the same impact pressure can be created by many combinations of working pressure and volume flow [118].
  - Test with jetting at the material under multiple angles, what cleans the wall the fastest?
  - Investigating the effect of multiple nozzles and multiple nozzle types. Can they be combined into a favorable combination?
  - Test the cleaning performance in a hold to properly evaluate the speed. If possible, do a direct comparison between the currently used steel brush and the new prototype by cleaning 2 holds with the same material.
  - Test in a hold to see if splashback is a problem. If so, what can be done to alleviate this?
- Automation:
  - Investigate how an automatic (dis)connecting system between an excavator and a quay crane can work. Are there systems already in use at other terminals?
  - See if the excavators in inventory can be outfitted with remote control systems, or if new equipment is needed.

- Develop a way to scan the geometry of a hold and have an excavator operate autonomously in that hold. A first step could be to implement a remote control system so that the operator does not have to be present in the cabin.

A

Appendix A: Scientific paper

Improving the cleaning process of bulk carrier holds

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MSc Mechanical Engineering, TU Delft

Bulk carriers load and unload large quantities of iron ore and coal at bulk terminals. The loading and unloading process on the EMO terminal is largely automated, but for the last 5% an excavator is used to remove material stuck on stairs and walls in the hold. This process takes many manhours, can be dangerous, and can cause damage. The research question is: Is it possible to clean the hold of a coal bulk carrier by machine, and have the hold be cleaned faster and with less damage? A design is made, and based on that a test is set up. The results show that higher pressures, closer distances, and certain nozzle types result in better cleaning, without causing damage. The conclusion is that a hold can be cleaned by a machine with less damage, and possibly faster.

I. Introduction

Bulk carriers make up around 20% of the global merchant fleet [1], and thus have a vital position in the operations of the maritime sector. These ships load and unload at places like the EMO terminal, where enormous quantities of bulk solids, mostly iron ore and coal, pass through. In every operation that involves particulate solids, efficient storage and handling of the material is an essential part.

The loading and unloading of bulk carriers that dock at the EMO terminal is largely automated, but not completely. If a ship has docked, a crane with a grab will start digging out the hold, it can do this for 95% of the material. For the last 5% a front loader is used to scoop the material together in the center of the hold so the grab can also unload this material. However, material remains in various places such as walls and stairs due to sticking and compaction. To clean the stairs, personnel are using various hand tools to remove this material. After this has happened and the access to the bottom of the hold is clear, a front loader and excavator can be lifted into the hold to clean the remaining material in the hold. The excavator can be outfitted with various attachments and is then used to clean the walls, but they are not usable on more difficult-to-reach areas. The process of clearing the stairs takes many manhours and can be dangerous. Cleaning the rest of the hold is also not without risk because the grab simultaneously works in the hold. The machines in the hold can be used to clean the wall, but they are not usable on areas such as stairs. The use of these machines also can damage the ship resulting in extra costs. The high docking and demurrage costs also make any time savings financially attractive.

The aim is to develop a method and/or equipment that can clean the stairs so that people do not have to do this task and that the time spent in the danger zone and risks are minimized. This solution should also be able to clean the other parts of the hold where material is stuck, and should not damage the hold so that no extra costs are incurred. If the stairs have been cleared and a safe access has been created, the bottom of the hold can still be cleaned by a local human operator in a front loader. Making the whole cleaning process autonomous such that no people are needed is the ultimate goal of EMO. The research question of this report is: Is it possible to clean the hold of a coal bulk carrier by machine, and have the hold be cleaned faster and with less damage?

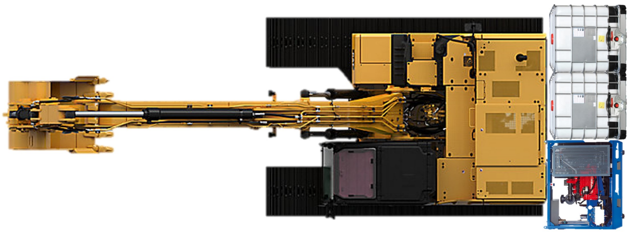
II. Design

A. Schematic design

The concept design is a CAT 329 excavator with a high-pressure pump of at least 200 bar on board at the back. A water tank of at least 1 m^3 is also present, so that the machine does not have a tether. In Figure 1 various views of the design are shown, including 2 water tanks of 1 m^3 to show the size. This could be 1 tank of a custom design. The width of the excavator is a little over 3 m [2], the water tanks 1 m, and the pump (L x W x H) 1.5 x 1 x 1.2 m so the design is roughly to scale. Hoses are run from the water tank to the pump and from there to the boom, arm, and finally to a custom attachment where one or more nozzles are mounted so the material in the hold can be removed with the water jet.

B. Cleaning attachment

The attachment is a piece of steel on which at least 1 nozzle is mounted that is connected to the pump, see Figure 2 for a prototype design. The pipe and nozzles are placed on the underside of an HEB 200 wide flange beam so that when it is used in a hold and large pieces of bulk material fall, the water pipe and nozzle are



(a) Top view. Original image from [2]

(b) Left side view. Note: Pictured is not the exact same type of excavator. Original image from [3]

Figure 1. Views of the design of an excavator with water tank and high-pressure pump equipment

not damaged. Also, when it is set on the ground, the geometry prevents contact between the nozzle and the ground so that it will not be damaged. At the tip of the attachment the pipe bifurcates so that multiple nozzles can be mounted. The other end is currently simply a steel plate, so that a coupling mechanism can be attached to it.

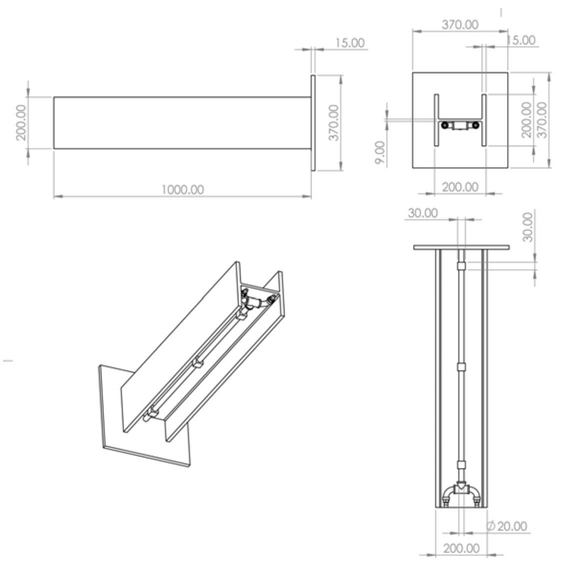


Figure 2. Drawing of a concept design of the cleaning attachment

III. Testing methodology

The practical performance of using high-pressure water jetting for cleaning holds has been tested. There are multiple things that are interesting to know before continuing towards a practical deployment. These are the impact of the water jet, if the water jet does damage to a hold, how fast it cleans, and how this all is influenced by the pressure, standoff distance, and nozzle type.

A. General setup

In Figure 3 the equipment used is shown. This includes the excavator attachment with a rigid pipe on it which can be connected to a standard 3/8" high-pressure hose and different nozzles. Also shown is the high-pressure pump with its water tank filled with tap water. The pump unit is located on a trailer so that it can be placed nearby. It connects with a hose to the pipe on the attachment. The pressure gauge of the pump is shown, which is used to determine the pressure.

(a) Excavator attachment with a nozzle

(b) CAT 329 excavator used for testing

(c) High-pressure diesel pump

(d) Pressure gauge on the pump

Figure 3. The general components of the testing setup

The standoff distances during testing are 0.5, 1, and 1.5 m distance. The pump that was available could, depending on the nozzle, produce a pressure of 180 bar or 170 bar. The pressures at which the test is done are 100, 140, and 180(/170) bar. There are 3 different nozzle types used, see Figure 4. Nozzle 1 is just a round hole that generates a round jet of water. It has an opening of 1.52 mm. Nozzle 2 is also a round hole, but the exit has a slit that forms a planar jet of water that has an internal angle of 15°. It has an opening of 2.05 mm. Nozzle 3 is a special nozzle wherein a ball with a hole in it rotates when water flows through it. This generates a cone of water that has an internal angle of 20°. The opening diameter when measured is 1.7 mm.

A datasheet gives the maximum volume flow for

(a) Nozzle 1 (b) Nozzle 2 (c) Nozzle 3

Figure 4. Nozzle spray shapes

various pressures for the different nozzles. This data is plotted in Figure 5. For nozzles 1 and 2 all the visible data points are directly from the manufacturer, however for nozzle 3 only the volume flow at 200 bar is available. Nozzle 3 is given a similar curve as the other nozzles using interpolation. The trendline function in Excel is used to generate a formula for the curves of the nozzles, with a fit quality of $R^2 > 0.99$. This formula is then used to generate data points at 180 bar, since the data only specifies 175 and 200 bar.

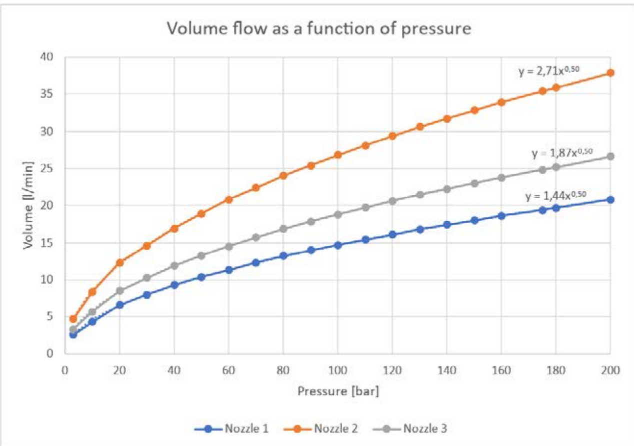


Figure 5. The volume flow through the different nozzles at different pressures. Nozzle 3 is interpolated data.

B. Impact test

To measure the impact of the water spray, the following setup is used as seen in Figure 6. The force sensor is a Phidgets CZL301 S type load cell [4], which has a maximum capacity of 500 kg, but has been calibrated up to 1000 N by the measuring department of the 3ME faculty of the TU Delft. According to this department, the accuracy of the load cell is one-thousandth of its measuring range, which with this calibration means 1 N. The ADC is a National Instruments USB-6002 [5], and the signal conditioner is a Scaime CPJ [6]. The load cell is mounted to a steel table with dimensions of (W x L x H) 1000 x 1100 x 550 mm with an M12 bolt. On top of the load cell a 580 x 580 x 2 mm steel interface plate is mounted also with an M12 bolt. The excavator attachment is lifted vertically above the plate that is mounted to the load cell, and the water jet is centered on the plate by eye. The water jet is maintained for approximately but at least 10 seconds during which the load cell output is measured. Every 100 ms a data point is saved, resulting in 110 to 140 data points. To zero the data later, 10 seconds of data is gathered of only the weight of the plate without a water jet. The average value of this measurement can then be subtracted from the data that is measured during jetting, giving the net impact force.

(a) Measuring electronics (b) Testing

(c) Load cell mounted between a table and a plate (d) Table with the force measuring plate

Figure 6. Impact measuring setup

C. Damage test

This test is meant to evaluate the damage done by a water jet to the paint of a hold. This is done by using a water jet on a painted surface and measuring the thickness of that paint layer. Before the jetting, the control thickness of the layer of paint is measured. This is done with an ultrasonic thickness gauge as seen in Figure 7. The measuring of the layer is done in 3 locations, to give an average value. The water jet is aimed at a painted steel plate that lies on the ground, the paint is a typical heavy-duty outdoor type paint that is used at EMO. The test is done only at 180 bar (170 bar for nozzle 3), since that would be most likely to damage the paint. During 10 seconds the plate is subjected to the water jet, after which the layer thickness is measured again to see if the layer is thinner. Then the distance is decreased from 1.5 m to 1 m, to increase the chance of damage. The thickness is measured again and the distance is decreased a final time to 0.5 m and the layer thickness is measured a final time. This process is repeated for every nozzle, which are all tested on a new and identical plate.

(a) Ultrasonic thickness gauge [7]

(b) Jetting during damage testing

Figure 7. Damage testing setup

D. Speed test

This test is done to see the relative speed of cleaning using different nozzles and distances. The test is done only at 180 bar (170 bar for nozzle 3), because that pressure would most likely give the shortest cleaning times. Doing the test in an actual hold of a docked bulk carrier is not possible due to tight scheduling at EMO, so as an alternative a section of sheet pile wall is used, see Figure 8. The filled sections of the sheet pile wall have dimensions of (L x H x W) 800 x 800 x 300 mm approximately. They are filled with a mixture of coal and iron ore. Every pressure & nozzle combination is used to clean one section of the sheet pile wall, and the time this takes is measured. The excavator (and its attachment) is moved by an operator so that the whole section is hit with the water jet.

(a) Filled sheet pile wall section

(b) Excavator cleaning section of sheet pile wall

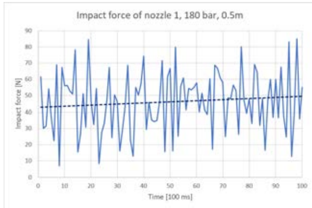
Figure 8. Speed testing setup

IV. Testing Results

A. Impact test results

In Figure 9a the measured impact force over time of nozzle 1 at a pressure of 180 bar at 0.5 m distance, is plotted. In the same figure is the calibration measurement of the setup plotted, this is only the weight of the test setup without any water. It can be seen that the calibration signal has much less variance than the measurement using water, so the variance is a physical property of the setup. In Figure 9b the actual impact force, which is the measured forces minus the average calibration value, is plotted. Here the variation in the measurement becomes much more apparent.

(a) The measured force



(b) The net impact force

Figure 9. The measured impact force and the net impact force over time of nozzle 1, 180 bar at 0.5 m. The time between measurement points is 100 ms, the total measured time is 10 s.

It can be seen in Figure 10 that there is very little difference in the force between 0.5 m and 1 m using nozzle 1. However, at 1.5 m the force decreases, more so at 140 and 180 bar. There is a slight downward trend for increasing distance when using nozzles 2 and 3 with some exceptions e.g. nozzle 3 at 140 and 170 bar between 1 m and 1.5 m.

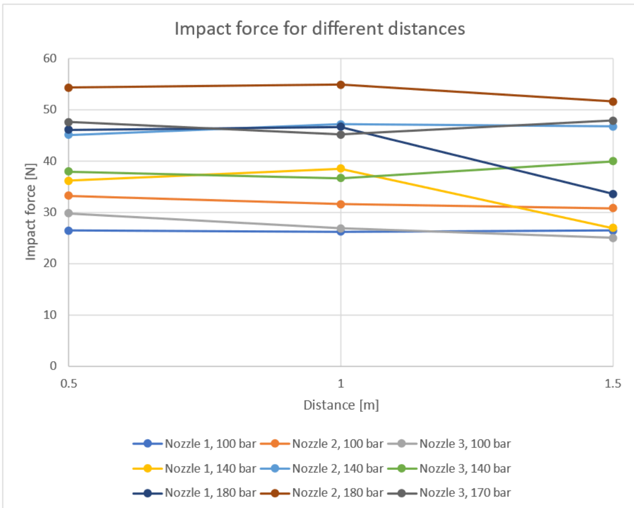


Figure 10. Average impact force for various distances

The impact force always trends upwards for increasing pressure in Figure 11. For nozzles 1 and 3 this is almost linear, but for nozzle 2 a bit less between 140 and 180 bar. It can be seen that nozzle 2 has the largest force at all distances at all pressures, with nozzles 1 and 3 having similar results at 0.5 m and at 1 m. But at 1.5 m the force of nozzle 1 is significantly smaller.

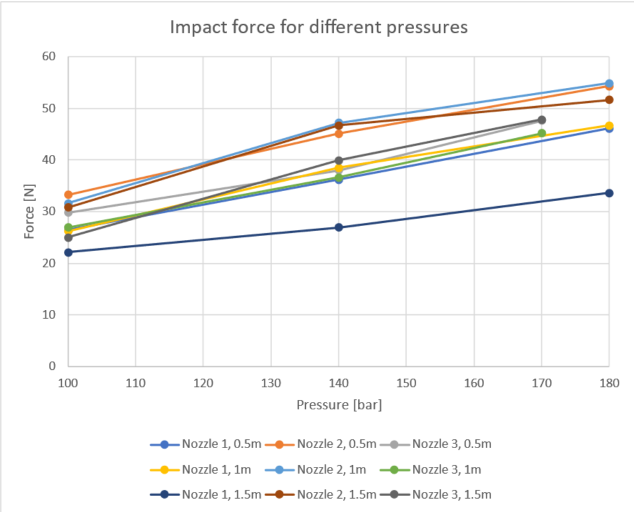


Figure 11. Average impact force for various pressures

Only looking at the impact force does not paint a complete picture. When a greater standoff distance is used, the force seems to largely remain the same. This force is however spread over a larger area due to the internal angle of the core water jet (measured as 1°) and the angle of the spray pattern. The impact area of nozzle 1 is a circle, nozzle 2 is a rectangle, and nozzle 3 is a ring. The impact area is plotted against the distance in Figure 12.

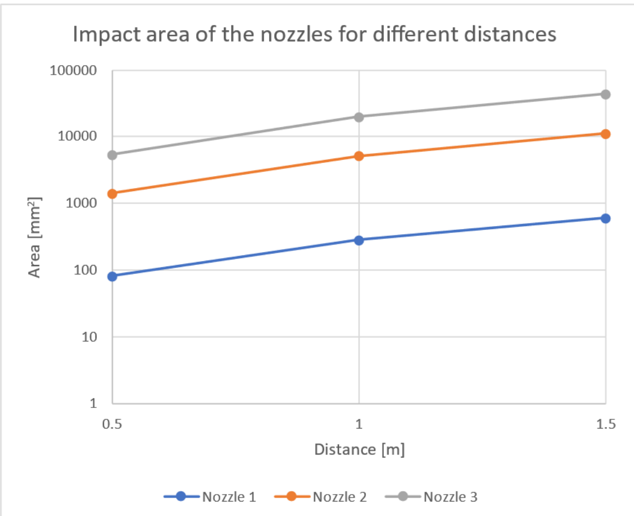


Figure 12. Impact area of the nozzles for various distances. Note: A logarithmic y-axis is used.

In Figure 13 the impact pressure of the different nozzles is plotted against the standoff distance. It can be seen that nozzle 1 has the highest pressures, then nozzle 2 and lastly nozzle 3. This is logical, since this is also the order of increasing impact area, and thus lower pressures. Also, for increasing distance the absolute difference between the impact pressure decreases, while the relative difference in impact pressure stays the same.

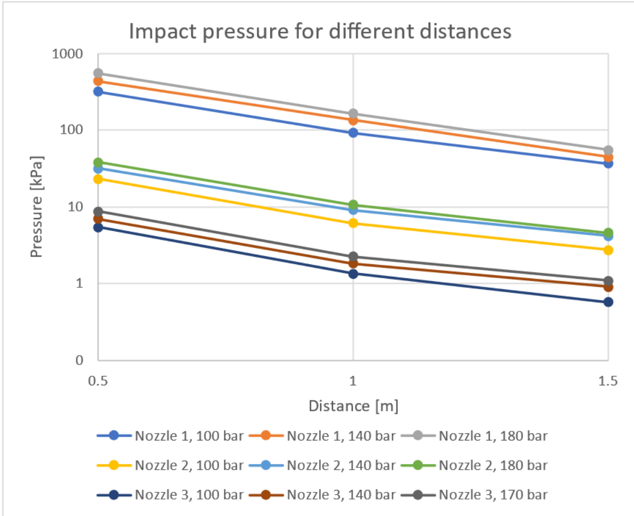


Figure 13. Average impact pressure force for various distances. Note: A logarithmic y-axis is used.

In Figure 14 the impact pressure of the different nozzles is plotted against the working pressure. It can be seen that increasing working pressure causes increasing impact pressure at the same distance. This is consistent with earlier data, since it was shown that increasing working pressure caused increasing impact force.

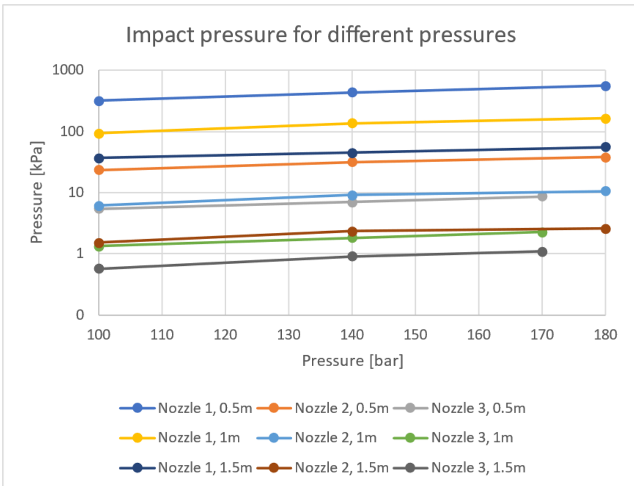


Figure 14. Average impact pressure force for various pressures. Note: A logarithmic y-axis is used.

B. Damage test results

Figure 15 shows the measured average layer thickness during the damage tests. The order of tests of a painted steel plate is from left to right. First, the reference is measured, then after water jetting at 1.5 m, then at 1 m, and finally at 0.5 m. Also shown is the standard deviation of the sample values measured. While there is some variation in the layer thickness between measurements, there is no significant decrease in layer thickness for any nozzle, and thus no damage to the paint.

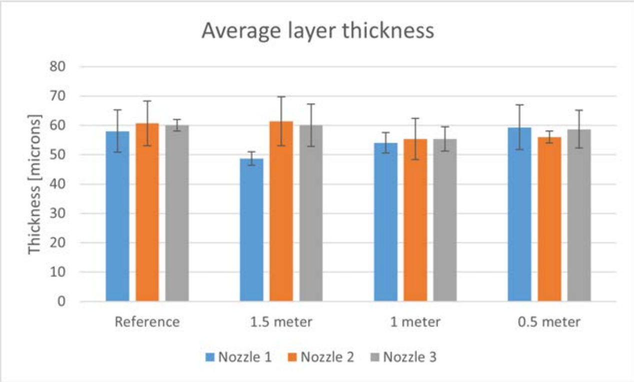


Figure 15. Average paint layer thickness after water jetting at decreasing distances

C. Speed test results

In Figure 16 the cleaning times of all the nozzles and distances are shown. Nozzle 1 was effective in cleaning the section. A larger standoff distance caused the cleaning time to increase for nozzle 1 from just above 60 seconds to over 3 minutes.

The cleaning times of nozzle 2 are a lot higher than those of nozzle 1. At 1.5 m distance the nozzle was not able to clean the section completely. It is unexpected that the cleaning time at 1 m is shorter than at 0.5 m. The material subjected to nozzle 2 at a distance of 1 meter seemed quite soft during the test, this could explain the shorter time for this measurement. The tests were started in the morning when the outside temperature was just below freezing, while later it was thawing.

The cleaning times of nozzle 3 are for every standoff distance 240 s, because it could not clean the sections of sheet pile wall. At 0.5 m some material has been removed, but at the other distances very little difference is seen.

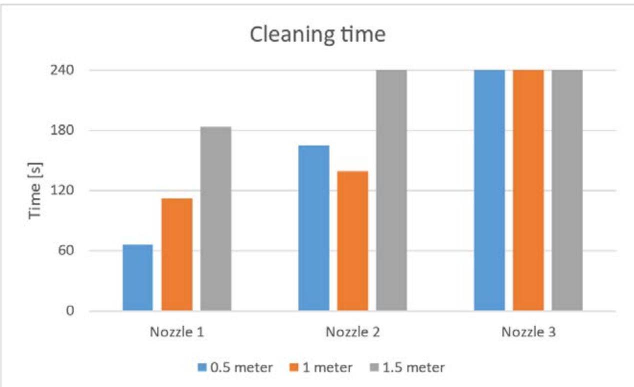


Figure 16. The time it takes to clean a section of sheet pile wall. Results of 240 s are at the cutoff time of measuring.

V. Discussion

The testing was limited by the time available. There were two testing days possible which were fully utilized. If there had been more time, more extensive tests could have been executed.

Since the water jet in the impact test was aimed downward, gravity was acting in the jet's favor. This means that when jetting horizontally or even upwards, there might be a more significant difference in the impact force at larger distances. Also, there was some sort of oscillation during the impact test, because while positive outliers are not very unexpected, there were also negative values recorded.

Since the measured values in the damage test had quite a large variance under the same conditions, the averaged values of three measurements still have a large standard deviation and there was no correlation visible between tests. So a larger number of measurements, or a more even paint application, is beneficial.

The speed test has various limitations. The movement of the attachment, and the nozzle, was done by an operator, so the movement will not be identical between tests. It was also inexact to determine when a section was completely cleaned. The material composition between sections was also possibly not identical, since it was material that naturally accumulated, causing differences in material properties. Also, since the night before it was freezing and later in the day the temperature climbed, this caused the material to transition from frozen to thawed, changing the properties between tests. The speed test is also limited in its contribution to understanding how fast the concept would clean a hold, due to a small and non-representative area.

VI. Conclusions & Recommendations

The main research question was: Is it possible to clean the hold of a coal bulk carrier by machine, and have the hold be cleaned faster and with less damage? However, the main research question is difficult to answer.

Firstly, from the testing it was evident that the water jet does not damage a paint layer. This means that a hold can be cleaned with the concept with no damage at all to the hold from the water jet. So the objective to cause less damage has been amply achieved.

Secondly, the speed test gave valuable information about the relative performance of the nozzles and standoff distances. However, the material conditions during the speed test are not comparable to an actual dirty hold, so the data it generated and that was used in calculating the cleaning time of an actual hold is inexact. The actual cleaning time of a hold can most easily be tested by cleaning a (section of a) hold. And while the impact force did not drop much at increasing standoff distance, the impact pressure does, and this effect was also visible in the speed test results where a greater distance resulted in longer cleaning times. So it is uncertain how well the concept would perform on spiral stairs in the hold where the standoff distance could be as much as 2-3 m. It was however also shown what working pressure is needed to maintain the minimum impact pressure needed for cleaning.

Lastly, for there to be no need for people in the hold, a remote (de)coupling system needs to be in place for the excavator. Similar systems as used for shipping containers are very common, so this can probably be relatively easily implemented. Also, a remote control system for the excavator itself is necessary, but such systems are commercially available on new models so this is also possible. The automation of the cleaning process will be difficult, but parts of this problem have already been tackled by the mining industry, and EMO has experience in this field so it is certainly possible.

The process of cleaning the stairs in a hold takes a lot of time and can be dangerous so a new concept can be a safer way to deal with the problem. The current machines used in the hold are not always usable in difficult-to-reach areas e.g. stairs. The use of these machines also can result in damage to a ship resulting in extra costs, while also damaging the reputation of EMO. The high docking costs, and potential demurrage costs, of bulk carriers also create a large financial incentive to reduce the cleaning time. So if the concept performs well in a hold time-wise, large savings can be realized, and potentially not only for EMO. Also, the new method is better at cleaning the difficult-to-reach last bits of material, so a higher cleaning standard can be attained, which is good for the reputation of EMO. Since no specific research has been done about the cleaning of large quantities of stuck material in bulk carrier holds, this topic of study is very relevant for EMO and on a global scale and worth further investigation.

Further, the following recommendations for further study are proposed:

- Further research into oscillating flow, since the initial transient pressure is very large relative to the steady-state impact pressure [8, 9].
- Can air be added to the jet to decrease the water usage without losing too much impact force?
- Are moveable nozzles better than always having to move the entire excavator boom & arm.
- Further testing:
  - Testing more nozzle types.
  - Testing more nozzle sizes. Is a bigger nozzle better? Or is too much water used?
  - Test with a more powerful pump at higher pressures.
  - Test with jetting at the material under multiple angles, what cleans the wall the fastest?
  - Investigating the effect of multiple nozzles and multiple nozzle types.
  - Test the cleaning performance in a hold to properly evaluate the speed.
  - Test in a hold to see if splashback is a problem.
- Automation:
  - Investigate how an automatic (dis)connecting system between excavator and shore crane can work.
  - Develop a way to scan the geometry of a hold and have an excavator operate autonomously in that hold.

References

[1] Statista, "Number of ships in the world merchant fleet as of January 1, 2019, by type," , 2019. URL https://web.archive.org/web/20191222052736/https://www.statista.com/statistics/264024/number-of-merchant-ships-worldwide-by-type/, accessed on June 7, 2021.

[2] Caterpillar, "Medium Excavators 326," , 2021. URL https://www.cat.com/en_US/products/new/equipment/excavators/medium-excavators/15970425.html, accessed on January 6, 2022.

[3] Caterpillar, "Frontless Excavators 374F OEM," , 2021. URL https://www.cat.com/en_US/products/new/equipment/excavators/frontless-excavators/1000005964.html, accessed on January 6, 2022.

[4] EZtronics, "S Type Load Cell (0-500kg) - CZL301," , 2021. URL https://www.eztronics.nl/webshop2/catalog/Sensor/Force-Pressure?product_id=466, accessed on January 5, 2022.

[5] Instruments, N., "USB-6002," , 2021. URL https://www.ni.com/nl-nl/support/model.usb-6002.html, accessed on January 5, 2022.

[6] Scaime, "Strain gage conditioner CPJ / CPJ2S," , 2021. URL https://scaime.com/product/post/cpj---cpj2s, accessed on January 5, 2022.

[7] sheen, T., "LAAGDIKTEMETER POSITECTOR 6000," , 2021. URL https://tqcsheen.com/nl/product/laagdiktemeter-positector-6000/, accessed on January 6, 2022.

[8] Huang, F., Mi, J., Li, D., and Wang, R., "Impinging Performance of High-Pressure Water Jets Emitting from Different Nozzle Orifice Shapes," *Geofluids*, 2020, pp. 1–14. doi: 10.1155/2020/8831544.

[9] Foldyna, J., Sitek, L., Ščučka, J., Martinec, P., Valíček, J., and Páleníková, K., "Effects of pulsating water jet impact on aluminium surface," *Journal of Materials Processing Technology*, Vol. 209, 2009, pp. 6174–6180. doi: 10.1016/j.jmatprotec.2009.06.004.

B

Appendix B: Data

B.1. Multi-criteria analysis scores

	Safety & Environment			Damage			Costs & Speed					
	Noise level	Risk	Dust pollution	Hold damage	Ship damage	Cargo pollution	Initial cost	Robustness	Cleaning perf.	Speed	Feasible	YO
Score weight (1-5)	2	5	3	4	4	3	4	4	5	4	5	
Low pressure washer	4	5	5	5	5	1	4	4	3	3	5	175
High pressure washer	3	4	5	5	5	4	4	3	5	4	5	187
Air compressor	3	4	2	5	5	5	4	3	2	3	5	162
Air/water HP combi	3	4	5	5	5	5	4	3	4	4	5	185
Vibration needles	4	5	4	4	5	5	3	2	2	2	5	159
Vibration plate	1	4	4	3	3	5	4	3	4	5	4	161
Air cannon	1	2	2	5	5	5	3	4	3	3	3	143
Sound horn	1	2	4	5	5	5	3	3	3	3	3	145
Aeration nozzle	4	4	3	5	5	5	3	2	2	2	2	140
Explosives	1	1	2	4	4	5	3	3	3	3	2	121
Pneumatic transport	4	3	5	4	5	5	1	2	2	1	1	120
Hydraulic transport	4	3	5	4	5	3	1	2	2	1	1	114
Large brush	5	4	4	3	5	5	4	2	3	3	5	165

(a) MCA scores of cleaning method of Yolt Oudshoorn

	Safety & Environment			Damage			Costs & Speed					
	Noise level	Risk	Dust pollution	Hold damage	Ship damage	Cargo pollution	Initial cost	Robustness	Cleaning perf.	Speed	Feasible	GV
Score weight (1-5)	2	5	3	4	4	3	4	4	5	4	5	
Low pressure washer	5	5	5	5	5	2	4	4	3	2	5	176
High pressure washer	3	3	5	5	5	3	4	3	5	4	5	179
Air compressor	4	4	1	5	5	5	4	3	2	3	5	161
Air/water HP combi	3	4	4	5	5	4	4	3	4	4	5	179
Vibration needles	3	4	3	4	5	5	4	2	2	2	5	153
Vibration plate	1	3	3	3	3	5	4	3	4	5	4	153
Air cannon	1	2	2	5	5	5	3	4	3	3	3	143
Sound horn	1	1	3	5	5	5	3	3	3	3	2	132
Aeration nozzle	3	3	2	5	5	5	3	2	2	2	2	130
Explosives	1	1	2	4	4	3	3	3	3	3	2	115
Pneumatic transport	3	3	5	4	5	5	1	2	2	1	1	118
Hydraulic transport	4	3	5	4	5	3	1	2	2	1	1	114
Large brush	5	3	4	3	5	5	4	3	3	2	5	160

(b) MCA scores of cleaning method of Geert Volmer

	Safety & Environment			Damage			Costs & Speed					
	Noise level	Risk	Dust pollution	Hold damage	Ship damage	Cargo pollution	Initial cost	Robustness	Cleaning perf.	Speed	Feasible	FL
Score weight (1-5)	2	5	3	4	4	3	4	4	5	4	5	
Low pressure washer	2	4	5	5	5	4	4	3	4	3	3	166
High pressure washer	3	3	5	5	5	3	4	3	5	4	4	174
Air compressor	3	3	3	5	5	2	3	3	4	3	3	147
Air/water HP combi	2	3	4	5	5	2	4	3	5	4	4	166
Vibration needles	3	4	3	3	3	5	2	4	3	4	4	149
Vibration plate	1	2	2	3	3	5	2	3	3	4	4	128
Air cannon	1	2	1	2	2	5	3	3	3	3	3	112
Sound horn	1	2	2	4	4	5	2	2	4	5	3	136
Aeration nozzle	4	3	3	5	5	5	3	3	4	3	3	158
Explosives	1	1	1	2	2	2	4	4	4	4	2	110
Pneumatic transport	1	3	3	3	3	5	4	2	3	3	2	126
Hydraulic transport	3	2	4	3	3	5	4	2	3	3	2	128
Large brush	3	3	4	3	3	4	2	2	3	3	3	127

(c) MCA scores of cleaning method of Fred Leurs

Figure B.1: Individual MCA scores of cleaning method

	Reach & Control			Operations		Costs & Speed				
	Reach in hold	Ease of reach	Ease of control	Crane impedance	Remote control	Initial cost	Robustness	Speed	Feasible	YO
Score weight (1-5)	5	3	2	4	4	4	4	3	5	
Fixed to crane	4	4	3	1	4	4	4	4	3	117
Concrete pump truck shore	3	1	2	2	4	2	4	3	2	89
Crane on extra ship	4	1	2	4	4	1	4	2	2	95
CAT329	4	5	5	4	4	4	4	4	5	146
Platform lift	4	4	4	4	2	3	4	4	4	124
Magnetic wall vehicle	2	4	3	5	5	2	2	5	4	119
Hang from (machine on) deck	3	4	4	3	4	4	4	4	3	122
Handheld	1	2	2	4	1	5	3	5	2	92
All terrain vehicle in hold	4	4	3	4	5	4	3	5	4	137

(a) MCA scores of reaching method of Yolt Oudshoorn

	Reach & Control			Operations		Costs & Speed				
	Reach in hold	Ease of reach	Ease of control	Crane impedance	Remote control	Initial cost	Robustness	Speed	Feasible	GV
Score weight (1-5)	5	3	2	4	4	4	4	3	5	
Fixed to crane	4	2	3	1	4	4	4	3	3	108
Concrete pump truck shore	3	2	3	5	5	3	3	3	2	110
Crane on extra ship	3	2	2	4	4	1	4	3	2	96
CAT329	4	5	4	3	4	4	4	4	5	140
Platform lift	4	4	4	3	2	3	3	4	3	111
Magnetic wall vehicle	4	4	4	4	5	3	2	2	4	122
Hang from (machine on) deck	3	4	3	3	4	2	4	3	2	104
Handheld	1	2	4	5	1	5	3	1	4	98
All terrain vehicle in hold	3	4	3	4	5	3	3	4	4	125

(b) MCA scores of reaching method of Geert Volmer

	Reach & Control			Operations		Costs & Speed				
	Reach in hold	Ease of reach	Ease of control	Crane impedance	Remote control	Initial cost	Robustness	Speed	Feasible	FL
Score weight (1-5)	5	3	2	4	4	4	4	3	5	
Fixed to crane	4	3	3	2	5	3	4	5	2	116
Concrete pump truck shore	3	1	3	1	5	5	4	4	3	111
Crane on extra ship	5	4	3	2	3	5	5	4	3	130
CAT329	4	4	4	2	4	4	3	4	4	124
Platform lift	5	5	5	4	5	4	3	5	5	154
Magnetic wall vehicle	1	4	4	4	5	4	2	3	3	109
Hang from (machine on) deck	2	4	4	3	3	3	4	3	3	106
Handheld	5	4	3	4	1	5	2	3	3	115
All terrain vehicle in hold	1	1	3	1	3	3	3	2	3	75

(c) MCA scores of reaching method of Fred Leurs

Figure B.2: Individual MCA scores of reaching method

B.2. Testing raw data

B.2.1. Impact test

Calibration	n1p100x0.5	n1p140x0.5	n1p180x0.5	n2p100x0.5	n2p140x0.5	n2p180x0.5	n3p100x0.5	n3p140x0.5	n3p170x0.5	n1p100x1	n1p140x1	n1p180x1
97.754	117.856	141.636	159.705	116.630	138.571	161.447	130.859	165.190	185.13	133.86	138.248	150.509
98.464	122.405	127.439	128.310	128.439	128.278	157.414	129.407	119.727	132.698	119.856	158.543	140.313
97.529	119.276	114.371	129.601	147.347	150.154	150.412	115.985	159.221	150.541	118.017	137.054	123.696
97.593	131.892	141.797	152.219	129.375	136.280	167.642	134.957	137.893	150.896	129.439	122.889	150.864
99.142	127.891	151.767	134.150	118.308	136.990	154.607	131.182	122.470	116.081	127.181	128.02	127.536
96.883	135.473	139.700	120.502	153.219	147.605	163.448	113.500	124.600	148.476	129.536	142.636	124.729
98.367	140.378	133.215	167.094	129.310	138.732	179.032	124.729	149.896	119.566	125.793	130.02	140.119
98.174	121.567	130.988	105.014	109.564	136.183	153.606	120.018	142.894	140.829	118.082	131.795	144.249
99.077	118.372	135.441	165.545	159.479	147.670	155.478	131.311	123.373	153.542	116.694	113.597	134.408
96.625	117.985	109.112	154.220	115.597	146.185	150.606	120.792	128.794	116.694	135.247	125.019	150.057
98.69	126.697	127.278	154.445	114.145	118.727	163.544	130.020	124.503	161.06	144.378	134.796	138.248
97.819	132.505	126.471	150.864	142.023	152.187	169.933	117.469	123.890	123.696	127.181	138.409	119.372
98.497	120.276	129.407	148.928	131.085	122.599	151.735	142.313	157.478	161.77	134.57	154.155	144.378
98.787	125.955	112.887	176.418	133.247	144.992	152.477	115.856	131.440	167.578	138.829	165.835	151.671
97.916	119.792	148.670	113.694	127.826	138.506	147.670	125.471	151.671	127.987	103.853	149.928	172.417
93.915	91.592	130.246	124.793	156.349	140.313	138.377	134.796	113.145	181.129	134.086	106.498	159.898
102.013	126.374	127.310	149.218	135.731	152.768	157.478	140.797	141.475	111.919	120.631	136.667	158.93
98.69	113.565	127.503	128.955	119.405	139.668	150.832	125.793	149.735	134.505	120.889	126.955	151.445
98.561	114.049	119.986	182.549	154.413	154.768	172.740	123.244	126.761	166.706	122.793	145.637	129.439
98.529	137.506	118.211	144.540	120.308	141.120	162.770	132.860	164.480	146.702	126.471	136.344	135.925
98.755	124.309	138.764	130.569	122.470	138.183	131.020	141.862	121.986	170.804	113.436	130.924	184.001
98.884	117.824	141.475	152.445	138.409	134.376	146.798	139.442	149.412	159.931	132.795	142.443	129.956
98.077	135.505	125.729	106.402	127.503	137.732	144.443	112.403	133.634	196.423	136.215	120.663	149.864
98.561	151.445	130.762	125.632	128.407	141.636	151.800	143.959	121.115	135.215	115.307	139.377	153.026
97.593	132.279	156.930	131.408	135.860	131.601	161.673	148.025	119.502	129.568	127.858	151.122	170.675
96.915	129.698	130.472	146.089	136.990	156.155	134.408	107.757	141.475	185.324	115.759	124.729	148.767
98.303	119.502	129.181	165.480	124.793	154.768	158.769	140.603	133.602	145.863	128.633	122.535	123.986
95.431	134.860	163.867	122.470	124.374	142.281	157.414	123.793	132.860	164.932	130.956	111.306	152.961
100.497	125.890	146.863	148.638	133.989	131.117	148.379	131.892	130.246	137.28	122.373	141.345	133.731
98.98	108.692	136.409	144.443	131.633	142.410	170.417	121.437	118.275	132.731	139.055	150.477	154.478
97.174	122.728	123.083	114.242	123.115	157.995	119.018	120.663	155.542	163.835	119.05	100.755	141.152
97.883	112.823	129.827	127.600	160.737	158.124	155.349	128.697	126.987	111.403	125.438	137.345	169.062
102.917	125.987	143.507	141.636	127.858	138.119	181.581	121.986	126.826	134.376	127.342	145.121	159.027
98.561	125.858	156.381	166.900	121.986	145.959	141.507	118.179	122.986	161.802	105.466	150.283	149.283
97.658	115.210	149.186	121.050	148.702	154.994	147.379	125.503	149.638	107.918	126.6	135.215	127.116
97.593	126.890	155.317	111.177	135.602	153.865	162.028	132.634	127.084	145.798	116.823	158.511	164.061
98.916	120.308	112.758	153.316	127.762	139.506	150.928	121.083	120.889	121.276	113.758	123.341	148.186
94.496	120.340	149.767	148.347	135.570	152.864	157.317	126.116	160.770	128.73	122.115	132.247	132.634
97.754	125.374	126.955	155.510	139.764	137.345	157.672	122.405	103.046	177.386	116.694	125.471	150.186
98.626	136.602	152.864	172.353	120.599	148.734	130.730	114.920	123.309	119.405	124.858	136.344	136.667
97.819	133.279	121.405	127.503	144.927	140.378	171.933	132.247	135.667	135.344	111.338	148.121	161.673
98.626	139.829	143.604	144.024	125.858	139.668	146.960	140.442	127.536	164.9	118.985	147.928	153.123
97.399	117.566	128.213	133.279	115.049	141.700	177.870	134.731	182.775	162.544	118.146	136.925	135.021
98.174	119.953	127.278	132.311	133.021	129.923	130.859	121.405	136.796	162.221	120.018	117.404	174.224
99.497	126.858	120.373	133.053	148.250	142.636	142.894	138.022	145.863	122.631	118.953	136.344	146.476
98.303	122.083	141.249	144.508	130.536	137.119	167.836	129.084	127.633	162.383	128.084	148.573	132.795
96.722	122.986	133.408	169.675	135.054	139.474	134.182	131.375	135.796	138.926	118.275	140.087	157.123
98.335	107.273	118.017	113.984	146.250	140.732	159.898	122.470	138.538	155.091	136.506	137.861	148.121
96.915	121.244	153.671	159.608	140.668	156.285	159.447	121.986	157.930	145.508	126.116	139.022	152.251
97.69	122.825	142.572	164.738	123.438	140.603	155.833	127.439	95.593	113.081	122.76	127.891	147.218
97.045	110.725	134.053	114.242	139.119	143.346	168.126	135.764	139.603	157.575	145.83	155.607	160.221
99.723	143.346	153.897	177.967	129.698	141.475	149.831	123.890	150.477	144.185	127.052	146.411	154.09
100.142	125.019	133.215	123.341	112.500	158.834	149.864	125.568	162.641	134.957	117.275	110.467	129.698
97.27	135.667	138.442	153.961	143.120	142.668	128.439	135.183	136.506	159.35	128.149	144.798	130.117
97.69	134.925	124.374	158.995	122.180	151.445	140.603	119.308	144.798	132.924	121.147	129.246	169.094
96.657	127.342	145.185	139.539	128.278	150.993	150.186	126.535	108.209	165.545	134.763	153.348	130.117
97.529	137.699	135.796	152.509	122.535	145.217	150.541	120.921	126.439	108.467	129.536	149.025	129.73
98.367	125.309	148.831	151.541	133.376	141.797	164.964	117.307	135.150	137.538	122.341	152.961	129.956
97.916	130.440	110.854	153.187	122.147	148.444	150.735	125.213	148.605	145.217	127.374	153.703	146.411
98.013	129.407	138.054	155.994	127.955	136.538	161.479	110.177	135.215	151.703	103.949	124.987	142.023
98.884	124.664	151.380	138.313	146.605	163.706	161.673	130.633	129.439	171.224	129.601	140.152	125.729
99.464	124.116	120.921	149.541	117.437	151.316	145.863	139.119	135.860	180.355	131.311	149.864	120.115
98.142	118.469	140.410	139.506	123.502	144.637	161.221	140.378	125.342	164.996	133.311	139.603	114.145
99.594	128.020	119.050	136.893	151.154	143.217	162.673	126.342	152.832	130.827	137.119	144.959	132.085
96.915	109.241	129.117	158.414	127.503	145.056	154.768	133.311	115.017	131.343	129.601	113.016	120.502
98.238	121.244	146.766	115.178	118.275	131.246	154.155	132.698	137.248	143.475	127.503	123.696	137.667
97.625	116.243	99.368	166.868	158.221	131.795	141.991	143.378	140.345	155.284	119.179	146.218	144.766
97.561	120.115	164.093	164.964	134.989	152.187	152.961	127.568	119.082	152.993	113.403	139.313	133.085
98.755	122.147	147.379	159.253	121.889	137.474	147.411	123.244	157.123	147.089	138.377	134.021	116.92
99.464	131.730	127.019	156.123	133.085	144.217	164.125	128.181	140.087	125.89	132.182	138.506	137.345
97.754	134.828	119.147	123.051	139.216	149.444	130.698	125.406	166.448	169.126	132.634	132.537	169.836
97.754	122.535	142.475	146.766	101.465	140.507	156.026	124.277	123.309	109.951	143.894	140.216	126.665
97.206	128.730	153.800	146.250	143.023	136.796	146.282	123.115	129.472	158.866	128.6	119.953	142.797
98.206	120.018	105.498	154.607	140.894	136.022	160.318	117.404	148.638	144.83	119.695	165.835	148.412
100.078	109.660	141.991	151.154	122.083	131.343	159.253	126.245	126.987	126.568	120.276	150.703	151.025
97.464	126.890	133.989	124.406	128.988	137.054	143.185	139.022	138.313	126.665	112.08	140.829	165.351
96.819	116.920	130.633	178.129	133.537	166.771	158.866	104.562	155.349	149.735	132.892	133.666	131.472
98.593	133.344	167.771	145.346	134.312	133.279	125.084	129.020	101.336	150.961	118.792	124.922	187.002
97.593	128.471	115.436	137.570	118.953	130.278	140.410	131.698	152.251	127.536	126.148	125.697	137.861
100.529	114.178	146.540	146.024	142.313	146.540	139.894	111.984	136.280	125.697	128.439	145.572	156.026
97.948	137.441	136.506	131.117	138.732	142.830	154.478	133.957	138.474	128.407	110.532	136.861	156.93
98.432	114.210	114.662	167.287	113.629	149.831	163.351	129.665	167.642	145.153	120.373	137.054	155.51
98.626	136.893	148.412	162.544	141.184	149.896	138.926	134.666	110.951	154.833	97.109	117.888	160.866
97.464	119.372	129.665	130.020	138.861	164.577	141.829	122.760	151.219	174.741	115.339	142.927	134.441
97.399	121.889	137.441	146.250	113.436	144.443	147.670	133.957	109.757	156.93	128.6	157.543	125.374
97.238	109.983	144.604	114.920	135.247	139.022	161.092	134.602	161.189	138.732	122.922	131.311	129.73
97.593	106.821	130.601	144.637	137.958	143.669	132.117	123.277	120.050	168.965	129.762	131.601	179.58
99.948	118.405	154.929	158.027	114.178	150.186	169.772	140.765	136.377	132.376	127.665	111.177	144.153
97.883	123.632	144.959	134.957	133.731	144.378	150.832	110.048	153.187	138.635	119.921	139.926	153.606
97.109	118.114	136.473	158.027	141.733	165.351	142.765	127.955	114.726	157.737	125.18	145.605	129.665
98.174	122.696	121.986	134.634	113.113	134.828	142.604	141.507	136.635	141.281	122.793	143.346	137.829
96.625	124.148	115.985	165.771	122.857	153.897	125.019	137.764	158.834	133.731	128.31	133.053	156.607
97.787	130.988	121.631	136.022	137.119	141.313	160.737	129.698	136.538	137.829	119.856	134.796	134.86
98.529	129.988	139.377	122.922	128.052	145.282	131.053	125.084	148.347	119.889	121.76	132.827	148.67
98.238	127.826	137.603	181.097	104.530	123.502	154.671	134.086	108.305	157.156	117.469	135.86	166.061
97.754	153.961	97.722	110.790	150.638	136.022	162.705	126.955	143.862	148.025	122.728	120.599	152.993
97.045	122.147	124.309	137.183	127.213	143.927	166.835	119.147	169.449	158.995	115.856	147.541	139.829
96.625	118.308	143.314	183.130	128.471	136.667	169.675	135.150	113.726	163.48	119.437	126.729	118.437
101.045	139.829	145.282	133.892	141.991	146.121	131.246	128.762	134.666	150.283	126.923	150.315	159.672
98.432	125.116	118.372	153.284	125.148	139.635	156.672	143.023	119.598	147.831	126.148	137.474	143.54

Table B.1: Impact force part 1/2

n2p100x1	n2p140x1	n2p180x1	n3p100x1	n3p140x1	n3p170x1	n1p100x1.5	n1p140x1.5	n1p180x1.5	n2p100x1.5	n2p140x1.5	n2p180x1.5	n3p100x1.5	n3p140x1.5	n3p170x1.5
134.828	165.48	152.219	129.439	126.987	144.088	113.887	128.052	148.831	127.471	146.185	143.572	140.184	153.123	151.187
143.185	118.759	151.541	124.503	138.183	159.769	134.473	115.597	122.276	126.051	157.769	171.353	115.856	123.986	130.956
136.022	179.806	153.8	129.988	132.505	111.177	99.013	157.059	148.605	133.731	157.672	124.567	136.764	163.222	160.608
133.698	149.283	134.666	141.765	142.539	163.802	143.346	123.696	100.207	123.341	146.96	156.414	137.99	105.143	144.54
135.731	128.568	152.187	106.66	129.568	125.051	120.018	149.218	124.116	146.605	142.313	135.376	111.177	162.673	140.119
124.051	156.833	180.484	136.409	134.053	151.671	112.435	130.633	143.83	123.857	142.378	157.704	119.534	127.116	159.995
122.115	128.31	109.306	116.404	130.666	145.863	138.054	138.409	120.405	123.148	137.764	159.672	129.504	131.73	136.602
132.795	159.737	165.158	119.824	139.087	130.214	121.502	130.924	138.603	148.734	163.125	136.344	124.341	161.673	156.639
127.6	136.602	161.641	119.598	121.567	155.026	121.631	120.47	130.02	110.919	148.218	180.194	125.729	102.949	121.792
119.147	144.12	116.823	141.313	147.379	140.7	125.793	141.894	153.187	137.086	158.511	122.631	126.245	158.801	134.537
150.348	148.702	179.968	125.471	124.987	135.247	115.985	127.019	149.476	145.83	129.084	177.096	140.7	123.986	165.803
124.406	149.154	108.66	139.571	145.056	156.962	122.373	98.755	119.727	110.822	161.253	146.314	131.763	139.506	144.54
138.571	146.992	191.099	119.921	134.989	140.023	116.178	150.574	126.406	149.541	133.892	131.02	106.176	151.283	141.12
127.407	146.992	144.153	124.825	141.636	154.671	107.725	103.982	90.817	131.601	152.284	185.421	132.956	147.734	171.224
136.828	138.248	150.767	137.538	128.923	142.701	126.406	150.799	131.956	128.213	150.864	114.726	131.149	120.76	135.828
128.794	145.766	163.738	124.18	139.41	153.542	105.046	136.861	148.057	130.795	138.603	157.833	91.656	168.384	183.517
113.694	151.735	135.118	131.859	123.212	131.956	128.568	118.663	125.987	127.116	151.025	177.031	149.186	94.818	128.697
158.575	143.862	166.029	130.859	127.633	158.511	121.567	133.053	132.989	140.862	129.407	107.434	117.404	155.22	138.635
105.627	140.248	150.348	124.083	144.378	136.506	115.049	127.955	134.376	125.793	168.546	148.347	142.249	105.272	156.188
159.124	141.765	165.158	136.312	117.566	149.735	131.666	134.796	132.537	132.505	136.183	164.512	122.889	154.252	136.183
134.86	132.989	168.158	117.759	151.961	152.058	114.92	128.181	135.86	130.052	147.218	129.02	112.468	128.6	160.382
107.402	151.154	149.896	129.665	125.245	137.506	130.666	127.6	114.404	126.665	152.025	170.191	124.567	124.18	139.958
151.832	138.345	165.125	121.76	136.506	144.766	113.048	129.665	152.864	119.179	129.536	149.315	119.276	147.282	140.991
123.244	161.802	166.416	127.923	132.731	162.092	129.794	128.6	127.342	136.247	151.219	143.314	115.468	128.439	151.703
136.602	123.599	145.669	131.149	134.441	140.474	129.214	111.855	115.856	97.045	133.537	155.833	137.054	134.247	137.119
120.986	153.252	131.73	110.241	126.084	147.734	121.567	135.699	141.733	168.029	154.607	133.344	113.887	124.374	127.245
133.795	157.898	172.772	137.829	134.118	132.569	125.084	111.5	119.663	104.53	137.312	152.025	125.148	136.022	172.998
126.439	136.602	135.441	125.213	141.829	145.863	132.731	124.245	142.378	124.503	151.283	180.097	142.83	126.535	122.438
118.856	154.316	152.832	124.019	127.31	144.282	109.047	138.764	113.726	144.249	140.862	134.408	92.915	157.898	170.482
146.282	131.956	169.868	140.442	144.959	137.119	123.115	111.274	138.764	96.883	133.053	163.738	130.666	123.341	146.411
121.502	130.601	126.6	125.535	122.857	143.927	112.177	130.924	131.117	131.149	168.61	131.537	114.952	159.188	136.635
119.276	153.639	177.064	123.502	152.961	153.187	109.919	121.728	111.693	123.664	121.663	163.48	123.954	119.631	157.575
112.984	129.956	166.222	131.666	122.535	142.701	121.76	109.047	114.533	129.827	149.606	123.793	130.44	142.184	133.731
150.477	171.837	123.696	110.983	141.216	162.641	126.632	121.405	147.766	123.567	141.475	155.188	119.792	135.021	154.994
120.115	155.542	175.87	148.444	139.345	132.731	118.921	120.631	122.599	127.149	137.054	170.352	119.114	133.505	139.603
128.439	128.536	149.831	124.148	125.955	157.091	133.505	132.021	146.573	151.445	146.379	136.828	126.31	134.344	170.643
139.474	142.346	161.479	125.148	138.119	153.897	111.467	130.214	147.153	102.336	156.769	173.514	112.887	155.478	145.605
105.24	147.024	142.959	126.535	127.923	134.796	128.02	134.279	114.468	148.831	125.277	135.086	109.306	138.151	127.439
140.345	158.091	154.123	112.693	146.508	168.094	119.921	121.534	137.441	134.666	165.254	157.317	113.5	118.695	148.412
121.986	138.796	136.28	135.183	119.018	133.376	130.44	105.046	131.537	110.435	163.835	168.32	137.054	133.44	138.087
141.733	148.928	174.321	123.244	138.99	152.542	133.763	138.313	128.988	109.338	118.921	146.347	106.95	125.471	154.284
111.08	148.896	161.124	126.277	119.114	155.93	89.398	119.534	116.178	149.283	178.774	133.989	119.34	125.664	127.439
135.731	158.995	155.575	129.536	136.602	114.371	117.017	108.112	144.249	124.535	147.799	142.991	133.085	147.282	166.739
151.703	155.833	154.381	116.985	138.087	172.934	135.505	118.437	148.896	128.6	141.539	133.763	95.076	127.019	147.895
108.757	145.25	161.834	128.084	126.116	135.473	122.147	121.115	124.18	143.443	174.418	176.773	143.54	137.829	144.927
135.925	140.313	173.256	119.76	145.798	135.28	132.763	117.566	129.827	113.21	115.081	138.022	104.078	142.217	154.736
131.246	140.926	151.703	131.311	100.432	176.741	111.596	126.858	140.926	140.442	150.993	148.638	132.537	123.954	145.701
125.084	138.345	155.801	118.695	167.029	104.756	115.791	139.313	129.278	125.503	147.024	136.99	140.345	117.727	151.638
128.084	154.994	154.736	126.051	101.239	175.773	107.37	135.925	138.248	129.859	133.795	130.311	106.24	134.537	138.99
129.343	150.412	145.25	131.02	140.571	137.635	108.789	118.017	126.051	122.793	160.737	179.355	136.764	149.702	159.188
133.86	132.408	154.123	121.244	134.602	132.117	119.76	141.313	118.598	126.084	152.348	103.24	120.437	112.532	137.441
111.564	169.998	147.702	112.887	110.048	160.35	124.212	101.142	148.767	150.09	134.989	181.742	131.633	176.193	143.54
141.055	140.926	176.515	146.476	142.83	111.209	123.277	128.633	125.342	101.11	144.024	145.379	121.341	113.339	163.932
137.409	139.732	149.347	118.372	126.245	162.157	124.212	112.919	146.831	149.057	151.251	152.735	114.629	148.154	139.151
113.436	163.544	152.348	136.861	130.182	149.573	119.856	122.051	124.922	130.44	122.76	180.194	129.504	111.822	152.671
145.734	128.633	156.188	122.889	144.411	130.569	118.275	128.213	128.762	97.206	171.095	138.506	120.05	130.827	145.024
131.408	148.347	140.023	116.339	122.115	168.158	112.113	120.179	158.608	164.48	121.437	146.895	120.986	134.892	133.892
138.442	147.379	164.803	138.99	129.762	132.956	124.116	119.566	108.079	108.176	163.77	145.766	116.598	130.407	166.061
114.565	130.472	133.344	109.725	153.252	148.605	125.245	130.246	157.188	135.473	147.508	145.992	134.731	139.474	134.312
134.57	159.447	168.255	127.762	109.144	148.379	127.955	115.113	135.764	136.538	135.505	179.258	110.403	148.638	146.411
114.888	123.277	147.734	138.087	148.831	126.826	119.631	130.536	117.178	125.438	162.996	139.668	147.508	137.732	157.091
121.825	143.991	146.056	110.79	127.245	154.897	121.47	128.181	130.117	131.117	136.957	151.477	113.597	149.38	143.733
155.091	149.864	153.348	145.734	124.083	118.469	129.956	121.405	123.825	119.727	121.018	154.381	127.6	130.859	152.897
123.632	136.957	178.419	107.337	160.834	174.547	110.983	145.443	141.733	136.731	153.413	132.376	127.052	147.024	160.834
107.789	156.091	160.673	148.863	116.953	116.727	128.73	115.436	149.573	115.856	113.21	176.87	110.467	124.761	132.537
149.638	140.248	160.737	118.727	159.608	148.541	107.241	114.113	132.666	153.51	156.155	127.923	143.475	147.831	163.802
129.31	170.159	161.479	122.986	130.375	150.928	114.662	106.563	119.986	128.859	163.77	139.571	99.013	158.575	141.571
119.018	117.662	156.639	124.6	133.053	148.218	107.241	98.497	144.766	117.566	141.7	178.677	148.96	108.273	140.603
138.183	154.897	163.577	120.276	141.249	119.76	122.341	122.212	130.311	142.83	157.962	99.594	119.018	181.807	148.508
131.73	146.669	132.666	131.988	118.308	147.992	125.309	137.958	133.053	125.535	142.797	213.169	125.6	97.238	157.414
126.632	157.123	173.031	129.278	143.604	151.8	98.948	114.565	127.923	133.828	140.7	81.621	130.311	163.577	144.217
117.017	159.802	149.347	125.438	124.18	129.73	131.343	148.67	130.407	137.377	135.312	160.705	114.726	120.018	148.283
159.705	130.698	165.9	128.342	144.153	142.83	113.468	109.08	143.798	141.765	159.156	143.733	131.085	148.573	136.312
109.37	167.513	145.734	123.793	122.502	125.826	135.893	140.378	137.28	128.988	142.249	138.667	112.758	139.216	144.927
119.76	142.088	128.471	123.728	136.957	156.93	134.15	101.788	129.568	124.212	145.895	179.355	107.821	150.928	157.414
142.088	142.862	160.931	129.536	142.991	157.317	120.244	110.725	139.184	156.575	155.93	103.498	137.99	154.639	127.245
122.599	147.057	139.894	136.183	146.508	123.761	124.277	137.441	120.695	108.467	127.374	165.964	121.954	138.635	155.381
113.436	133.763	146.605	114.307	128.052	148.089	132.214	126.89	148.96	152.606	132.279	135.473	121.179	160.737	153.09
158.543	149.444	158.317	144.217	148.315	129.02	112.145	135.505	123.728	133.989	175.225	141.894	136.377	112.435	147.895
113.113	152.703	147.895	119.631	146.218	146.089	121.308	156.22	115.372	110.661	113.629	142.83	130.504	172.353	146.992
143.152	150.799	147.863	115.694	115.017	139.055	129.407	110.564	153.09	152.348	158.479	172.353	107.821	121.341	138.829
135.215	111.855	157.317	124.987	157.091	147.96	117.275	142.023	130.73	115.92	146.314	123.18	134.828	149.057	139.216
117.469	160.156	155.349	99.884	123.083	144.572	125.6	120.695	126.697	113.855	123.244	181.71	112.597	133.408	159.059
136.118	145.25	123.922	142.152	142.475	143.54	120.534	104.885	128.665	126.6	182.872	116.049	131.504	148.605	140.958
97.335	101.562	165.416	110.144	148.025	140.378	122.276	151.541	108.531	136.764	105.498	174.192	124.696	140.345	143.83
149.606	176.515	130.44	113.177	118.985	148.896	105.176	114.307	119.05	124.406	162.189	157.091	118.082	146.96	151.703
128.794	133.053	160.318	125.471	138.345	137.925	111.371	138.345	124.083	108.241	130.891	149.896	136.022	127.6	134.408
109.757	137.893	139.668	103.207	131.698	155.575	113.5	110.08	160.221	154.574	127.568	163.222	117.824	140.507	138.119
158.834	158.479	153.219	136.796	154.768	124.793	110.822	133.311	148.025	94.754	167.449	152.735	118.695	161.028	156.123
124.438	132.279	157.898	119.566	148.444	128.536	117.759	144.83	111.338	128.504	119.921	157.317	122.405	137.086	142.152
105.111	144.475	161.512	113.694	130.956	153.477	124.89	129.02	148.089	154.51	166.319	152.025	127.084	145.605	143.249
163.189	154.316	133.892	113.242	159.059	120.663	122.373	135.764	116.598	88.623	129.827	150.67	107.563	157.382	154.574
110.274	139.829	173.676	122.954	114.145	149.993	116.275	120.566	98.142	144.669	121.244	159.866	126.084	123.632	137.441
114.404	142.475	129.665	91.947	163.512	132.634	120.631	110.015	130.988	125.89	192.68	148.96	113.21	161.221	126.019
155.155	147.67	146.895	129.988	116.081	138.183	110.693	112.145	111.338	105.466	109.37	159.543	119.018	115.63	145.734
110.693	151.703	171.191	127.6	149.444	159.35	127.762	113.984	136.247	144.217	142.12	133.085	156.026	136.054	124.664
151.187	118.534	124.116	115.952	140.152	119.921	122.954	105.176	149.38	111.08	149.283	152.606	105.24	162.609	144.895
119.372	164.093	173.127	126.729	118.243	142.83	111.145	126.665	139.829	154.09	116.049	142.378	111.177	123.212	106.595
138.99	138.861	137.764	102.949	155.962	133.86	129.665	113.21	144.992	109.531	171.546	166.835	139.7	181.581	145.153
122.405	135.602	149.122	134.763	133.215	135.538	99.626	115.823	138.442	135.409	114.21	145.282	87.268	120.018	152.025

Table B.2: Impact force part 2/2

B.2.2. Damage test

	1.5 m	1 m	0.5 m	Reference
nozzle 1	50	52	56	66
	46	58	54	56
	50	52	68	52
nozzle 2	68	56	54	64
	64	62	58	66
	52	48	56	52
nozzle 3	66	60	56	60
	62	52	54	58
	52	54	66	62

Table B.3: Paint layer thickness measurements in microns

B.2.3. Speed test

	0.5 meter	1 mter	1.5 meter
Nozzle 1	66	112	184
Nozzle 2	165	140	>240
Nozzle 3	>240	>240	>240

Table B.4: Speed measurements in seconds

B.3. Complete impact results graphs

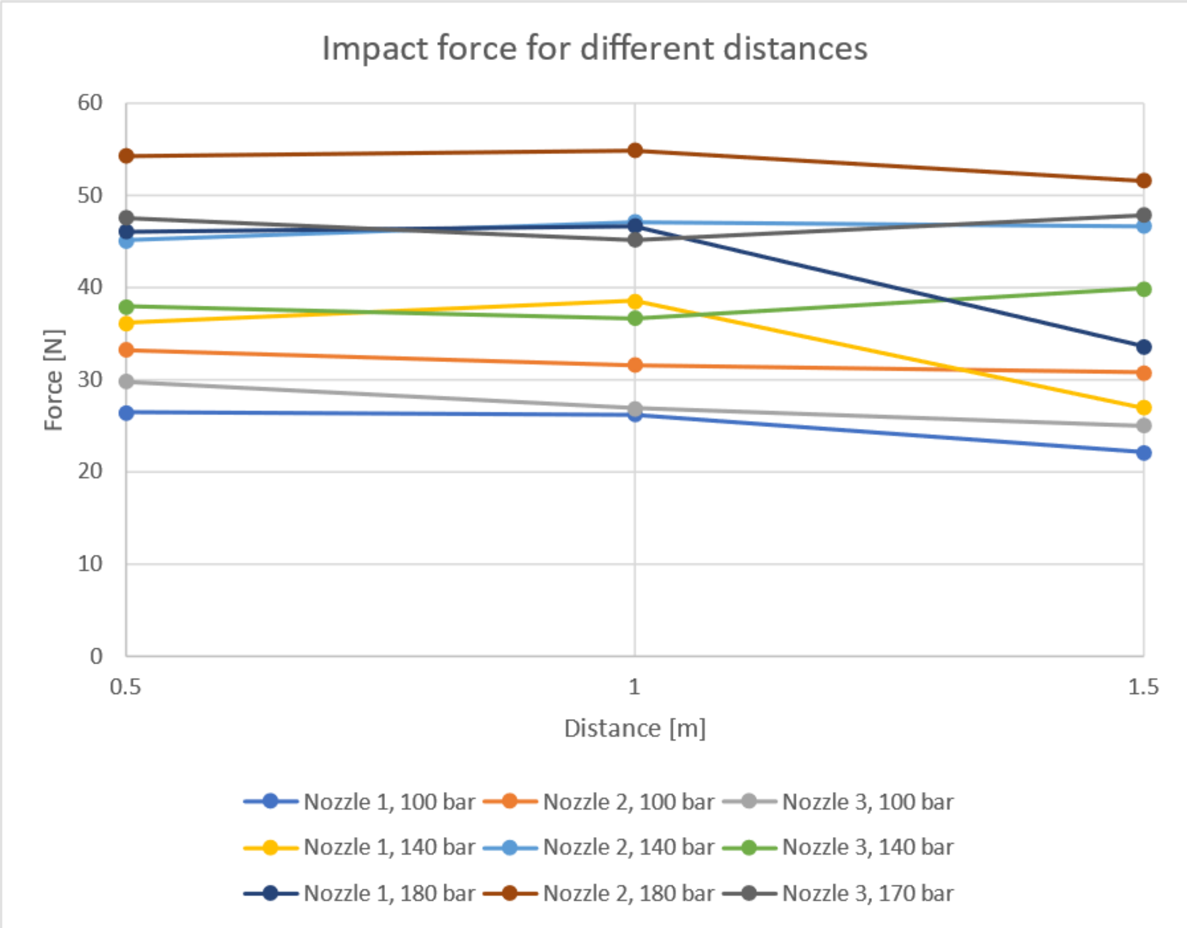


Figure B.3: Average impact force for various distances

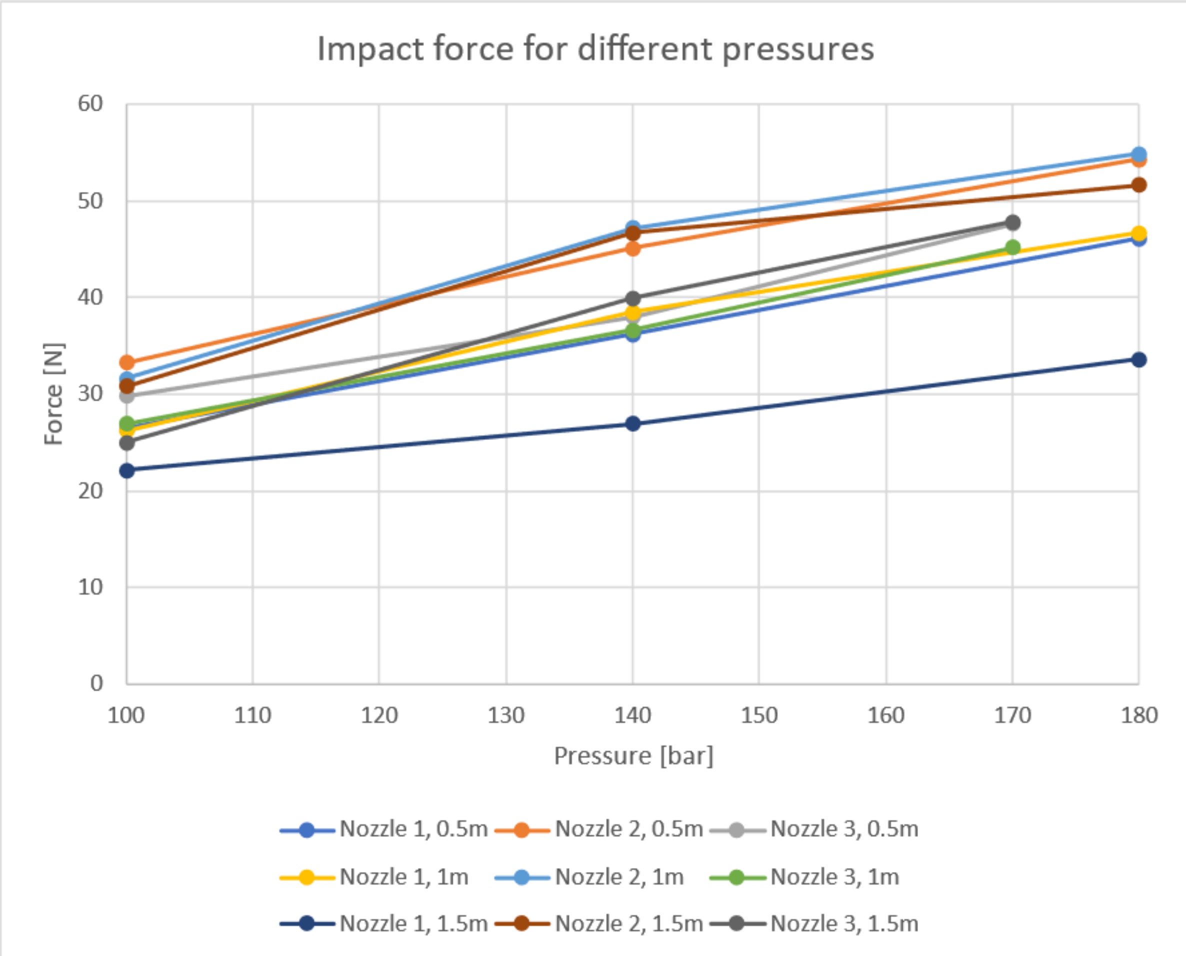


Figure B.4: Average impact force for various pressures

B.4. Complete impact pressure results graphs

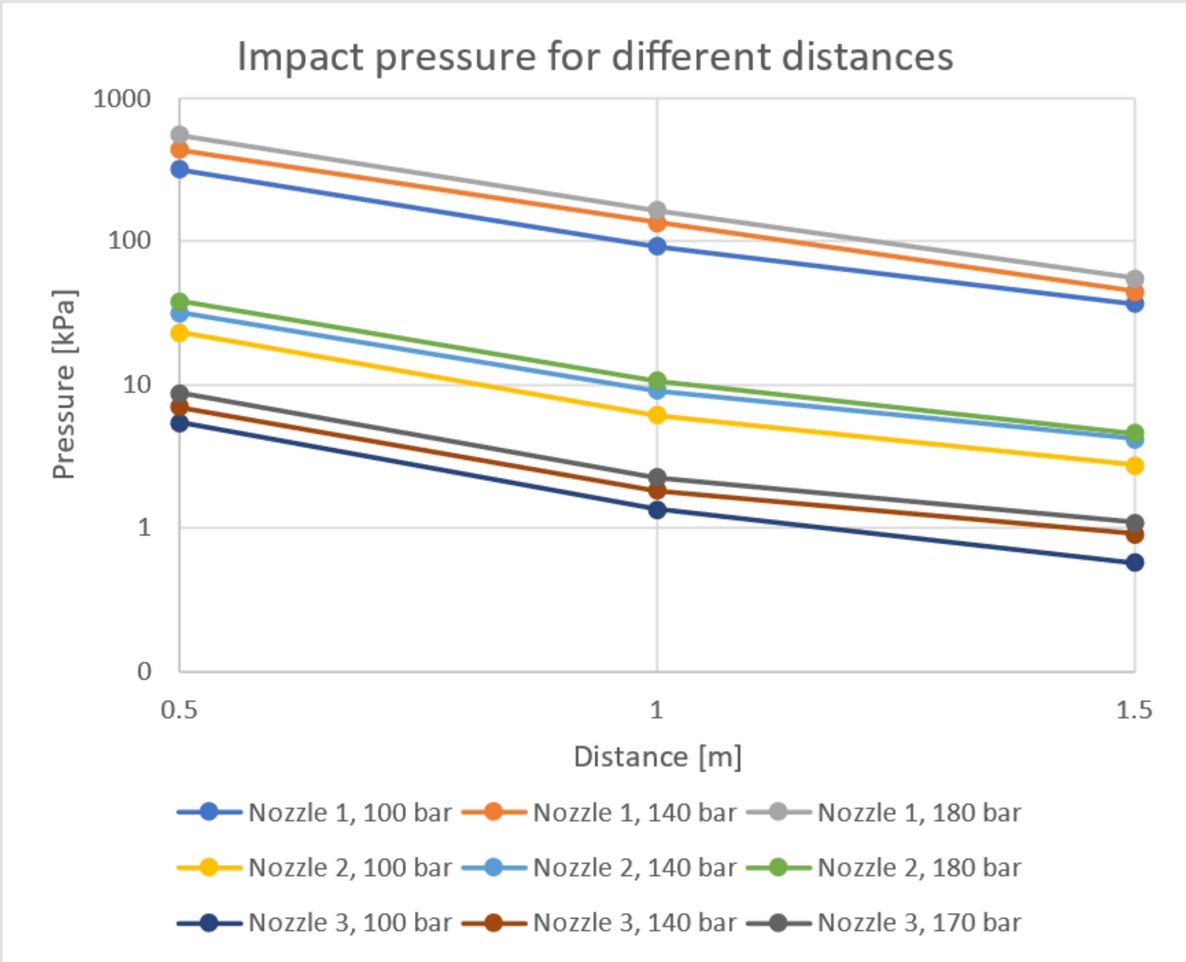


Figure B.5: Average impact pressure force for various distances. Note: A logarithmic y-axis is used.

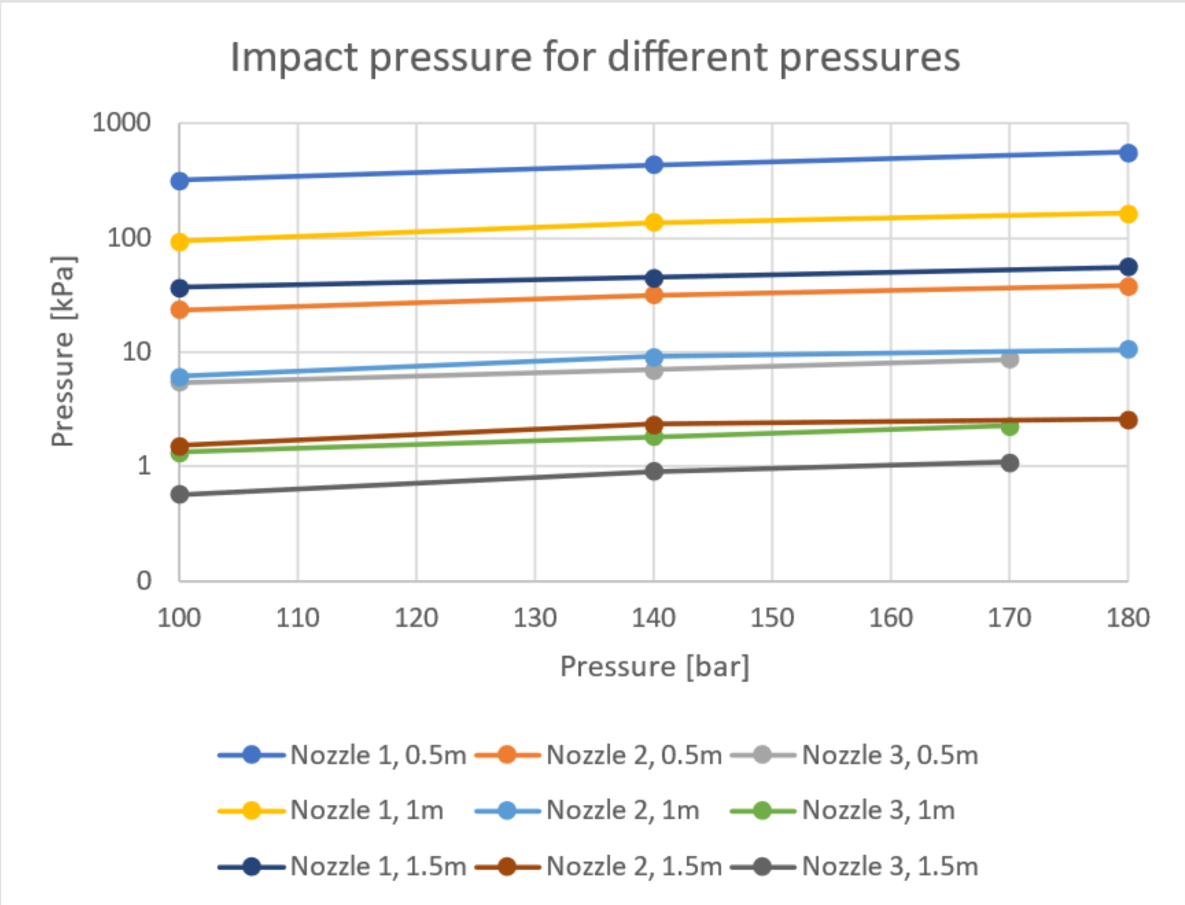


Figure B.6: Average impact pressure force for various pressures. Note: A logarithmic y-axis is used.

Bibliography

[1] Statista. Number of ships in the world merchant fleet as of january 1, 2019, by type, 2019. URL https://web.archive.org/web/20191222052736/https://www.statista.com/statistics/264024/number-of-merchant-ships-worldwide-by-type/. Accessed on June 7, 2021.

[2] P. A. Shamlou. *Handling of bulk solids: Theory and Practice*. Butterworth & Co., 1990. 0-407-01180-3.

[3] M. Klop. Unloading vessels - dozer activities. Technical report, TU Delft, 2012.

[4] K. Hazeghi and F. Weinberg. Optimization of the unloading strategy for bulk carriers: Part II: Unloading of a ship. *OR Spektrum*, 11:101–110, 1989. doi: 10.1007/BF01746006.

[5] M. J. Mohajeri. *Grabs and Cohesive Bulk Solids: Virtual prototyping using a validated co-simulation*. PhD thesis, TU Delft, 2021.

[6] M. J. Mohajeri, A. J. Van den Bergh, J. Jovanova, and D. L. Schott. Systematic design optimization of grabs considering bulk cargo variability. *Advanced Powder Technology*, 32:1723–1734, 2021. doi: 10.1016/j.apt.2021.03.027.

[7] D. Barletta, G. Donsì, G. Ferrari, M. Poletto, and P. Russo. Solid flow rate prediction in silo discharge of aerated cohesive powders. *AIChE Journal*, 53:2240–2253, 2007. doi: 10.1002/aic.11212.

[8] L. Zhu, H. Lu, M. Poletto, H. Liu, and Z. Deng. Hopper discharge of cohesive powders using pulsated airflow. *AIChE Journal*, 66, 2020. doi: 10.1002/aic.16240.

[9] A. Cannavacciuolo, D. Barletta, G. Donsì, G. Ferrari, and M. Poletto. Arch-free flow in aerated silo discharge of cohesive powders. *Powder Technology*, 191:272–279, 2009. doi: 10.1016/j.powtec.2008.10.013.

[10] C. Zhang, C. Qiu, C. Pu, X. Fan, and P. Cao. The mechanism of vibrations-aided gravitational flow with overhanging style in hopper. *Powder Technology*, 327:291–302, 2018. doi: 10.1016/j.powtec.2017.12.077.

[11] C. R. Wassgren, M. L. Hunt, P. J. Freese, J. Palamara, and C. E. Brennen. Effects of vertical vibration on hopper flows of granular material. *Physics of fluids*, 14:3438–3448, 2002. doi: 10.1063/1.1503354.

[12] R. Van der Wardt. Double diamond model (nieuwe versie): uitleg bij de 4 fases, 2021. URL https://designthinkingworkshop.nl/double-diamond/. Accessed on September 13, 2021.

[13] R. Costa. The double diamond model: what is it and should you use it?, 2018. URL https://www.justinmind.com/blog/double-diamond-model-what-is-should-you-use/. Accessed on September 13, 2021.

[14] M. Rivkin. *Bulk Material Handling: Practical Guidance for Mechanical Engineers*. Partridge Publishing Singapore, 2018. 9781543746426.

[15] IACS. Bulk carriers: Guidance and information on bulk cargo loading and discharging to reduce the likelihood of over-stressing the hull structure. Technical report, The International Association of Classification Societies, 2018.

[16] L. Pie-Ya and C. Chien-Chang. Standard operating procedure for loading/unloading operations and navigational safety of bulk carriers as per charter party requirements. *Journal of Engineering for the Maritime Environment*, 23:728–739, 2020. doi: 10.1177/1475090219875860.

[17] EMO, 2021.

[18] Sustainable agriculture. Level 8: Guiding question: What is the big deal about bulk density?, 2021. URL https://wccag.weebly.com/l-8-bulk-density.html. Accessed on June 30, 2021.

[19] T. Isiacik and T. Satir. Cargo liquefaction and dangers to ships. In *TransNav 2014*. TransNav, 2014.

[20] R. Linemann, J. Runge, M. Sommerfeld, and U. Weißgüttel. Cargo liquefaction and dangers to ships. *Particle and Particle Systems Characterization*, 21:261–267, 2004. doi: 10.1002/ppsc.200400938.

[21] C. R. Woodcock and J. S. Mason. *Bulk solids handling: An introduction to the practice and technology*. Blackie academic & professional, 1987. 10.1007/978-94-009-2635-6.

[22] D. McGlinchey. *Bulk Solids Handling: Equipment Selection and Operation*. Blackwell Publishing, 2008. 978-1-4051-5825-1.

[23] Q. Li, K. Wang, Y. Zheng, M. Ruan, X. Mei, and B. Lin. Experimental research of particle size and size dispersity on the explosibility characteristics of coal dust. *Powder Technology*, 292: 290–297, 2016. doi: 10.1016/j.powtec.2016.01.035.

[24] D. McGlinchey. *Characterisation of bulk solids*. Blackwell Publishing, 2005. 978-14051-1624-4.

[25] C. Liu. Bulk density and angle of repose of coal. Master's thesis, University of New South Wales, 2007.

[26] L. Giroux and T. Todoschuk. Industrial study on coal handling bulk density control. In *METEC 2015*. METEC, 2015.

[27] K. J. Dong, R. P. Zou, K. W. Chu, R. Y. Yang, and A. B. Yu. Effect of cohesive force on the formation of a sandpile. In *AIP Conference Proceedings 1542, 646*. CWE, 2013. doi: 10.1063/1.4812014.

[28] E. M. H. Braga, G. L. R. Da Silva, R. C. V. Amaral, M. D. C. Carias, P. S. Assis, and L. R. Lemos. Influence of moisture and particle size on coal blend bulk density. *REM-International Engineering Journal*, 72:237–242, 2019. doi: 10.1590/0370-44672018720006.

[29] J. Q. Xu, R. P. Zou, and A. B. Yu. Quantification of the mechanisms governing the packing of iron ore fines. *Powder technology*, 169:99–107, 2006. doi: 10.1016/j.powtec.2006.08.004.

[30] M. E. Fayed and L. Otten. *Handbook of powder science & technology*. International Thomson Publishing, 1997. 0-412-99621-9.

[31] M. J. Ajrash, J. Zanganeh, and B. Moghtaderi. Methane-coal dust hybrid fuel explosion properties in a large scale cylindrical explosion chamber. *Journal of Loss Prevention in the Process Industries*, 40:317–328, 2016. doi: 10.1016/j.jlp.2016.01.009.

[32] K. L. Cashdollar. Coal dust explosibility. *Journal of Loss Prevention in the Process Industries*, 9: 65–76, 1996. doi: 10.1016/0950-4230(95)00050-X.

[33] M. Mittal. Limiting oxygen concentration for coal dusts for explosion hazard analysis and safety. *Journal of Loss Prevention in the Process Industries*, 26:1106–1112, 2013. doi: 10.1016/j.jlp.2013.04.012.

[34] D. Myers, P. Cooke, and N. Crouch. Carriage of coal cargoes: Self-heating and explosion risks, 2016. URL https://www.skuld.com/topics/cargo/solid-bulk/coal-cargoes/carriage-of-coal-cargoes-self-heating-and-explosion-risks/. Accessed on June 7, 2021.

[35] L. Bates, S. Dhodapkar, and G. Klinzing. Shapa technical paper 12: Discharge aids. Technical report, Shapa, 2007.

[36] D. Schulze. *Powders and bulk solids: Behavior, characterization, storage and flow*. Springer, 2008. 978-3-540-73767-4.

[37] H. Lu, X. Guo, X. Gong, X. Cong, and W. Dong. Study on the fluidization and discharge characteristics of cohesive coals from an aerated hopper. *Powder Technology*, 207:199–207, 2011. doi: 10.1016/j.powtec.2010.10.030.

[38] H. Lu, X. Guo, X. Gong, X. Cong, K. Liu, and H. Qi. Experimental study on aerated discharge of pulverized coal. *Chemical Engineering Science*, 71:438–448, 2012. doi: 10.1016/j.ces.2011.11.006.

[39] H. Lu, X. Guo, X. Gong, D. Barletta, and M. Poletto. Prediction of solid discharge rates of pulverized coal from an aerated hopper. *Powder Technology*, 286:645–653, 2015. doi: 10.1016/j.powtec.2015.09.017.

[40] F. Y. Fraige, P. A. Langston, A. J. Matchett, and J. Dodds. Vibration induced flow in hoppers: DEM 2D polygon model. *Partcuology*, 6:455–466, 2008. doi: 10.1016/j.partic.2008.07.019.

[41] P. A. Langston, A. J. Matchett, F. Y. Fraige, and J. Dodds. Vibration induced flow in hoppers: continuum and DEM model approaches. *Granular Matter*, 11:99–113, 2009. doi: 10.1007/s10035-009-0125-7.

[42] A. Janda, D. Maza, A. Garcimartín, E. Kolb, J. Lanuza, and E. Clément. Unjamming a granular hopper by vibration. *Europhysics letters Journal*, 87, 2009. doi: 10.1209/0295-5075/87/24002.

[43] TH. Kollmann and J. Tomas. Effect of applied vibration on silo hopper design. *Particulate science and technology*, 20:15–31, 2002. doi: 10.1080/02726350290057949.

[44] V. A. Golovanevskiy, V. A. Arsentyev, I. I. Blekhman, V. B. Vasilkov, Y. I. Azbel, and K. S. Yakimova. Vibration-induced phenomena in bulk granular materials. *International Journal of Mineral Processing*, 100:79–85, 2011. doi: 10.1016/j.minpro.2011.05.001.

[45] M. L. Hunt, R. C. Weathers, A. T. Lee, C. E. Brennen, and C. R. Wassgren. Effects of horizontal vibration on hopper flows of granular materials. *Physics of fluids*, 11:68–75, 1999. doi: 10.1063/1.869903.

[46] D. Yang, G. Li, Y. Wang, Q. Wang, J. Li, Q. Huang, Y. Xia, and Q. Li. Prediction of horizontal pneumatic conveying of large coal particles using discrete phase model. *Advances in Materials Science and Engineering*, 2020, 2020. doi: 10.1155/2020/1967052.

[47] J. Zhou, Y. Liu, C. Du, and S. Liu. Effect of the particle shape and swirling intensity on the breakage of lump coal particle in pneumatic conveying. *Powder Technology*, 317:438–448, 2017. doi: 10.1016/j.powtec.2017.05.034.

[48] J. Zhou, Y. Liu, C. Du, S. Liu, and J. Li. Numerical study of coarse coal particle breakage in pneumatic conveying. *Particuology*, 38:204–214, 2018. doi: 10.1016/j.partic.2017.07.003.

[49] J. Zhou, D. Chang-Long, and Z. Ma. Influence of swirling intensity on lump coal particle pickup velocity in pneumatic conveying. *Powder Technology*, 339:470–478, 2018. doi: 10.1016/j.powtec.2018.08.043.

[50] D. Yang, B. Xing, J. Li, Y. Wang, N. Hu, and S. Jiang. Experiment and simulation analysis of the suspension behavior of large(5–30 mm) nonspherical particles in vertical pneumatic conveying. *Powder Technology*, 20354:442–455, 2019. doi: 10.1016/j.powtec.2019.06.023.

[51] D. Yang, B. Xing, J. Li, Y. Wang, K. Gao, F. Zhou, Y. Xia, and C. Wang. Experimental study on the injection performance of the gas-solid injector for large coal particles. *Powder Technology*, 364:879–888, 2020. doi: 10.1016/j.powtec.2019.11.087.

[52] ProductPlan. Stakeholder analysis, 2021. URL https://www.productplan.com/glossary/stakeholder-analysis/. Accessed on August 3, 2021.

[53] MindTools. Stakeholder analysis, 2021. URL https://www.mindtools.com/pages/article/newPPM_07.htm. Accessed on August 3, 2021.

[54] Wilhelmsen. Tornado 3 cargo hold cleaning jet, 2021. URL https://www.wilhelmsen.com/product-catalogue/products/cleaning-equipment/cargo-hold-cleaning/cleaning-jets/tornado-3-cargo-hold-cleaning-jet/. Accessed on June 15, 2021.

[55] Wilhelmsen. Unitor instruction manual tornado 3 cleaning jet, 2010. URL https://media.bluestonepim.com/e4deb258-8122-4fdf-9d12-b42f3e0e812d/df283194-3abc-478b-8ec6-25987522953b/2IPvX8EWBrSZiH6Q9RPcH2wok/xk1dRuLQE3gWrlQcNMaFCC6Q0.pdf. Accessed on June 15, 2021.

[56] Navadan. High pressure water stream for cargo hold cleaning, 2021. URL https://www.navadan.com/images/pdftankcleaning/PDS_EQUIPMENT/PDS_NAVADAN-Hold-Cleaning-Jet-Kit.pdf. Accessed on June 15, 2021.

[57] RBM Hold Solutions. Hold cleaning equipment – RBM hydroblaster, 2021. URL https://www.holdsolutions.com/rbm-hydroblaster. Accessed on June 15, 2021.

[58] Wilhelmsen. HPC extreme 520 440V/60HZ, 2021. URL https://www.wilhelmsen.com/product-catalogue/products/cleaning-equipment/mobile-high-pressure-cleaners/hp-cleaners-300---500-bar/hpce-520-inox-3-x-440v60hz. Accessed on June 15, 2021.

[59] Wilhelmsen. Unitor HPCE anaconda lance kit, 2021. URL https://www.wilhelmsen.com/product-catalogue/products/cleaning-equipment/mobile-high-pressure-cleaners/spares--accessories-for-hp-cleaners-300---500-bar/unitor-hpce-anaconda-lance-kit. Accessed on June 15, 2021.

[60] Navadan. Cleaning cargo holds with high pressure in heights, 2021. URL https://www.navadan.com/how-to-clean-cargo-holds-with-high-pressure. Accessed on June 15, 2021.

[61] Navadan. In-depth cleaning of rusty or dirty surfaces, and maintenance on deck., 2021. URL https://www.navadan.com/images/pdftankcleaning/PDS_EQUIPMENT/PDS_HPC350-2.pdf. Accessed on June 15, 2021.

[62] Marine Care. High pressure cleaning equipment, 2021. URL https://marinecare.nl/wp-content/uploads/2019/04/Leaflet-CaretechHPCmachines.pdf. Accessed on June 15, 2021.

[63] Cliin Robotics. Cargo hold robot, 2021. URL https://cliin.dk/robots. Accessed on June 15, 2021.

[64] Cliin Robotics. Faq, 2021. URL https://cliin.dk/faq. Accessed on June 15, 2021.

[65] Cliin. Shipowners save time and money with cliin cargo hold robot, 2019. URL https://www.maritime-executive.com/features/shipowners-save-time-and-money-with-cliin-cargo-hold-robot-1. Accessed on June 15, 2021.

[66] Vertidrdive. Magnetic robot crawler vertidrive M8, 2021. URL https://www.vertidrive.com/products/m8-series/. Accessed on June 15, 2021.

[67] Combijet. RJE1000 high pressure cleaning robot, 2021. URL https://combijet.com/product/rje1000-high-pressure-cleaning-robot/. Accessed on June 15, 2021.

[68] Van Aalst Bulk Handling. Road mobile ship unloaders, 2021. URL https://vanaalstbulkhandling.com/products/road-mobile-ship-unloaders. Accessed on June 15, 2021.

[69] VIGAN Engineering S.A. Mobile machines - specifications, 2021. URL http://www.vigan.com/en/machines-pneumatique-mobile-specifications.php. Accessed on June 15, 2021.

[70] Lion Bulk Handling. Ship unloaders, 2021. URL http://www.lionbulkhandling.com/ship-unloaders/. Accessed on June 15, 2021.

[71] FLSmidth A/S. Pneumatic ship unloaders, 2021. URL https://www.flsmidth.com/en-gb/products/material-handling/pneumatic-ship-unloaders. Accessed on June 15, 2021.

[72] VIGAN Engineering S.A. Mobile & portable pneumatic machines, 2021. URL http://www.vigan.com/en/download-mobile-machines.pdf. Accessed on June 15, 2021.

[73] The Big Smile B.V. The big smile: A mind blowing cleaning technique!, 2021. URL http://thebigsmile.eu/?page_id=65. Accessed on June 21, 2021.

[74] Hans Kooijman. In bedrijf, 2021. URL https://media-exp1.licdn.com/dms/image/C512DAQHzXlzCuJyF0A/profile-treasury-image-shrink_1280_1280/0/1598681318389?e=1624352400&v=beta&t=EGnSwvyGsabFQ8fRxKkaj6IO8tggyHZonOul7bi09AU. Accessed on June 21, 2021.

[75] Conservator Group. Detonative cleaning, 2017. URL https://www.conservatorgroup.com/onlinecleaning/en/. Accessed on June 21, 2021.

[76] Conservator Group. Detonatief, 2021. URL https://www.conservatorgroup.com/oplossingen/detonatief/. Accessed on June 21, 2021.

[77] Martin Engineering. Use the power of compressed air to keep the interior walls of kilns, silos, hoppers and chutes free of obstructions., 2021. URL https://www.martin-eng.com/content/product_subcategory/491/air-cannons-products. Accessed on June 22, 2021.

[78] Supair group. Pneumatic air cannons, 2016. URL https://supairgroep.nl/producten/goyen-mecair/filter-cleaning-system-accessories/pneumatic-air-cannons/. Accessed on June 22, 2021.

[79] Integrated Global Services. Air cannons – cement, 2021. URL https://integratedglobal.com/services/environmental-products/air-cannons/. Accessed on June 22, 2021.

[80] WAMGroup. PG air cannons, 2021. URL https://wamgroup.com/en-GB/corporate/Product/PG/Air-Cannons. Accessed on June 22, 2021.

[81] Chicago Vibrator Products. Air cannons for silos and hoppers, 2021. URL https://www.chicagovibrator.com/Store/c/air-cannon-systems. Accessed on June 22, 2021.

[82] VIBCO Vibrators. ABS air cannons, 2011. URL http://www.vibco.com/products/air-cannons/abs. Accessed on June 22, 2021.

[83] Martin Engineering. When the flow of material gets stuck, shake it loose!, 2021. URL https://www.martin-eng.com/content/product_category/468/industrial-vibration-solutions. Accessed on June 22, 2021.

[84] WAMGroup. Flow aids, 2021. URL https://wamgroup.com/en-GB/corporate/Family/407/Flow-Aids. Accessed on June 22, 2021.

[85] Chicago Vibrator Products. Vibrator types, 2021. URL https://www.chicagovibrator.com/Vibrator-Types. Accessed on June 22, 2021.

[86] VIBCO Vibrators. Electric vibrators, 2011. URL http://www.vibco.com/products/electric-vibrators. Accessed on June 22, 2021.

[87] VIBCO Vibrators. Hydraulic vibrators, 2011. URL http://www.vibco.com/products/hydraulic-vibrators. Accessed on June 22, 2021.

[88] Epiroc Finland Oy Ab. Hydraulic compactor, 2021. URL https://www.epiroc.com/en-fi/products/excavator-attachments/hydraulic-compactor. Accessed on June 22, 2021.

[89] Jetblaster P/L. Ultra high pressure cleaners, 2020. URL https://jetblaster.com.au/ultra-high-pressure-cleaners/. Accessed on June 22, 2021.

[90] Airblast B.V. UHP - ultra high pressure, 2021. URL https://www.airblast.com/products/blasting/uhp-ultra-high-pressure/. Accessed on June 22, 2021.

[91] CombiJet. Ultra high pressure water blasters, 2020. URL https://combijet.com/ultra-high-pressure-water-blasters/. Accessed on June 22, 2021.

[92] Morclean. Ultra high pressure washers., 2021. URL https://www.morclean.com/products/ultra-high-pressure-washers/. Accessed on June 22, 2021.

[93] C. Spencer, N. Paines, J. Stryken, A. Bhargava, J. Kehagias, and M. Bozier. Standard cargo: Bulk cargoes - hold preparation and cleaning, 2011. URL https://www.standard-club.com/fileadmin/uploads/standardclub/Documents/Import/publications/standard-cargo/23964-15056CargoJan2011Bulletinv06.pdf. Accessed on July 9, 2021.

[94] C. Ott, N. Lulla, A. Bilyk, and D. Schaar. Guidance on preparing cargo holds and loading of solid bulk cargoes, 2014. URL https://www.skuld.com/contentassets/e2d486e683a84d7582fa1b867d18f8ac/preparing-cargo-holds_-loading-solid-bulk-cargoes.pdf. Accessed on July 9, 2021.

[95] International Maritime Organization (IMO). 866(20) guidance to ships' crews and terminal personnel for bulk carrier inspections. Technical report, Netherlands Regulatory Framework (NeRF), 1997. URL https://puc.overheid.nl/nsi/doc/PUC_1460_14/1/.

[96] NEDA Martitime Agency. Dry cargo bulk carriers, 2021. URL https://www.nedamaritime.gr/img/media_room/brochures/32P-NEDA-DRY-CARGO.pdf. Accessed on August 16, 2021.

[97] TWI Global. What is abrasive grit blasting? (AKA sandblasting), 2021. URL https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-grit-blasting. Accessed on October 12, 2021.

[98] Kaeser Compressors. Mobilair M250, 2021. URL https://www.kaeser.com/int-en/download.ashx?id=tcm:17-5782. Accessed on October 12, 2021.

[99] Caterpillar. Medium excavators 326, 2021. URL https://www.cat.com/en_US/products/new/equipment/excavators/medium-excavators/15970425.html. Accessed on January 6, 2022.

[100] Caterpillar. Frontless excavators 374F OEM, 2021. URL https://www.cat.com/en_US/products/new/equipment/excavators/frontless-excavators/1000005964.html. Accessed on January 6, 2022.

[101] STC B.V. Removable counterweight | Cat.349E UHD, 2015. URL https://www.youtube.com/watch?v=1kT76WAQ7TY. Accessed on January 6, 2022.

[102] Caterpillar. Cw series couplers CW-05 hydraulic 1 ton mini excavators, 2021. URL https://www.cat.com/en_GB/products/new/attachments/couplers-excavator/cw-series-couplers/108939674352.html. Accessed on January 6, 2022.

[103] Caterpillar. Brackets mounting bracket - CW-10, 2021. URL https://www.cat.com/en_ID/products/new/accessories/hammer-accessories/brackets/108939698061.html. Accessed on January 6, 2022.

[104] Caterpillar. Tilting dual lock pin grabber couplers - mini excavator, 2021. URL https://www.cat.com/en_GB/products/new/attachments/couplers-excavator/tilting-dual-lock-pin-grabber-couplers-mini-excavator/100740.html. Accessed on January 6, 2022.

[105] J. Evans. Water hammer: What & why, 2017. URL https://www.pumpsandsystems.com/water-hammer-what-why. Accessed on January 6, 2022.

[106] Greenfield Products LLC. Fully electric container spreader, 2021. URL https://www.greenfieldpi.com/products/fully-electric-container-spreader/. Accessed on December 2, 2021.

[107] Container Technics N.V. Operation instruction for semi-automatic spreaders: Mk-20 & mk-40., 2021. URL https://www.containertechnics.com/en/blog/blog-article-2. Accessed on December 2, 2021.

[108] Caterpillar. Cat command for excavating, 2021. URL https://www.cat.com/en_US/products/new/technology/command/command/15970437.html. Accessed on December 2, 2021.

[109] Australian Mining. Hitachi takes leap with remote-controlled ultra-large excavator trial, 2020. URL https://www.australianmining.com.au/news/hitachi-takes-the-leap-with-remote-controlled-ultra-large-excavator-trial/. Accessed on December 2, 2021.

[110] indurad GmbH. iRoadheader: Roadheader remote operation solution, 2021. URL https://www.indurad.com/solutions/by-application/remote-operation/. Accessed on December 2, 2021.

[111] Liebherr. Liebherr mining presents next generation, interoperable machine automation, 2021. URL https://www.liebherr.com/en/sgp/latest-news/news-press-releases/detail/liebherr-mining-presents-next-generation-interoperable-machine-automation.html. Accessed on January 6, 2021.

[112] indurad GmbH. iroadheader: Roadheader remote operation solution, 2022. URL https://www.indurad.com/solutions/isolutions/iroadheader/. Accessed on January 26, 2022.

[113] C. Saynat, A. Kealy, and K. Zhang. A performance analysis of future global navigation satellite systems. *Journal of global positioning systems*, 3:232–244, 2004. doi: 10.5081/jgps.3.1.232.

[114] EZtronics. S Type Load Cell (0-500kg) - CZL301, 2021. URL https://www.eztronics.nl/webshop2/catalog/Sensor/Force-Pressure?product_id=466. Accessed on January 5, 2022.

[115] National Instruments. USB-6002, 2021. URL https://www.ni.com/nl-nl/support/model.usb-6002.html. Accessed on January 5, 2022.

[116] Scaime. Strain gage conditioner CPJ / CPJ2S, 2021. URL https://scaime.com/product/post/cpj---cpj2s. Accessed on January 5, 2022.

[117] TQC sheen. Laagdiktemeter positector 6000, 2021. URL https://tqcsheen.com/nl/product/laagdiktemeter-positector-6000/. Accessed on January 6, 2022.

[118] D. Wright. Impact force of high pressure waterjets. In *WJTA-IMCA Conference and Expo*. WJTA, 2013. URL https://www.wjta.org/images/wjta/Proceedings/Papers/2013/C1%20-%20DW%20Impact.pdf.

[119] A. Guha, R. M. Barron, and R. Balachandar. An experimental and numerical study of water jet cleaning process. *Journal of Materials Processing Technology*, 211:610–618, 2011. doi: 10.1016/j.jmatprotec.2010.11.017.

[120] F. Huang, J. Mi, D. Li, and R. Wang. Impinging performance of high-pressure water jets emitting from different nozzle orifice shapes. *Geofluids*, pages 1–14, 2020. doi: 10.1155/2020/8831544.

[121] J. Foldyna, L. Sitek, J. Ščučka, P. Martinec, J. Valíček, and K. Páleníková. Effects of pulsating water jet impact on aluminium surface. *Journal of Materials Processing Technology*, 209:6174–6180, 2009. doi: 10.1016/j.jmatprotec.2009.06.004.