Development of Wärtsilä two-stage turbocharger wash unit

Wärtsilä Finland Oy

Thomas Korpisaari

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BACHELOR'S THESIS

Author: Thomas Korpisaari
Degree Programme: Mechanical engineering
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Supervisor(s): Kaj Rintanen
Kristian Mäki

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Abstract

This thesis is made on behalf of Wärtsilä Finland, technical services. The subject of this thesis is automatic washing of two-stage turbochargers with water on medium-speed diesel engines. The purpose of the thesis was to study the possibility to develop the Wärtsilä two-stage turbocharger wash unit to make it reach higher water flows to fit all kinds of two-stage turbochargers.

Wärtsilä has a prototype in use for washing two-stage turbochargers, the prototype does not have the possibility to supply enough amount of water to successfully clean all kinds of two-stage turbochargers. A renewed version of the wash unit with higher water flows enables the usage of the same unit for all kinds of turbochargers and a simplified version of the wash unit saves cost and time during the manufacturing of the unit. In this thesis, different kinds of methods are used to reach a desired result- theoretical simulations have been implemented to get an understanding of what affects the flow and to decide the size of the pipes and valves. 3D modeling has been used to create a new kind of prototype and to produce drawings that have been used in the manufacturing of a new prototype. Finally, different kinds of tests on the prototype have been performed to investigate if it fulfills the requirements given.

To fully understand the key contents of this thesis, studies and researches on the theory of the subject were made. As into study how the diesel engine works, with emphasis on the medium-speed diesel. Moreover, the fuel that is used in a medium-speed diesel and its impact on the engine and turbochargers were investigated. Finally, the effects of not cleaning the turbochargers and the importance of the washing were studied.

Language: english Key words: WTW, turbocharger wash, two-stage turbocharger

EXAMENSARBETE

Författare:	Thomas Korpisaari
Utbildning och ort:	Maskin- och produktionsteknik, Vasa
Inriktningsalternativ:	Konstruktion
Handledare:	Kaj Rintanen
	Kristian Mäki

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Abstrakt

Det här examensarbete är gjort på uppdrag av Wärtsilä Finland, teknisk service. Ämnet för examensarbetet är automatisk tvätt av tvåstegsturboladdare med hjälp av vatten på medium farts dieselmotorer. Syftet med examensarbetet var att undersöka möjligheten att utveckla Wärtsiläs tvättenhet för tvåstegsturboladdare för att få tvätten att uppnå högre vattenflöden som även räcker till de största turboladdarna.

Wärtsilä har en prototyp i användning för tvättning av tvåstegsturboladdare, prototypen har inte möjlighet att tillförse tillräckligt stort vattenflöde för att lyckas rengöra alla typer av två stegsturboladdare. En förnyelse av tvättenheten med ökat vattenflöde ger möjligheten till att kunna använda tvättenheten till alla olika typer av turboladdare. En förenklad typ av tvättenheten kan också spara in tid och pengar vid själva tillverkande av enheten. I examensarbetet har det använts olika metoder för att uppnå önskade resultat, teoretiska simuleringar har gjorts för att få en förståelse över vad som inverkar på flödet och för att bestämma storleken på rören och ventilerna. 3D-modellering har använts för att skapa en ny prototyp och att producera ritningar som har använts vid konstruktionen av en ny prototyp. Slutligen har det utförts olika tester på den nya prototypen för att säkerställa att den uppfyller alla krav.

För att fullt förstå detta examensarbete krävde det studier och undersökningar om teorin inom ämnet. Det krävde studier i hur dieselmotorer fungerar, särskilt medelhastighetsdieselmotorer. Det krävdes också att studera bränslet som används i medelhastighetsdieslar och studera vad bränslet har för inverkan på motorn och turboladdarna. Examensarbetet krävde också att man studerade effekterna ifall turboladdarna inte blir tvättade, för att sedan förstå vikten av att tvätta turboladdarna.

Språk: engelska Nyckelord: WTW, turbotvätt, tvåstegsturboladdare

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Content

Abbreviations

WTW	Wärtsilä Turbocharger Wash-unit
DF	Dual fuel engine
RPM	Revolutions per minute
EWG	Exhaust Waste Gate
TC	Turbocharger
HFO	Heavy fuel oil
SG	Pure gas engine
PLC	Programmable Logic Controller
HP	High pressure
LP	Low pressure
WOIS	Wärstilä Operator’s Interface System

1 Introduction

In this chapter, the background, purpose, goal, and disposition of this bachelor's thesis will be presented. It will also include a short briefing about the company this thesis is written on behalf of.

1.1 Background

This thesis is written on behalf of Wärtsilä Finland, technical services, more specific turbocharging and performance (TCP) team. The background to this thesis is Wärtsilä's increasing production of engines using two-stage turbochargers and the fact that today, they are also developing the Wärtsilä 46 to be a two-stage turbocharged engine. Larger engines require larger turbochargers to reach the desired airflow and charge air pressure. Wärtsilä engines are operated with various kinds of fuels and lubrication oils, some of those are causing contamination on the turbine side of the turbocharger. To prevent turbochargers' efficiency tendency to deteriorate due to contamination, the turbochargers are regularly washed with water. The amount of water needed is depending on the turbochargers frame size, the larger the turbochargers the greater the flow.

Wärtsilä introduced an automatic PLC-operated turbocharger wash unit in 2007. Today the WTW is a standard delivery with most of the engines. When two-stage turbochargers were introduced on the W31-engine an extended version of the wash unit was developed. Due to complexity with up to two low-pressure and two high-pressure compressors and turbines, and close to doubling the pressure ratio used the size of the frame increased on the wash unit, and some valves were added. On the larger bore two-stage engines the water flow requirements are roughly three times higher than on current medium bore engines two-stage turbochargers, the current design is not able to handle that requirement. Also, Wärtsilä would like to harmonize the frame size between the single-stage wash unit and the two-stage wash unit to be able to keep the same design for the wash units on the modular auxiliary modules. By frame size reduction and a clever design, the aim is to keep the cost of the parts at a similar level despite the increased flow performance.

1.2 Purpose

The purpose of the thesis is to design and construct a wash unit that can be used for all Wärtsilä engines equipped with two-stage turbochargers. The new wash unit will be exposed to different kind of tests and measurements to establish that it fulfills all requirement there are on the wash unit, if the prototype fulfills them it will then proceed to field test for at least 3000 working hours before Wärtsilä will change the development from prototype to limited sales release. The purpose is also to construct a two-stage wash unit with a price that does not increase noticeably and which will match the frame size to be the same as the prototype in use. A sub purpose of this thesis is to analyze the existing wash unit and to investigate how to simplify the design. The sub-purpose is also to get increased water flow and to find a better solution how to reduce the compressed air consumption when the unit is on standby. Also, a simplified design will reduce manufacturing time and improve the serviceability of the unit.

1.3 Delimitations

The delimitations are the mechanical design of the wash unit, possible automation changes that might be required to make it work are not included in this thesis. It is aimed to keep the size of the frame and the cover the same, thus, the dimensions and mountings will stay the same if possible. With delimitations on just the wash unit itself, the piping before and after the unit will not be considered in this thesis, if that would be considered this work would become all too extended. Also, all different engine types may need different piping before and after the unit and the piping to the wash unit and between the wash unit and the engine are different on each site and might be a part of customer delivery or yard delivery.

1.4 Disposition

In the following chapters of this thesis, the theory behind the thesis, the methodology used, the result of the thesis, and at last a conclusion including a discussion over the result and thoughts for further work will be explained. The theory chapter will explain the background on how a turbocharger works and why it is needed to clean them at regular intervals. The methodology chapter will explain what different methods are used to reach a result and it will also include a description of how the work has been performed. In the chapter after the methodology, the results received from the work will be presented, and in the chapter after that a discussion if the result received is what was asked for, anything that could have been done differently, and if there are opportunities for further development.

1.5 Wärtsilä

Wärtsilä is a global leading company for smart technologies and complete lifecycle solutions for the marine and energy markets. In 2019 there were over 19000 employees at Wärtsilä, and their net sales totaled 5.2 billion euros. The company is located in over 200 different locations in 80 different countries all around the world and the company consists of two business: Wärtsilä Marine business and Wärtsilä Energy business.

Wärtsilä Marine Business having the broadest offering in the industry, from initial vessel design, choices to everyday operations, in each voyage and throughout the vessel's lifetime. Wärtsilä marine business provides innovative and competitive hardware and software solutions for vessels.

Figure 1 Wärtsilä 31 – world's most efficient engine (Wärtsilä)

Wärtsilä Energy Business is in a leading position in the power plant market due to its advanced gas and dual-fuel engine technology, optimized for power plants. Wärtsilä energy business provides its customers with a full understanding of energy systems including advanced software, integrated assets, and lifecycle services. (Wärtsilä, 2020)

2 Theory

This chapter will explain the theory behind this thesis, the chapter will include the basics about how a large bore diesel engine works and about the fuel they are using, it will also include what a turbocharger is and the difference between one stage and two-stage turbochargers. This chapter will also go through what fouling is, how it occurs and the problems it may cause that later leads to the theory of turbocharger washing and WTW. This chapter will also include theories about product development.

2.1 Diesel engine

The diesel engine was invented by Rudolf Diesel in the late 1800s, his first experimental engine was done in 1893 and the first fully working diesel engine was built in 1896. The diesel engine is a type of internal combustion engine where the fuel gets injected into the combustion chamber through a nozzle, the fuel gets ignited by the heat caused by the mechanical compression in the cylinders. There are different kinds of fuel injection systems used on diesel engines, mechanical fuel injection, electronic fuel injection, or common rail fuel injection. The mechanical fuel injection works with a fuel pump usually driven by the engine speed; the pump increases the fuel pressure that later supplies the injectors with pressurized fuel. The electronic fuel injection works on the same principle but has solenoids and sensors to control the amount of fuel that is injected. The electronic injection has a much better timing on the fuel delivery than a mechanical system. With electronic injection, there are also possibilities to e.g. skip cylinder firing during low load to save fuel, dual fuel management system, and use of variable fuel quality. In mechanical injection systems, the speed and load of the engine affect the fuel pressure. At lower speeds and load the fuel pressure drops which causes the fuel to become large droplets when injected into the cylinder. If the fuel pressure is too low and the fuel is injected as droplets instead of a spray the combustion process is not ideal. Common rail fuel injection technology offers the possibility to always keep the same high fuel pressure independent of what speed and load the engine is on, the common rail system gives the engine a clean and very efficient combustion which leads to lower fuel consumption and contributes less pollution. (Taylor, 1990) (Proctor, 1999)

Diesel engines can either be performed as L-engines or V-engines, L-engines are also called in-line engine and have the cylinders placed in a row, the V-engine have the cylinders placed in a shape of a V. Compared with the petrol engine the diesel engine is constructed with a considerably higher compression ratio, diesel engines are constructed with compression ratios from 14:1 up to 22:1 a petrol engines compression ratio rarely exceeds 13.5:1. The diesel engine can either be designed as a two-stroke or four-stroke regardless of cylinder diameter, but engines with a cylinder diameter over 600mm are usually using the two-stroke system.

Diesel engines are categorized into three different categories, low-, medium- and high-speed engines, what category a specific engine model belongs to depends on at what speed the engine works, i.e. the revolutions per minute on the pistons. Low-speed engines are two-stroke engines constructed with 4 to 14 cylinders at a range of bore sizes from 260 mm up to 1080 mm and the rated speeds are from around 55 to 250 rpm. Low-speed engines are mainly used as the main propulsion system on large bulk carriers, tankers, and container ships since the low-speed engine can be directly connected to the shaft of the propeller. Wärtsilä's two-stroke low-speed engines come from Sulzer which Wärtsilä bought in 1997 and are continuing to develop the successful RTA series that develops power output from 3500 to 80000 kW. (Woodyard, 2009)

The medium-speed diesel working speed area varies from 250 to 1200 rpm and is mainly four-stroke engines. The medium-speed diesel engines are mainly run on heavy crude oil but there are also medium-speed engines run as dual-fuel (DF) or as gas engines. Dual fuel gives the possibility to run the engine on two different fuels in the same engine by having two different fuel injectors for each cylinder and the gas engine is run completely on gas mainly liquid natural gas (LNG). Medium-speed diesel engines have also started to use common rail fuel injection system, the flexibility of the injection system gives access to optimize the engines and by Wärtsilä's common rail injection system the Wärtsilä 31 has become the world's most efficient 4-stroke diesel engine. Medium-speed diesel is mainly used in diesel powerplants and as powerplants on vessels but can also function as propulsion engines on cargo ships, tankers, cruise ships, and on fast passenger and ropax ferries.

High-speed engines are very much like the medium-speed engines but with a compacter design, smaller bore diameters, and a higher engine speed, the high-speed engines are working on from 1200 rpm and up. A high-speed diesel is mainly used in boats, trucks, and cars, the Wärtsilä 14 is a high-speed diesel that is available in 12- or 16-cylinder configuration and is intended for use in multiple applications when it can serve both main propulsion of a ship or function as an auxiliary genset application. (Proctor, 1999) (Woodyard, 2009)

2.2 Turbocharger

A turbocharger is a mechanically driven compressor or blower that is used to introduce more air with a higher density into the cylinders, this leads to the possibility of burning more fuel and reaching higher power output. Turbochargers have been used since the 20th century and were originally patented by Alfred Butchi in 1905, turbochargers have been as standard equipment on medium-speed diesel engines since 1960 and roughly 80% of engine output is received by turbochargers. Turbochargers are constructed by two main components, a turbine side where the exhaust gases pass through and a compressor side where ambient air is being compressed. The turbochargers used on a Wärtsilä engine are constructed with a cartridge concept. The cartridge concept is a concept where the internal parts of the turbochargers can be removed without removing the turbocharger from the engine. The concept is mainly used to simplify the maintenance of the turbochargers when it is not needed to remove the turbocharger from the engine to perform the maintenance. (Performance training for PME, 2013)

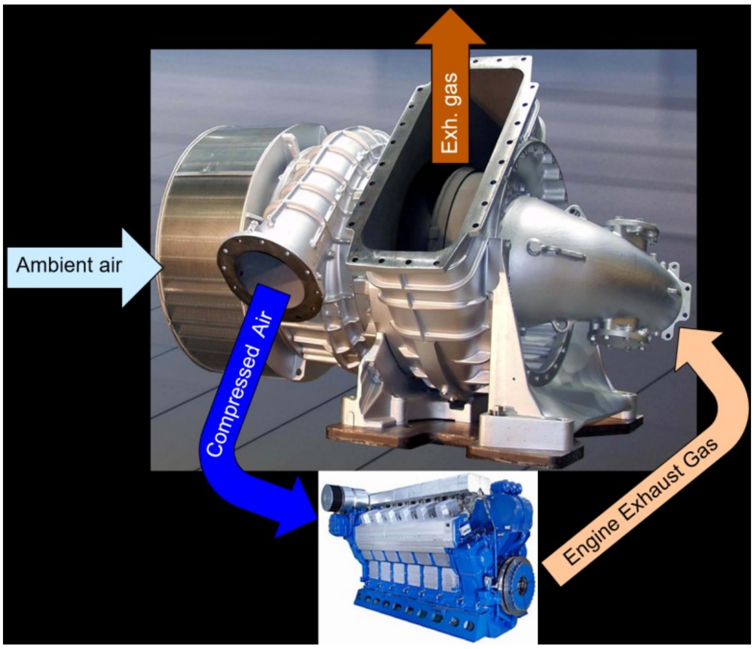


Figure 2 Turbocharger (Performance training for PME, 2013)

The turbine side and compressor side each consist of a wheel and the wheels are connected by a shaft, the turbine wheel rotates due to the exhaust gases that are passing through the turbocharger, and when the turbine wheel starts rotating the shaft ensures that the compressor wheel compresses the ambient air. Turbine wheels are constructed in two different ways, radial and axial types of wheels, the compressor wheel is of the radial type. The radial execution of the turbine wheel is the most common type, medium, and low-speed diesel engines that are using very large turbochargers can have an axial turbine wheel. (Jääskeläinen, 2017)

A turbocharger gives the possibility to burn higher fuel quantity in the cylinder and that way it increases the engine power. When talking about pressure ratio, it refers to how much air the turbocharger compresses compared with the ambient air pressure. With pressure ratios exceeding approximately 1.5 bars a charge air cooler is required. A charge air cooler lowers the temperature of the compressed air and in such ways allows higher pressure ratios. The charge air cooler is placed between the turbochargers compressor and the air intake on the engine, a charge air cooler can either be air-cooled or water-cooled, Wärtsilä is using water-cooled charge air cooler because the engines are usually placed in an engine room where the air can be relatively hot and also very little airflow which gives an air-cooled charge air cooler low efficiency. (Performance training for PME, 2013)

A high turbocharger efficiency contributes to reduced carbon dioxide emissions since the turbocharger improves the overall efficiency of the engine. An exhaust gas wastegate (EWG) is used to limit and control the charge air pressure at high load to protect the engine from overcharging which can lead to serious damage to the engine or the turbocharger, on Wärtsilä engines an EWG can only be used on single exhaust pipe system like Wärtsilä's SPEX (single pipe exhaust) system. (Performance training for PME, 2013)

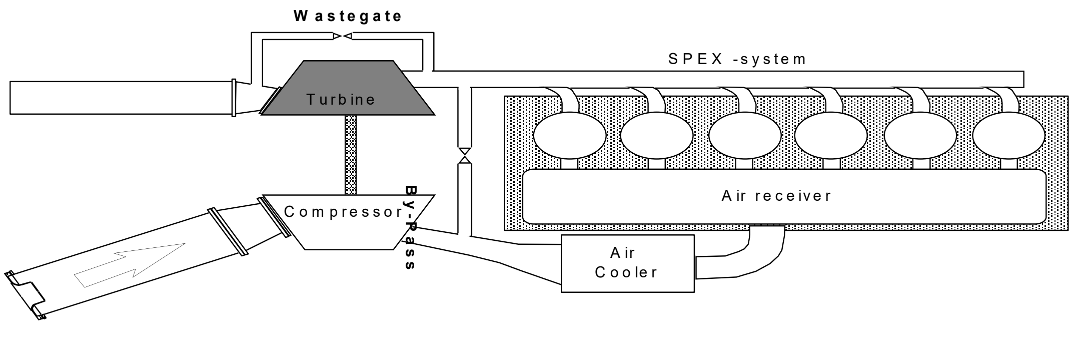


Figure 3 Picture of EWG and charge air cooler placement (Performance training for PME, 2013)

As earlier mentioned, the turbocharger is driven by the exhaust gases from the engine, and when the load or speed of the engine changes the pressure in the exhaust system changes, and that in its turn changes the speed of the turbocharger and the charge air pressure. If the load on the engine changes rapidly and often the fluctuation in the exhaust gas pressure leads to unfavorable effects such as surging. Surging occurs when the pressure after the compressor in the turbocharger is higher than the pressure in the compressor itself. When the surging occurs, a reversed airflow is created towards the compressor wheel and inlet of the compressor and this reduces the speed of the turbocharger and creates vibration and loud noises. The surging can cause severe damages to the turbocharger if it is recurring, sporadic surging does not influence the durability of the turbocharger nor the engine. The efficiency of the turbocharger is as highest just before the surging occurs, a turbocharger's efficiency is considered higher when the pressure ratio received is as high as possible and the air mass flow is as low as possible is better seen in the graph below. (Bright hub engineering, 2009)

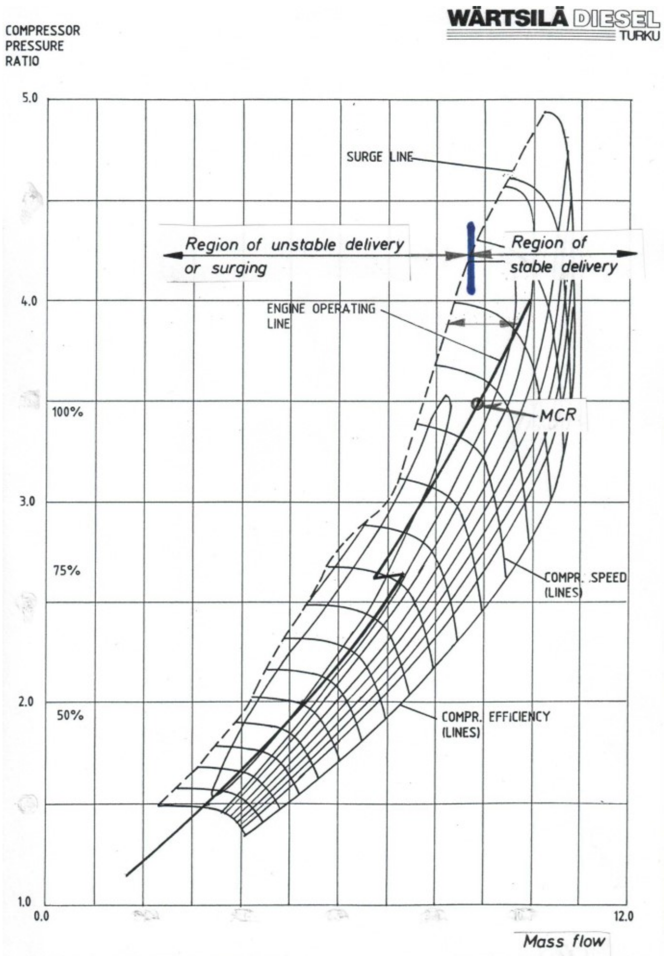


Figure 4 Compressor characteristics (Wärtsilä service, 2004)

A turbocharger system can be performed in a couple of different ways, it can be as a single-stage system, a two-stage system, or a sequential system. How the different systems works will be explained below.

2.2.1 Single-stage turbocharger

Single-stage turbocharger associates with the use of one turbocharger on the engine but this is not quite true, engines of the V-engine type are using two turbochargers of the same size, one for each bank. A single-stage turbocharger does not define the use of only one turbocharger instead does it mean that there is only one stage of charge air pressure and the charge air pressure are depending on the engine load and speed. On single-stage turbocharging the charge air pressure are between 4.0 to 4.5 bar but on newer engines even higher charge air pressure is received, on Wärtsilä 46F e.g. charge air pressure up to 5.0 bar is in use. On the single-stage turbochargers, the charge air cooler is located as close to the air intake as possible to keep the temperature of the air as low as possible, on V-engines the charge air coolers are located just before the air receiver on the engine. (Performance training for PME, 2013)

2.2.2 Two-stage turbocharger

A two-stage turbocharger is structured by two turbochargers of different sizes lined after each other. One so-called high pressure (HP) and one low pressure (LP) turbocharger where the LP turbocharger is bigger due to the need for high flow capacity at relatively low charge air pressure ratio and the HP turbocharger are smaller because it needs lower flow capacity at the low charge air pressure, there is also necessary to use an intercooler (IC) between the LP and HP turbocharger to keep the temperature of the inlet air on an acceptable level. To receive the best overall performance on an engine with a two-stage turbocharger is by having the same pressure ratio on both stages, but the best ratio between the turbocharger size is received when the pressure ratio is at 60:40 between HP and LP. Single-stage turbochargers can as earlier mentioned reach a pressure ratio of 6.0:1 and by comparison, can two-stage turbocharger reaches pressure ratios of 12.0:1, by reaching higher pressure ratios allows closing the inlet valve earlier (miller cycle). The earlier closure of the inlet valve reduces the temperature of the exhaust gas. Lower temperatures on the exhaust gasses reduce the NOx emissions since the NOx is produced during combustion at very high temperatures (Woodyard, 2009) (Performance training for PME, 2013)

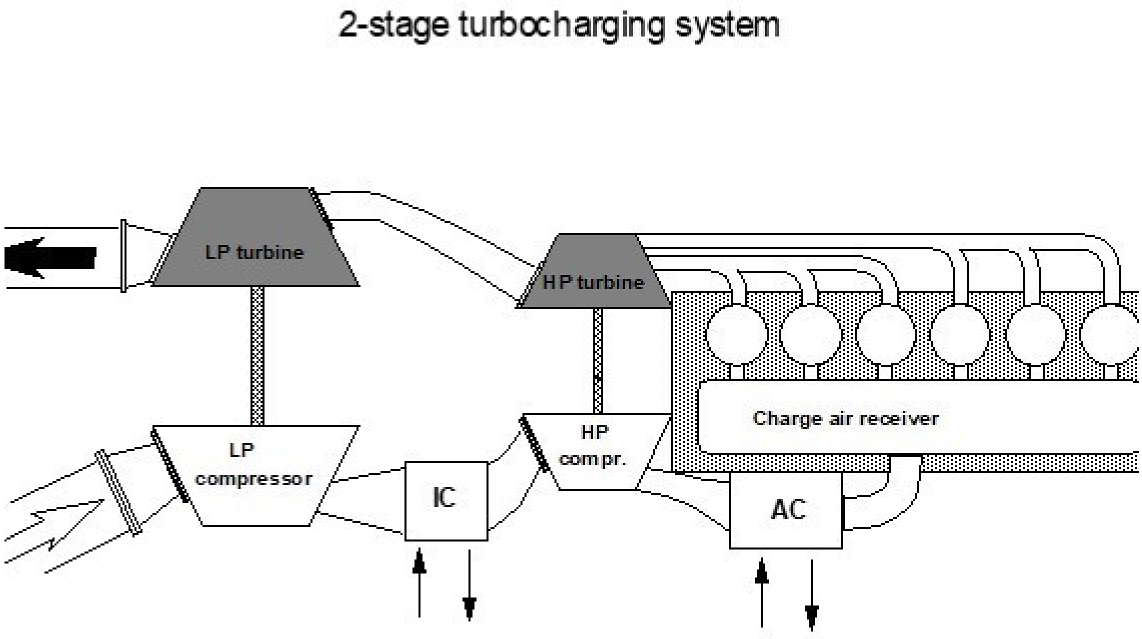


Figure 5 Two-stage turbocharger placement (Performance training for PME, 2013)

2.2.3 Sequential turbocharger

Sequential turbocharger systems (STC) are turbocharger systems that are mainly are using two turbochargers, one for lower load and one for higher load, the turbochargers can be of a different size where the smaller turbocharger is in use during the lower load and the bigger one when the load increases.

A sequential turbocharger system is used in applications where there is a need for high torque at low speed which is hard to receive with a standard turbocharging system because of that the turbocharger speed reduces when engine speed is lowered. STC is preferred in applications where the engine is usually run on low load but requires to have a good response when the load is increased, navy ships are an example of an application that often is run on low load for a long time but have the need to be able to quickly come up to speed.

The construction of an STC system in Medium speed diesel use is easier on a V-engine because it is normally already equipped with two turbochargers and gives the possibility to at loads below 50% disconnect one turbocharger and lead all exhaust gases through only one, on an L-engine, it is used two turbochargers that are connected parallel. The drawback with the use of STC is the very complicated piping and a large number of valves that needs to be fitted in both on the exhaust gas pipe and charge-air pipes, the controlling of the valves are complex when the valves have to be differently operated depending on if the load is increasing or decreasing.

2.3 Heavy Fuel Oil (HFO)

The fuel used in an engine together with intake air and the lubrication oil used is the main components that affect the emissions and how dirty the exhaust gases are. The most common fuel used in Wärtsilä engines are the heavy fuel oil (HFO) other common fuels used are light fuel oil (LFO) and different kind of gases, the most common gas used are the liquid natural gas (LNG).

HFO is a byproduct that comes from the distillery and cracking process of the crude oil where gasoline and distillated fuel are extracted, the gasoline is made for use in cars and smaller engines that requires fuel with lower viscosity and density. HFO is mainly used in engines used in marine and powerplant applications and HFO can also be called e.g. bunker fuel, black oil, marine fuel, etc. The fuel consists of a variety of different substances such as mainly carbon and hydrogen, but the fuel also consist of components remaining from the crude oil after the distillery and cracking process, all the substances in the HFO are:

- Carbon (C)
- Hydrogen (H)
- Sulfur (S)
- Nitrogen (N)
- Vanadium (V)
- Calcium (Ca)
- Sodium (Na)
- Ash

Some of the components in the fuel and lubrication oil and to some extent the intake air causes fouling in the exhaust gas system and turbochargers, the fouling will be explained in the following chapter and this thesis will not treat what substances the lubrication oil includes. The components that are the biggest reason for fouling are sulfur, ash, vanadium, water, and sodium, the water in the exhaust gases comes mainly from the intake air, however, this thesis will not further treat the involvement of intake air in the fouling. (Nyman, 2020)

2.4 Fouling

Fouling in short words are small particles that get stuck in unwanted places, when the particles stick to a surface it starts a build-up causing the surface or object to become heavier and impairs the flow through the air. The particles that stick to a surface may also create a roughness to the surface and may to some degree change the airfoil. Fouling can be reduced by appropriate air filtration, choice of fuel, optimization of the engine, and regular washing of vulnerable components. (Kurz & Brun, 2011)

Fouling in a turbocharger is when particles, often smaller than 2 to 10 µm sticks to the wings and nozzles of the blades of the turbine and compressor, the compressor shroud, and the casing are also affected by fouling. What causes the fouling in the turbochargers are the formations that are formed from the particles in the fuel, lubrication oil, and intake air the most concerning formations of the particles are:

- Carbon (C)
- Vanadium (V)
- Sodium (Na)
- Sulphur (S)
- Calcium (Ca)
- Ammonia (NH_3)

The particles "melt" at the beginning of the exhaust system where the temperatures are very high and when the exhaust gases cool down further down the exhaust gas system the particles start to stick to a surface, the phenomenon often occurs when exhaust temperatures drop down to around 550-600°C. The emergence of fouling increases if the engine is run at a higher temperature the increase of fouling also depends on what fuel the engine is run on, the HFO is still the most common fuel in a medium speed diesel but nowadays it becomes more and more common that a medium speed diesel is run as a DF engine or GS engine. With the use of a different fuel other than the HFO, the exhaust emission becomes lower, and with that also the fouling decreases. Typically, as earlier mentioned the components of the particles that stick to the surfaces of the exhaust system and TCs comes from the fuel, lubrication oil, and intake air but there are also small traces of components that come from the wear of the engine the components from the engine wear becomes more critical as the engine ages. (Fouling in turbochargers, 2009)

When fouling occurs, it will lead to a higher charge air pressure, increased turbocharger speed, and decreased efficiency, the fouling also impacts the stability of the turbocharger and might impact the airflow pattern to the turbochargers this can result in unwanted vibrations in the blades or operational issues such as surging. Fouling also leads to an increasing in the temperature in the exhaust system and higher temperatures lead to even more particles sticking to the blades in the turbocharger, and so on until the exhaust system is clogged up or the turbochargers fail. Too much fouling on the nozzle ring will set the turbocharger into a condition called "choke" where the charge air pressure will stop to increase and that will cause extreme exhaust gas temperatures. The build-up in the exhaust system can only be decreased as much as possible by keeping the temperature as low as possible, in the turbochargers on the other hand the fouling can almost be eliminated by regular washing, the washing of a turbocharger can be performed by injecting different subjects before the turbocharger or manually by removing components from the turbocharger. The washing of the turbochargers is important because if there is a large build-up on the blades on the turbocharger surging and backpressure may occur and that may also damage the turbocharger and in worst-case scenarios, the turbochargers must be replaced and that is expensive. (Kurz & Brun, 2011)

Besides the fouling the exhaust system and turbochargers are also exposed for corrosion, the corrosion is mainly caused by vanadium and sodium at high temperatures and the degree of the corrosion are dependent on the temperature, fuel composition, material used on pipes and turbochargers, and the level of oxygen in the exhaust gas. At exhaust gas temperatures over 600° different kind of sulfates causes an increase on the corrosion, the corrosion also increases considerably when vanadyl-vanadate are present in the exhaust gases. When the temperatures of the exhaust gasses are between 530 and 560° the amount of adhesive ash and extent of corrosion are depending on the ratio between vanadium and sodium. (Bludszuweit, S; Jungmichel, H; Buchholz, B; K, Prescher; Bunger, H, G, 2000)

2.5 Wärtsilä Turbocharger Wash (WTW)

The washing of the turbochargers on an engine that is used in powerplants and marine applications has been performed almost as long as the turbochargers themselves have been used, the turbocharger has been standard equipment on medium speed engines since the 1980s. Washing of turbochargers is performed to maintain the efficiency and reduce the build-up caused by the fouling, by frequently washing can the designed lifespan of a turbocharger be reached.

The washing can be performed in three different ways, mechanical cleaning, wet washing, or dry washing. Mechanical cleaning is performed by removing the turbocharger or parts of the turbocharger and cleaning it by hand, on Wärtsilä engines it is usually only the turbocharger cartridge that is removed. Cleaning the turbocharger mechanically is a very time consuming and cost-ineffective way because it demands very much work and the engine has to stand still for a longer period, this is only done if there is some other reason the engine has to stand still or if the regular washing has been skipped for various reasons and the layers of fouling are too thick to remove by wet washing. The wet washing is performed by injecting water through nozzles in the turbocharger when the engine is running, the wet washing can be done by manually controlling the water supply or by having valves that are operated by a PLC. The Wärtsilä Turbocharger Wash (WTW) unit is an automated water wash unit for the turbocharger that are using valves to control the water flow. The WTW allows the user to perform the cleaning sequence completely automated, the WTW is either controlled by a PLC or a separate control unit. The cleaning sequence can be started from Wärtsilä’s control and monitoring system (WOIS), or the separate control panel. Dry-washing uses different granulates, shells, or rice that are injected into the turbocharger through compressed airlines.

The water washing method will be the main subject in this thesis since that is the method the WTW is using. Water washing as earlier mentioned is performed when the engine is running but the load of the engine is reduced to lower the temperature in the turbine, this is done to avoid a thermal shock that may cause harm to the turbine and other parts of the engine. After the water has been injected the turbine is dried for a period of 10 minutes where the warm exhaust gasses dries the turbine, by injecting compressed air through the wash unit the water that remains in the lines is removed this is done to avoid corrosion on the pipes. Compressed air is also used to keep the nozzles in the turbine side unclogged between the washing sequences. The constant compressed airflow through the nozzles in the turbine is required because of the fouling, the fouling may cause build-up on the nozzles causing them to clog up. Also, the compressor of the turbocharger is cleaned in the same way as on the turbine but the time the water is injected is greatly reduced and the water flow per minute is reduced to the compressor side. The lower amount of water injected into the compressors is to reduce the risk of damaging the compressor wheel and with a small amount of water, it evaporates because of the heat before it reaches the intake manifold. The compressor side does not require compressed air to keep the nozzle open because the fouling is so much smaller on that side. Unlike in the turbines, the fouling in the compressors is not caused by the fuel instead it is the intake air that is causing fouling in the compressors. (Karan, 2019)

2.5.1 WTW Single-stage wash unit

The WTW wash unit for engines equipped with a single-stage turbocharger is built on a steel frame and is mounted stand-alone from the engine to reduce stress and vibrations in the components. The wash unit is built with valves for water and compressed air including actuators and pilot valves that are needed, both the water and compressed air line valves are connected with stainless steel pipes. The one-stage wash unit is constructed with 1” valves and piping the pipes to the compressor side is reduced to lower the water flow per minute. The unit was originally constructed with ¾” valves and pipes but turned out to be insufficient water flow to the larger turbochargers.

Figure 6 One stage wash unit (Wärtsilä, 2019)

The one-stage WTW is constructed with two inlet lines and three outlet lines, the inlet lines are for the water and compressed air supplies and the outlet connects to the turbocharger where one is connected to the compressor and one to the turbine the last one is for the purge air. Compressed air is also used to control the valves and to keep the nozzles before the turbine unclogged, the opening and closing of the valves are controlled by electronic actuators.

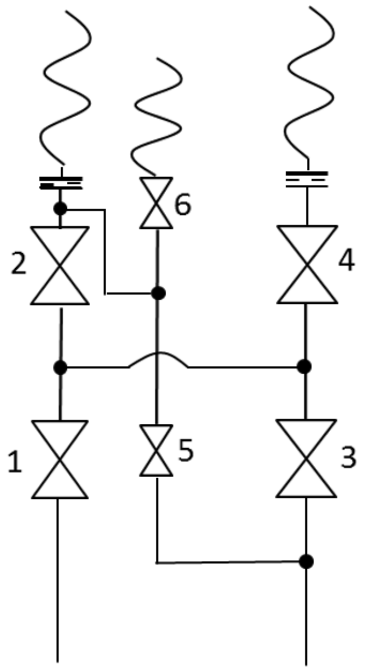


Figure 7 Piping diagram single-stage unit (Excluding control pipes for valves)

The figure above shows the main piping of the single-stage WTW, in the figure the compressed air pipes for the control air to the actuators are excluded to keep the figure simpler, how the compressed air pipes are lined can be seen in Figure 5. The numbers of the valve in the figure are following:

1. Main water valve
2. Turbine valve
3. Main air valve
4. Compressor valve
5. External compressed purge air valve
6. Internal compressed purge air valve

For the purge air, the internal valves take the purge air that is used to keep the nozzles unclogged from the compressor side of the turbocharger, when the load is lowered the pressure from the compressor is insufficient then the compressed air is taken from an external air compressor.

2.5.2 WTW Two-stage wash unit

The wash unit used today on engines equipped with two-stage turbochargers is similar to the unit for one-stage engines, the two-stage unit is constructed with two more valves that give the opportunities to clean both the high- and low-pressure turbocharger on the engine. The two-stage unit is built with ¾" valves and pipes and will not be able to reach the desired water flow for the two-stage turbochargers on the Wärtsilä46, the two-stage wash unit also uses compressed air to control the valves with help from the actuators.

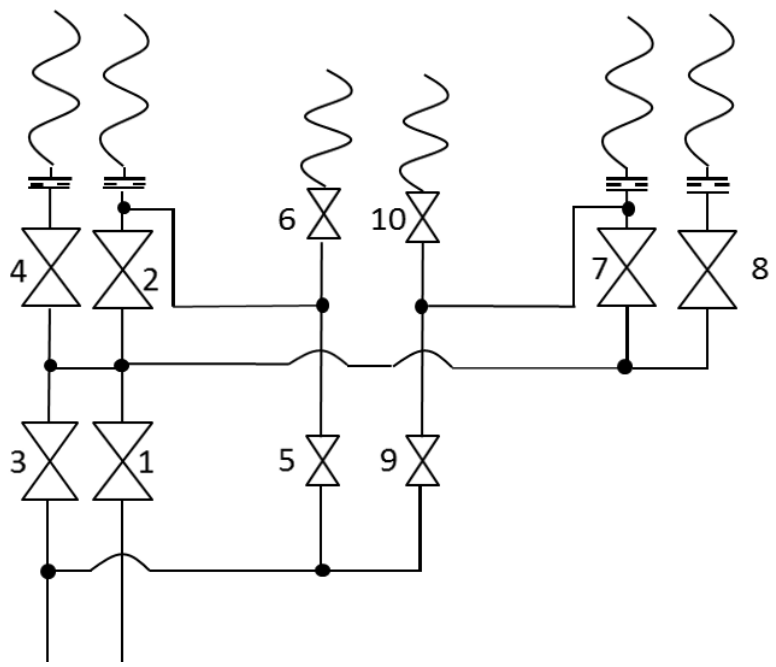


Figure 8 Piping diagram two-stage unit (excluding control pipes for valves)

As seen in figure 7 the piping on the two-stage wash unit is very similar to the one stage, the main difference between the two units are valves 7, 8, 9, and 10. Those four valves are added because of the second turbocharger that is added to the engine. The placement of the different lines is also a little bit different from the one-stage wash unit. The numbers in the diagram are following:

1. Main water valve

2. High-pressure turbine valve

3. Main air valve

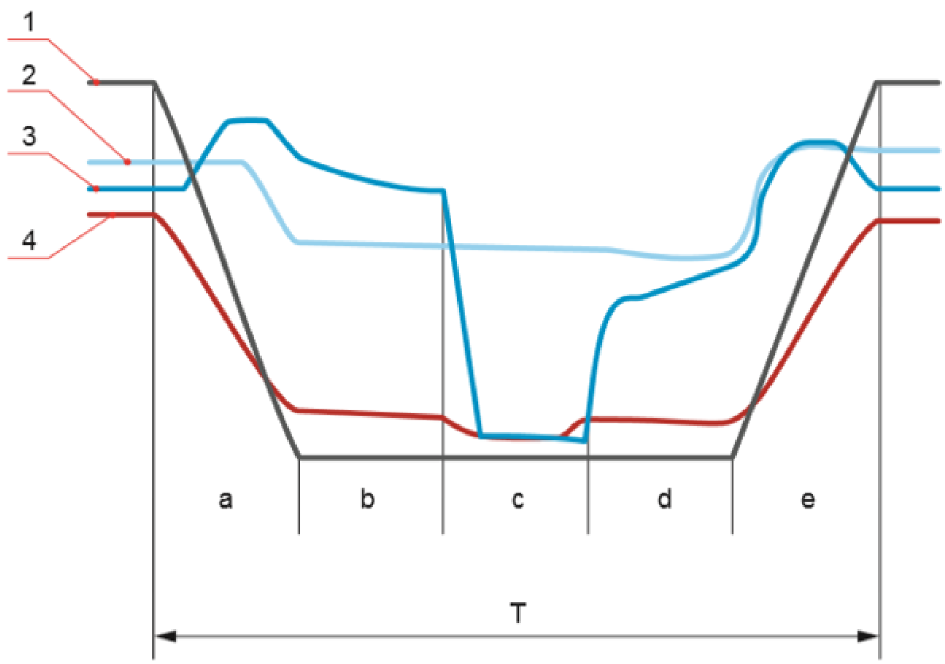
4. High-pressure compressor valve
5. External compressed purge air valve
6. Internal purge air valve
7. Low-pressure turbine valve
8. Low-pressure compressor side
9. External compressed purge air valve
10. Internal purge air valve

2.6 Washing procedure

As earlier mentioned in this thesis the WTW is using water and compressed air for the washing of the turbochargers, the sequence for the washing is performed in two different sequences. The turbine side and compressor side are washed differently where the turbine side is washed at low engine load and the compressor wash is washed at high load. The turbine side is washed at a low load to get down the temperature of the exhaust gasses to decrease the chance of a thermal shock to the turbocharger, the compressor side on the other half is washed at a high load. (Turbocharger cleaning procedure)

Example trend

To evaluate the efficiency of the turbine wash, record the operation data before and after the wash sequence in a turbocharger wash log book.



1 Generative power
2 Exhaust gas temperature before turbocharger
3 Exhaust gas temperature after turbocharger
4 Turbocharger speed

A.*Load reduction period*, B.*Stabilization period*, C.*Water injection period*, D.*Stabilization period*, E.*Load increase period*, T.*Total wash sequence*

Figure 9 Example trend of the turbocharger washing cycle

To wash the turbine of the turbocharger the temperature in the inlet of the turbocharger has to be lower than 430°C, on an engine with a two-stage turbocharger it is the temperature in the inlet of the HP turbocharger that has to be lower than 430°C. On Wärtsilä engines in powerplant applications, the load is automatically lowered by WOIS, on marine engines and powerplant engines operated in island mode the load must be lowered manually. During the load adjust and stabilization the purge air valves are open but if the charge air pressure in the air receiver drops below 1.5 bar the internal purge air valve closes, and the external purge air valve is opened. The wash sequence step by step for two-stage turbochargers are following:

- The turbine wash sequence is started
- The engine load is adjusted, and the water pressure is set to the specified pressure intended for the specific engine

- 10-minute temperature stabilization (valves 5 and 9 open)
- HP turbine wash period, purge air valves (5 and 9) closes and main water valve (1) and HP valve (2) opens to let water be injected for a 10 minutes period
- HP turbine are dried with compressed air, main water valve (1) closes and the main air valve (3) opens for 10 seconds
- The valves (3 and 2) are closed after the drying and the engine is stabilized for another 10 minutes before the LP turbine wash is started
- The LP turbine wash is commencing during the stabilization after HP turbine wash, the main water valve (1) and LP turbine valve (7) are opened so water can be injected for a 10 minutes period.
- The low-pressure turbine is also dried with compressed air, main water valve closed (1) and main air valve (3) are opened
- The LP turbine drying the valves (3 and 7) are closed and the external purge air valves (5 and 9) opens for a stabilization period of 10 minutes
- End of the turbine wash, engine load can now be increased

The turbine wash on a single stage engine is the same but shorter since there is only one turbine that needs cleaning, the steps after HP turbine stabilization is excluded and the engine load can be increased after the stabilization. (Cleaning the turbine with water injected, 2019)

The procedure of washing the compressor side is much less time consuming because the time intervals for the different steps are much shorter, also the engine does not have to be run on a low load, therefore the engine can be in normal use during the wash sequence of compressor side and that results in no loss of earnings.

- Compressor wash sequence is started
- Load control, check that the engine load is above 50% and LP compressor valve (8) opens
- After one second the main water valve (1) opens and allows water to be injected
- The main water valve (1) is open for 10 seconds before it closes

- After one second the main air valve (3) is opened allowing compressed air in to remove the water from the compressor
- The main air valve (3) is open for 10 seconds before it and the LP compressor valve (8) are closed
- After one second HP compressor valve (4) is opened and after another second the main water valve (1) is opened
- The main water valve (1) is open for 10 seconds before it closes
- After one second the main air valve (3) is opened to allow air in and after 10 seconds the main air valve (3) and HP compressor valve (4) are closed
- End of the compressor wash

For the engines with a single-stage turbocharger, the wash sequence for the compressor is almost the same as for the two-stage except that the steps after that the main air valve and LP compressor valve are closed are removed. (2-stage wash sequence description)

2.7 Product development

By product development, one means the process of developing a new product from an idea. When developing a product, many different areas need to be considered. It must be considered the needs for a new product and what functions the product must have and may have. The market for a possible new product must be considered and also the potential competitors. Another important aspect to consider is the price of the product.

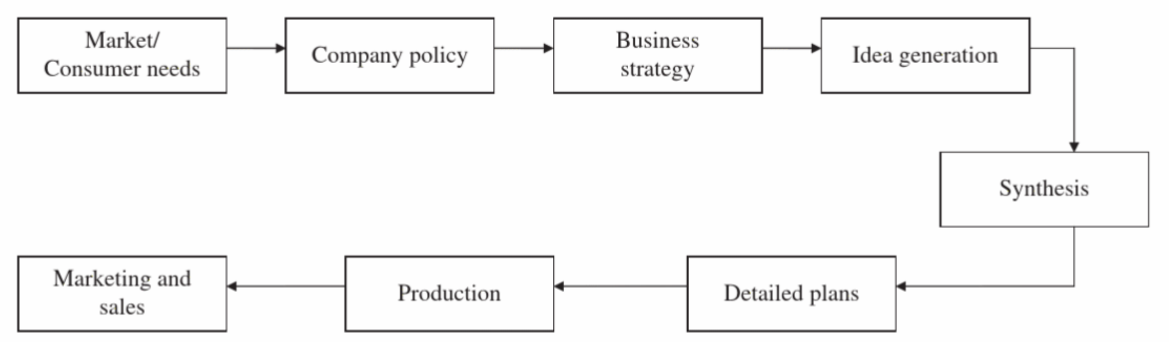


Figure 10 Product development stages (Mital, 2014)

Before a successful product can be developed there has to be an idea or there must be several different ideas to be evaluated before a plan for the development can be made. A development plan is made to have guidelines on the stages the process needs to go through and to keep track of what stage the development is at the moment. In the development plan, there is included how to approach the subject and what kind of methods should be used. In this thesis, there have been doing sketches and different possible designs, theoretical simulations, and modeling after the development plan has been made and before the production of a new unit has been started. Depending on the product type in question the methods used can differ. The different methods are used already at an early stage of development to be able to define and exclude ideas that will not fulfill the requirements. With proper product development, a company can eliminate the risk that a new product will have some serious faults. The company also has the opportunity to optimize the product and ensure its function. However, a company should develop a high-quality product quickly, easily, and efficiently for the market. The cost of producing the product determines its selling price, the selling price determines the profitability of the product. Also, the amount of money the company spends on the development from concept to prototype determines the profitability of the product. A product becomes profitable only after the development costs are paid. (Mital, 2014)

In product development, it is important to also think about how the design of the product should be. The design should be made according to where the product is intended to be used and that it appeals to the customer. The focus on how the design will be varies depending on the application, e.g. an industrial product usually has a simple and robust design. In an industrial application the customer focuses more on the functionality of the product instead of appearance, an everyday product usually requires a nicer design where serviceability is not as important. Before a product can be put up for sale it has to go through testing to determine if it fulfills its function and is safe to use for the customers. (Mital, 2014)

3 Methodology

This chapter will process the methodology used in this thesis and this chapter will also include how the approach to different areas of this thesis has been executed. This chapter will closely describe the different stages of this thesis and how each one of them has been executed and why. The approach to this thesis has also been to learn along the way and learning by doing to be able to fully understand the purpose of this thesis and to be able to execute the tasks of this thesis and reach desired results. This thesis is mainly done by studying the construction of the existing wash units and by doing necessary measurement that is needed to do simulations of the water and airflow in the pipes of the unit. The thesis is also done by researching how higher water flows could be reached without increasing the cost of the unit, there is also researched on how the unit could be made simpler and if there is a possibility to decrease the number of valves, couplings, and pipes, etc. When it is decided what kind of setup could be used and what kind of valve arrangement could be possible and how the design could look like, a 3D model of the wash unit is modeled in Siemens NX and a prototype is built using the drawings received from Siemens NX.

3.1 Collection of information and data

The work with this thesis started by gathering information and data needed to understand how the wash unit works and the theory behind the washing of turbochargers. For gathering data and information a few methods were used. The work with the thesis started with interviews and discussion with colleagues on how the single-stage and two-stage wash unit is constructed and how they function, this to more deeply understand the purpose of the thesis and what needs to be changed on the two-stage wash unit. The work is also approached by gathering basic knowledge about diesel combustion engines, turbochargers, fouling, etc. The knowledge is gathered through a lot of internal documents and internal training but also by reading books and articles about the subject. At the start of the thesis, there was a lot of reading, overall gathering of information, and discussions with colleagues to get more into the company and to understand how they work.

3.2 Simulations

The methods used to approach what pipe sizes the two-stage wash unit would need to reach the desired water flow are by doing simulations, the simulations are done in a program named GT-power the program is widely used in Wärtsilä because its efficient way of possibility to simulate a whole engine in real-time. The program is quite difficult to understand at first but once one has gotten an understanding of how to use it correctly it becomes very useful. The program allows changing many different parameters such as diameters, fluid, pressures, temperature, lengths, and many more. The simulations are done by setting up a model setup of both the single-stage and two-stage wash units. The two models are made as real as possible to give as trustworthy results as possible the simulations are performed with different values of the diameters and pressures, the diameters are changed to give an insight on what the smallest diameter in the valves that will be allowed and the pressure are varied to give an insight on what pressures will be needed later on during the testing of the prototype wash unit. Pictures and results from the simulations will be presented in the chapter presenting the result.

3.3 Creating a 3D model

The methods used to approach the modeling of a prototype are as earlier mentioned done by 3D modeling in Siemens NX. As a template for the prototype a model of the old version was imported to NX from which sizes of the valves and pipes were increased and the layout changed to fit the hand sketch that had been made, it is aimed to fit the new model to the same frame and under the same cover as the old unit this to avoid a problem with possible refitting of the new wash unit to an older installation. Using the old unit as a template has been very helpful when a lot of the couplings and pipe connections have been reused or used as a template in the search for a bigger one. For parts that are not in the old model Wärtsilä has a very good database where most of the standardized fasteners, couplings, connections, pipes, etc. are located and are very easily found and imported to the NX model, totally new parts as a new type of valve, for example, has been given as a CAD model from a different program that could be imported to NX and in that way be used in the model.

3.4 Testing of a Prototype

From the model that has been created in NX a prototype has been built at Procons in Malax, the prototype has been built to give the ability to perform a couple of different kind of tests to see how trustworthy the simulations have been and to see if the prototype fulfills the requirement that was given in the start of this thesis work and as a purpose. The test that has been performed is controlling the maximum water flow that can be achieved, opening and closing of valves when pressurized and the air consumption during low load. The air consumption is also tested by using different sized orifices to see what size is most suitable. The results of the testing will be presented in the following chapter.

4 Results

In this chapter, the results achieved in this thesis will be presented. The chapter is divided into four different subcategories that each treat a different area where one will be analyzing the results from the simulations, one will analyze the 3D modeling, one will analyze the results from the testing of the prototype and at last, there will be an overall analysis of the results.

4.1 Simulation results

The simulations in this thesis are as earlier mentioned performed in GT-Power and are made with two different models, one that is made to simulate the single-stage unit and one to simulate the two-stage unit. The first model, the single-stage wash unit is made to help with understanding the program and since the single-stage unit design is simpler it is easier to do small changes to the size of valves and pipes with a smaller risk of getting errors. The simulations of the one-stage unit and the measurements of the valves available introduce whether to valves used on the one stage also could be used in the two-stage unit. The valve that is used on the one-stage unit has a one-inch inlet but regardless of the size of the inlet at the smallest part of the valve it measures 17,3 millimeters and that can affect the results of the simulations. In the thesis there is a requirement on required flows and allowed flows, for the turbine side it is required to reach a water flow over 120 *l/min,* the flow on the compressor side should be around 20 *l/min,* and the airflow during purge air should be reduced to around 65 *l/min*. The results from all the different kinds of simulations will be presented as graphs of the flow in appendices, however, the graph and results from the simulations of water flow to HP turbine and HP compressor side will be presented later in this chapter since that is the main reason for this work.

From the results of the simulations of the one-stage model, it can be stated that the one-inch valves may not fulfill the requirement of water flow, however, it is also noticed during the simulations that the conditions in the turbine affect the flow through the wash unit. The simulations show that the required water flow for the two-stage unit can be reached by increasing the diameter of one of the valves, from further researches it is found that a one-inch three-way ball valve has a larger inner diameter than the needle valve used on the one stage unit. With increasing the diameter on the latter of the valves to the diameter of the three-way valve the water flow increases enough to fulfill the requirements. However, there are both advantages and disadvantages with using a three-way ball valve instead of the needle valves, as mentioned the inner diameter is larger and since it is a three-way valve it has two outlets instead of one and that leads to a decrease in the number of valves used. On the other hand, the cost of one three-way valve is significantly higher than one needle valve and the size itself is larger and there are also a lot more components in a three-way valve that could break or cause trouble. Another possible problem with a three-way valve solution is controlling the positions of the valve. After a discussion with stakeholders and Procons in Malax, which confirmed that the price of one three-way would roughly be the same as two-needle valves it was decided that a three-way valve would be used as a secondary valve if it fulfills the requirement according to the simulations.

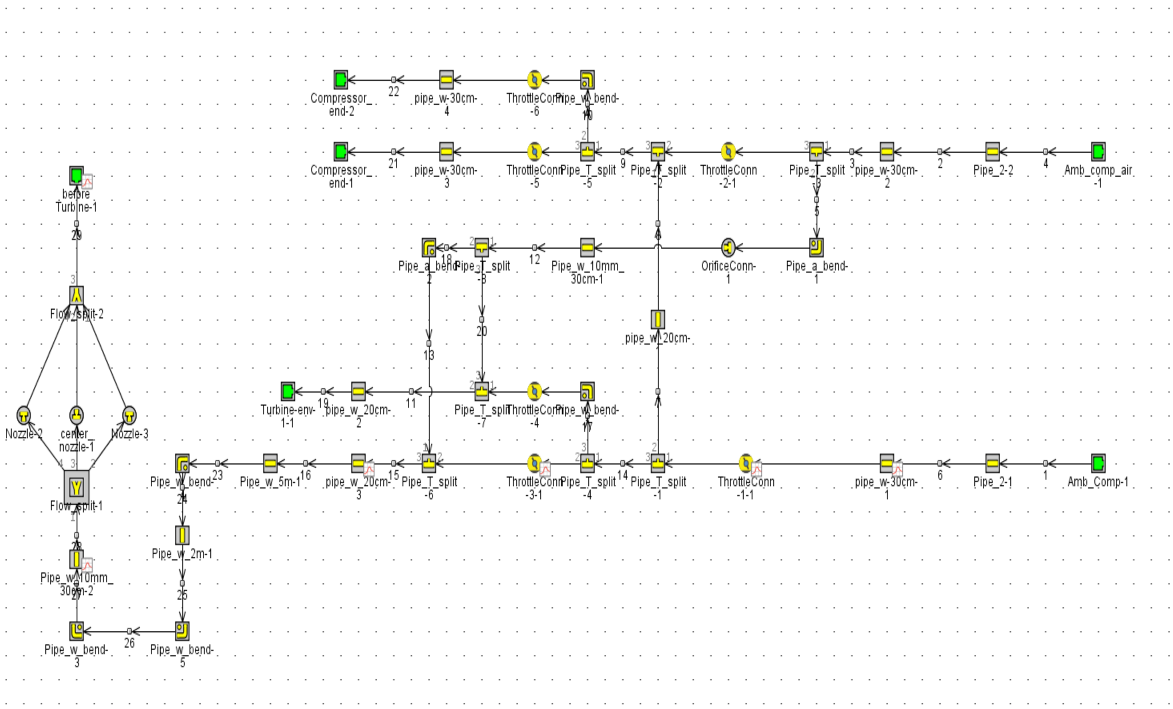


Figure 11 Two-stage unit model in GT-Power

After a couple of different simulations back and forth with different parameters on water and air pressure, it was possible to state that a one-inch three-way valve would fulfill the requirement of water flow as long as the water pressure is above 4 bar. As seen in the figure above there seem to be four different needle valves, that is because GT-Power does not have a three-way valve that would fit the simulations. Instead of having a three-way valve a T-union is placed before the secondary valve to split the pipes and another valve added on that line, the inner diameter of the valves is the same as on a standard one-inch three-way valve. Also seen in the same figure there is only simulated piping to the nozzles before the HP turbine and that is to keep the model simple and it is the water flow to the HP turbine that is the critical area that needs to be investigated. The flow through the wash unit is measured in liter per minute and is plotted as a graph depending on the time that has passed. The simulations are done on a period of five seconds for each case, it was noticed that after the five seconds the flow had stabilized that much that it was possible to read a trustworthy value from the results. When extending the time for each case the total time one simulation would take became very long and the same results were achieved.

On the old prototype, the airflow during purge air is reduced by using an orifice that is a very simple and robust way to reduce the airflow, the problem with the old version is where the orifice is placed. After simulations of the airflow with different pressures and different sizes of orifice it can be stated that to reduce the airflow down to around 65 *L/min* an orifice with a size of 2 *mm* would be suiting when the air pressure is between 6 and 8 *bar*. The size of the orifice should be such that the user can adjust the pressure on the compressed air slightly, according to the simulations a 2 *mm* orifice should be suited both for higher and lower air pressures.

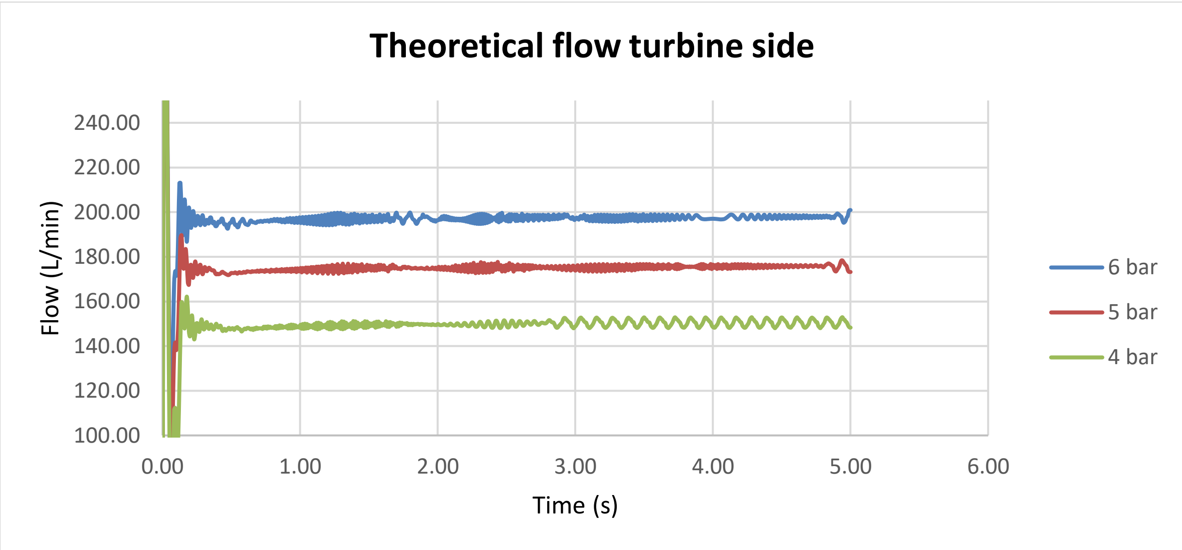


Figure 12 Graph over Waterflow HP turbine

As seen in the figure above the flow through the pipes and valves of the wash unit is depending on what water pressure is used, with an increase of 2 bars pressure a significantly higher flow rate is received. It is also seen that at 4 bars water pressure the flowrate is over 140 *L/min* and that is an acceptable result since the required water flow to the HP turbines should be over 120 *L/min*. It is also required to notify here that the water flow changes depending on the pressure in the exhaust gas system, a higher pressure decreases the flow. Even if the simulation model includes the piping and nozzles to the HP turbine the results to the water flow are received from the end of the wash unit because of the limitations to this thesis. The piping is included in the simulation model to simplify further simulations and to make it easy to adapt the parameters to suit the specific engine the simulations are performed for.

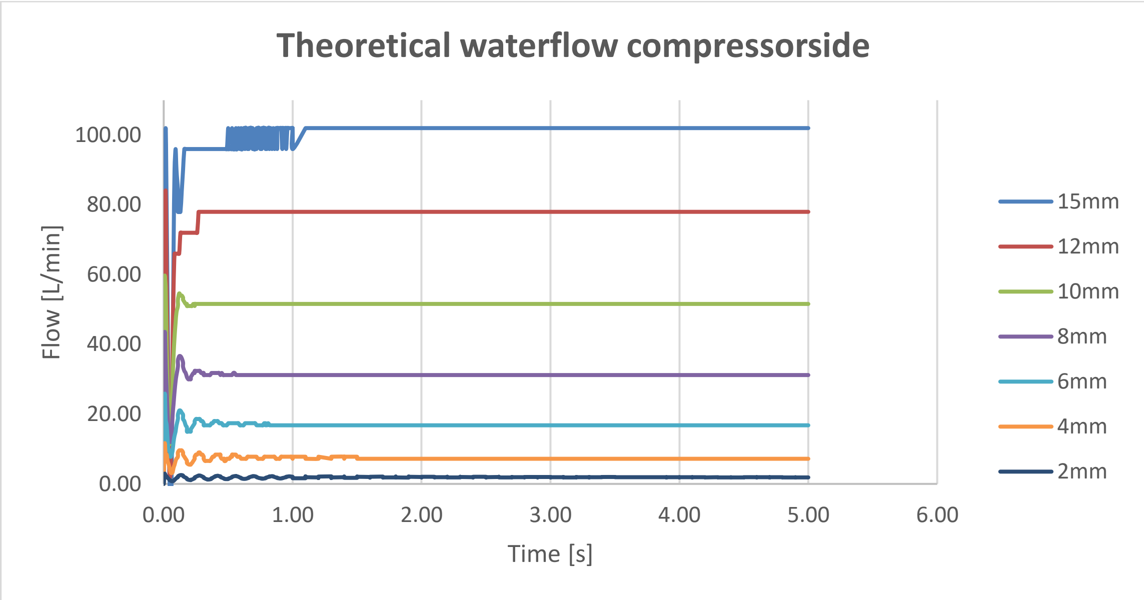


Figure 13 Graph over Waterflow HP compressor

The pipe that connects the HP side with the LP side after the needle valves in each line will be a pipe with a diameter of 15 *mm* and to be able to get different simulations done there is used an orifice to reduce the pipe diameter. in the simulations of the water flow to the compressors, there is an orifice used to be able to reduce the diameters of the pipe. The orifice is used to see how the flow is affected when the diameter of the pipe is reduced, the flow required to the compressors is a lot lower than to the turbine. As seen in the figure without any reduction other than the pipe between HP and LP side the water flow will be just over 100 *L/min* and the requirement is 20 *L/min*. According to the simulations, a reduction to 6 *mm* would keep the water flow just below 20 *L/min* but also here the condition in the compressor affects the water flow. The simulation of the reduction on the water flow to the compressor housings are done mainly just to get a perception of what pipe sizes it would be needed to use between the wash unit and the compressor housings, it is nothing that needs to be considered during the modeling and construction of the unit.

4.2 Modeling results

From the 3D modeling, almost a whole new prototype has been produced where most of the couplings and pipes are changed and the placement of the solenoids has been relocated from the first prototype that had been made. The piping from the solenoids to the control air of the valves is changed from steel pipes to silicone air hoses with quick couplings to decrease the material cost and to make the building of the unit faster, easier and also simplify the exchange of a broken hose. The modeling has been done in two different phases at first a 3D model was constructed, and draft drawings were created in the second phase the 3D model is updated to the final result and official drawings were created. The draft drawings have been sent to Procons that handles the manufacturing of the unit, and the final drawings are made to be same as the how the final unit turned out to be.

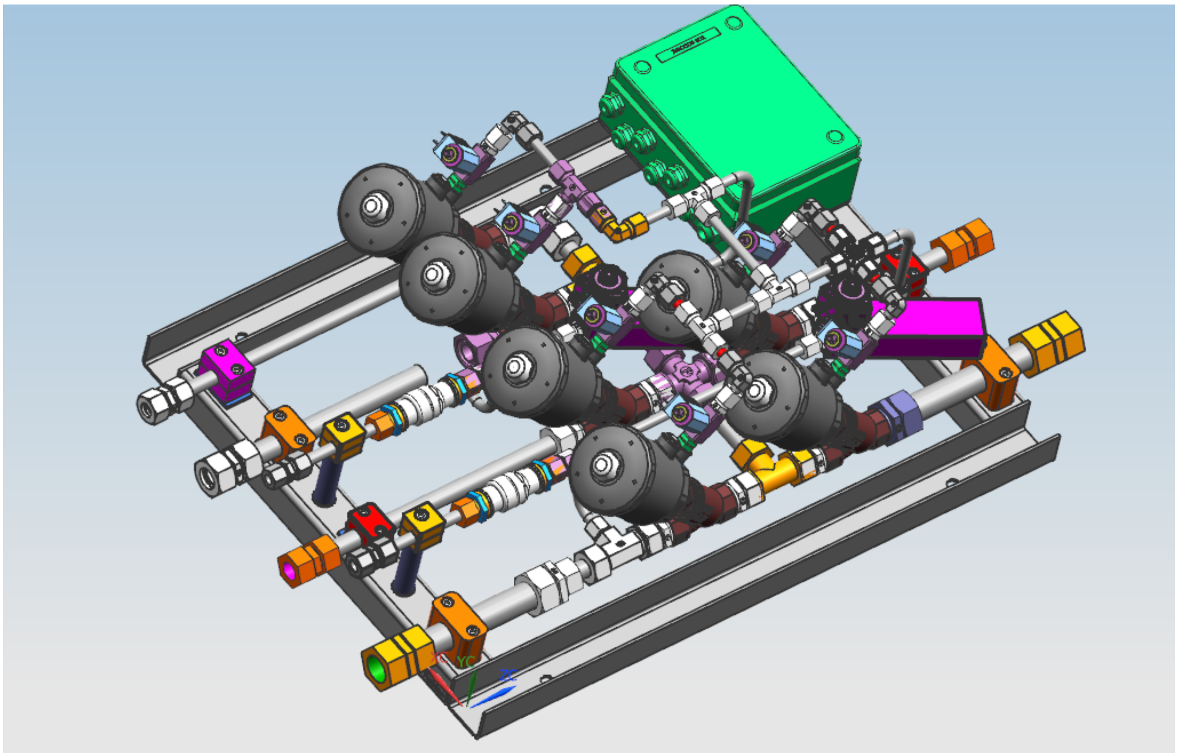


Figure 14 3D model of the old prototype

As seen in the figure of the old prototype above the original prototype's piping are very complicated and the piping for the control air requires quite a lot of different couplings and pipes, it can also be seen that some pipes are missing and some other minor faults this is because it is just a prototype that never has been finished. The old prototype also has a lot of bends on different pipes which can make the construction harder and lengthen the construction time since it can be hard to get the bend in the exactly right place, with bent pipes the risk of leakages increases significantly. The bent pipes can also make it complicated if a spare part would be needed, it is easier to send a straight pipe or an exchange coupling that will fit instead of a pipe with a certain bending. The old prototype was also fitted with T – unions that reduced the size of the diameters quite markable, the couplings were fitted on places where the flow would also be affected markable.

Since the new prototype will have 2 valves removed and changed into three-way valves instead of needle valves there is a lot of changes done to the piping and especially the purge airlines are changed quite a bit. The layout overall is changed quite a bit since there will be used three-way valves as secondary valves and the three-way valves have one incoming connection and two outgoing connections, one of the outgoing connections of the three-way valve are to the side which complicates the usage of space on the frame. There were two different options considered regarding how the three-way valves should be placed, one option was with the actuator would be placed lying down with the outgoing pipes to go above each other and the other option to have the actuator standing upright and the outgoing pipes to be placed beside each other. At first, it was considered it would save space to have the actuators lying down with the outgoing pipes going on top of each other but it turned out that how the actuators would be placed did not affect the space significantly, therefore the actuators will be placed upright to make the control air connections easier to reach and the design to look better.

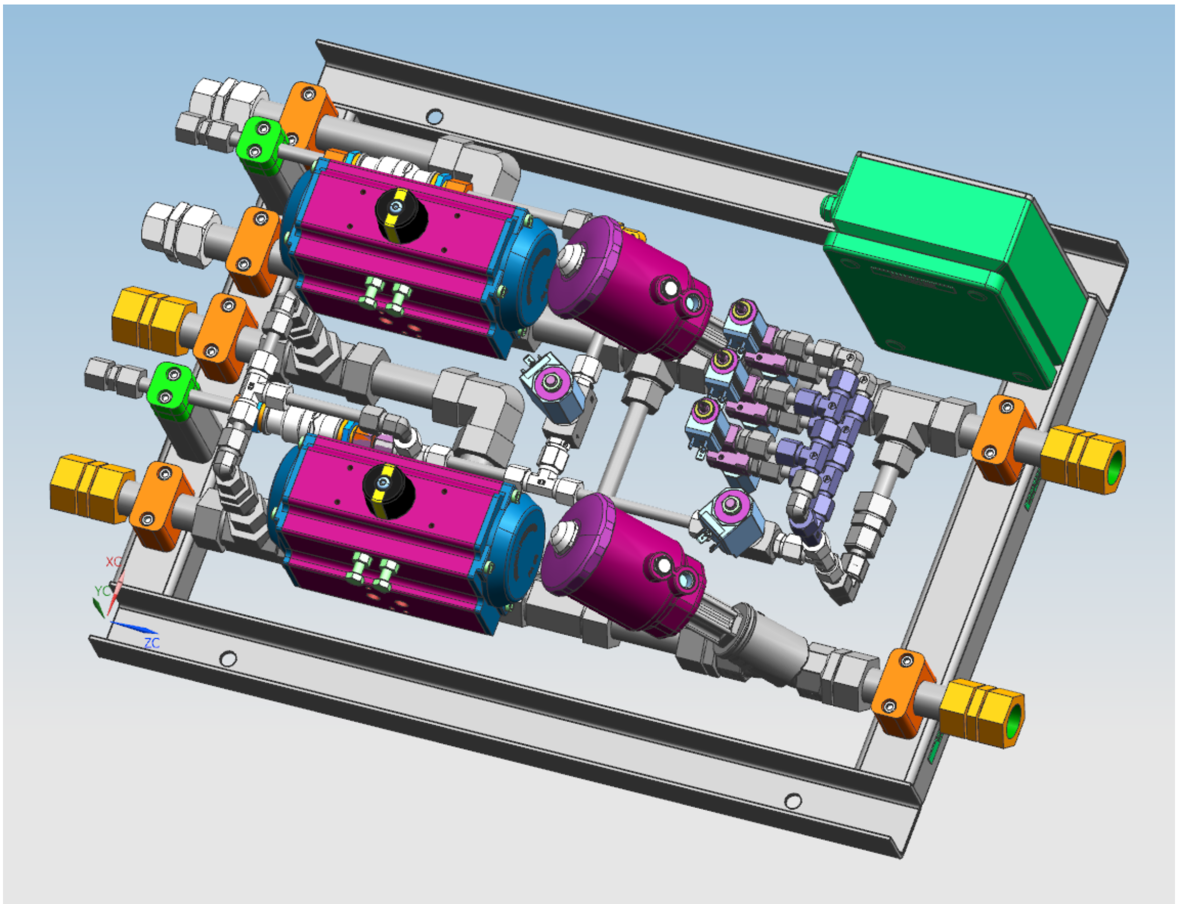


Figure 15 New prototype

In the figure above the new prototype with the three-way valves can be seen, it can also be seen the new arrangement of the solenoids that will control the valves. The solenoids are placed all in the same place since as earlier mentioned the piping of the control air will be changed from steel pipes to flexible silicone hoses. Except that the silicone hoses will be used to reduce the material cost and construction time they will also be useful because of where the placement of the connections to the control air is placed on the actuator on the three-way valve. The connections where the control air inlets are located are on the side of the actuator and since the connections are in such a place it would be needed a lot of different couplings and pipes to connect control air to the actuators, it would also make the manufacturing of the unit a lot harder and to get those pipes to align nice and neat with all the other pipes would be a hard task.

The assembly of the 3D model is made from different subassemblies, the subassemblies facilitate the creating of the drawing of the unit when the 3D model is divided into different subassemblies it is possible to make drawings for each assembly. When using subassemblies, the part list of the main assembly consists of drawings numbers to the subassemblies, and the different couplings and material numbers are in the subassembly's drawings.

4.3 Testing of prototype

The testing of the prototype is done on-site in Malax at Procons, the testing is performed by supplying the unit with compressed air and water just as in a real scenario, and the opening of the valves is controlled by switches. With the testing, the water flow during the wash sequence is controlled and the instrument air consumption during purge air, the flows are measured with help of two different flow meters that are connected before the wash unit. The instrument air that is supplied to the unit is taken from the compressed air line in the workshop, the pressure in that line was seven bars and to decrease the pressure a normal pressure regulator is fitted before the airflow meter. The water was meant to be supplied from a regular fire hose and the pressure increased with the help of a water pump but after several tries and research, it was found out that the pump that would be used did not have enough capacity to supply the water pressure needed to reach the desired water flow. To reach the desired pressure to test the water flow the fire department in Malax assisted. With water supplied from a fire truck and a water pressure of 4 *bar,* a water flow of 145 *l/min* was reached which is above the water flow that was required, in other words, the new prototype fulfills the requirement of water flow. The air consumption during purge air was tested with different air pressures and also with an orifice, the orifice reduced the diameter down to 2 *mm,* and also with the orifice it was tested with varying pressures. Without the orifice, the air consumption was around 100 *l/min* and with the orifice, the consumption was below 50 *l/min*, it can be found that with a 2 *mm* the air consumption is held below 65 *l/min* at all time and still allows enough air to keep the nozzles open during standby.

Figure 16 Test rig and supporting firetruck

4.4 Final result

The results received from the simulations, 3D modeling, and testing have achieved what was desired. The result from the simulation aligns well with the result from the testing of the prototype, the water flow received at 4 bar water pressure in the on-site testing is very close to the water flow at the same water pressure in the simulations. However, even if the testing of the water flow was successful it was noticed that the working way of the three-way valve used was not as expected, the ball valve was of an L-type and the actuator could only turn 90 degrees in one direction leading to that it was not possible to get water to both of the outlets. To get the three-way valve to work correctly it would be needed to get a ball valve with a T-port and an actuator with the possibility to turn 180 degrees with the ability to stop in three different positions. The actuator needs to stop at three different positions so it can close completely when the wash unit is not in use and be positioned so the water either goes to the high pressure or low-pressure side, to get a pneumatic actuator with this possibility caused a lot of problems and a lot of researches for an actuator with a valve that would work as needed.

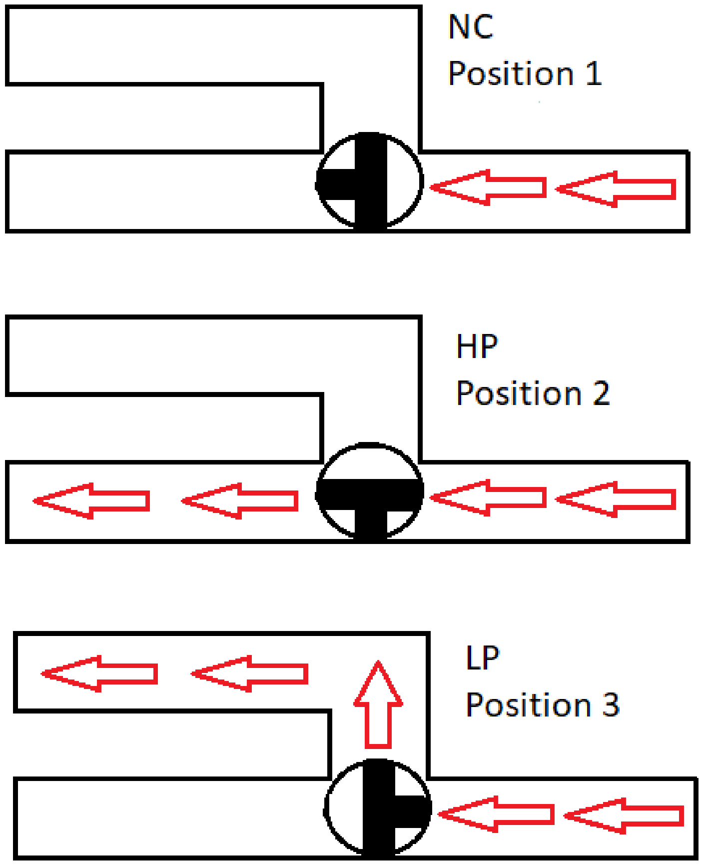


Figure 17 Picture of working ways of the three-way valve

A couple of different setups that would have the correct ways of working were found and evaluated, the different setups were compared in different points such as price, size, and function. One possible solution would have been a ball valve with a 180-degree actuator where the position would have been controlled by an electric controller, but this solution would increase the price by 1000€ for each valve and that makes the whole wash unit all too expensive since the goal was to keep the cost at the same level as the old prototype. Because of the significant price increase, this solution was not an opportunity. One other opportunity would be to use an electric actuator that rotates the ball valve depending on the voltage on the control signal to the actuator, this solution had a fair price but the problem with an electric operated actuator is the possibility that it jams open and as earlier mentioned that can have serious consequences or makes it difficult to decide the exact position of the valve. Another possible solution found was from bückert and their solution would be the use of two shut of valves placed in a special kind of mounting where depending on which valves are open the water flow exits through different outlets.

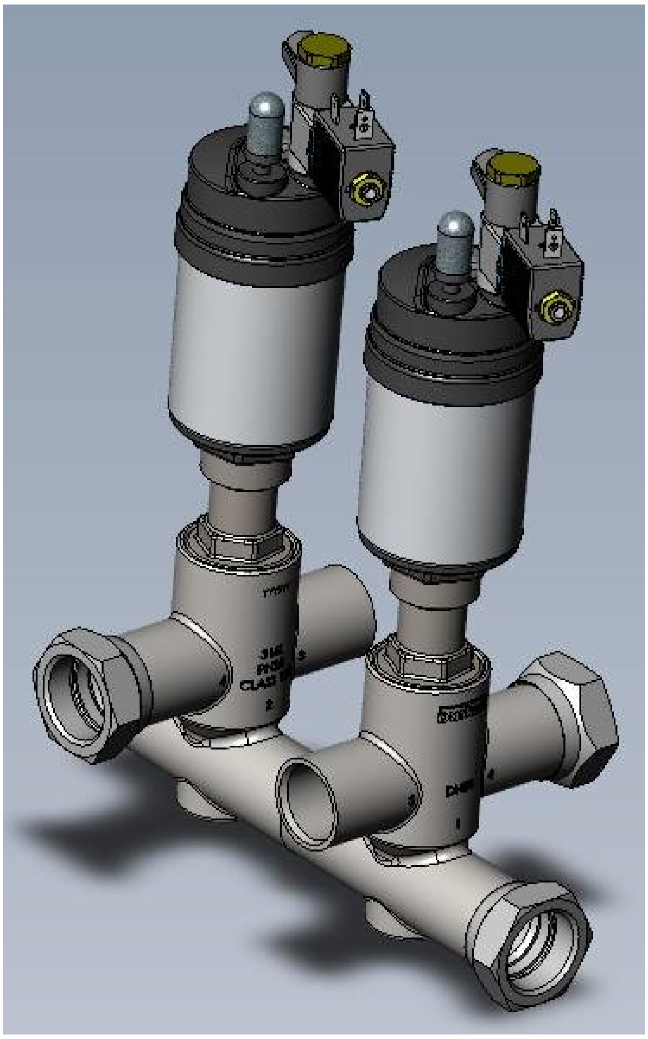


Figure 18. Buckert solution for three-way valves.

This solution complicates the construction of the wash unit and would need an increase in frame size and the height of the cover so after further investigations and discussions with stakeholders it was decided that four of the original shut off valves should be used to keep the cost down and to keep the sizes on frame and cover, also to keep the functioning simple and robust. Even with the original shut-off valves, it was needed to lengthen the frame and cover with 50 *mm* because the length of 1” pipes and components are obviously larger than 3/4”, but if that is what needs to be done to get a functioning wash it has to be done.

The final design of the wash unit simplified the construction and piping of the unit and reduces the construction time a little bit, with the use of hoses for control air to the valves instead of piping reduced the cost a little and simplified the construction. On the new unit, the outgoing pipes are in a more logical order where the two turbine pipes are placed beside each other and the outgoing turbine pipes beside each other. A wrong connected pipe, for example, switched place on turbine and compressor side can make severe damage to the engine, a pipe to the compressor side connected to the turbine side on the wash unit will lead to a water lock on the engine since there water amount used to wash the turbine are much more than the amount used for the compressor side. Fortunately, there is different size of the connections on the outgoing pipes for turbine and compressor. Also, on the final model, one of the pipes for the purge air is removed since it was discovered it would be unnecessary to keep it since both of the pipes that come from the engine would have been connected in the end.

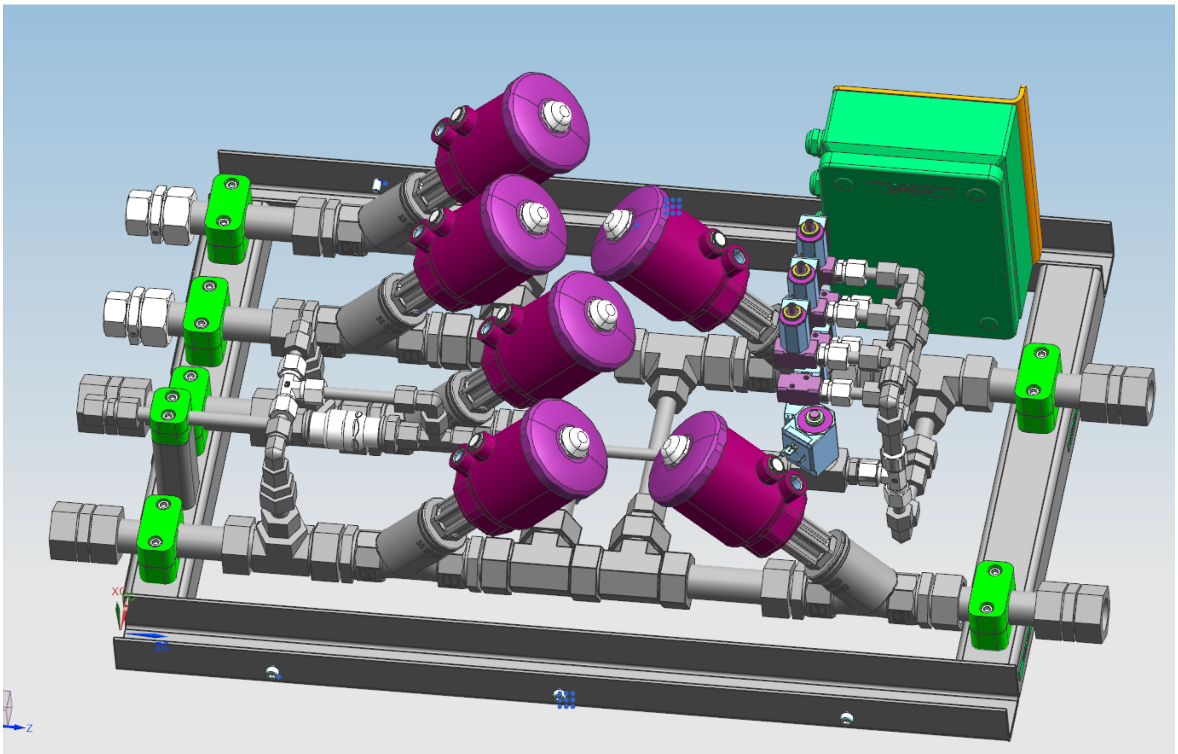


Figure 19. The final design of the wash unit.

To reduce the air consumption on the purge air a 2 *mm* orifice will be used as before, the difference here will be that the orifice will not be placed in the inlet of the compressed air. With the old placement, the orifice has not only reduced the airflow for purge air but also reduced the airflow during the drying sequence. The placement of the orifice was therefore moved to the pipe after all the solenoids and in such way only affecting the airflow to the purge air, with moving the orifice it was also needed to reduce the outside diameters of the orifice.

5 Conclusion

The prototype of the two-stage wash unit passed all the different test at last with a good margin and accepted by the stakeholders, the total price of the unit has increased a little bit but there it has to be kept in mind that almost all pipes and valves have increased in size and the larger size of the valves affects the raise of the price the most. Overall, the work has fulfilled the purpose and the goal of this thesis has been reached, it has also been constructed a new prototype that has been briefly tested and waiting on a suiting engine to do more in-depth tests of the prototype.

5.1 Further work

As further work on this subject, the possibility to simplify the wash unit even more and the possibility to reduce the cost of the wash unit to make it more attractive for the customers could be researched, as well as to continue the researches for a three-way valve instead of the shut-off valves. There could also be further researched if there is a possibility to perform the washing of the turbochargers could be executed in a completely different way. The subject could also be approached for further work to research the possibility to decrease the washing period for the turbine side of the turbocharger to decrease the time an engine has to be run on a lower load or if there is a possibility to wash both LP and HP side at the same time to save time, especially in powerplant application the need to lower the load during the washing becomes very costly.

5.2 Discussion

This thesis work has been very interesting and educational to work with. There is not much that I would have done differently if I had the changes to do it all over again, one thing I would have done differently would be to put more work and analyzing on the three-way valves. To find a suiting valve with an actuator that would work as needed was a lot more difficult than I ever could have imagined, after a lot of research it could be concluded that the normal way of working for a three-way valve was to be open to either side. To find an actuator with a 180 degrees rotation was not so hard, the hard part with the actuator was to find one that could stop at three positions. With refining analysis and studies of a three-way valve, this could have been avoided and a correct three-way valve could have been found before the prototype was completed and that would have saved both time and money. Here it also needs to be kept in mind that Wärtsilä has over 1 million working hours on the needle valves and implementing a new type of valve would have resulted in more testing and field follow-up.

Afterword

The work with this bachelor's thesis has been very interesting and challenging, it has given me a much wider understanding of medium-speed diesel engines and turbochargers and above all turbocharger washing. It has been very fun and interesting to have the opportunity to be involved in new product development.

I would like to thank my teacher and supervisor Mr. Kaj Rintanen for introducing me to this very interesting subject and for introducing me to Wärtsilä and the Turbocharging and Performance team. I would also like to thank him for all the help I have gotten during the work with this thesis.

I would also like to thank my supervisor at Wärtsilä Mr. Kristian Mäki for giving me the opportunity to work with this interesting, challenging, and very rewarding subject as my bachelor's thesis work. I would also like to say thanks for his supportive guidance and all the help and guiding I have got throughout the whole work.

A huge thanks to all the colleagues in the team Turbocharging and Performance for all the help and feedback I have got throughout the work, and also thanks to Procons and Mr. Adam Sandström who have been supporting with the building and testing of the prototype. Finally, I want to thank all others who have been involved and have been helping me with my work.

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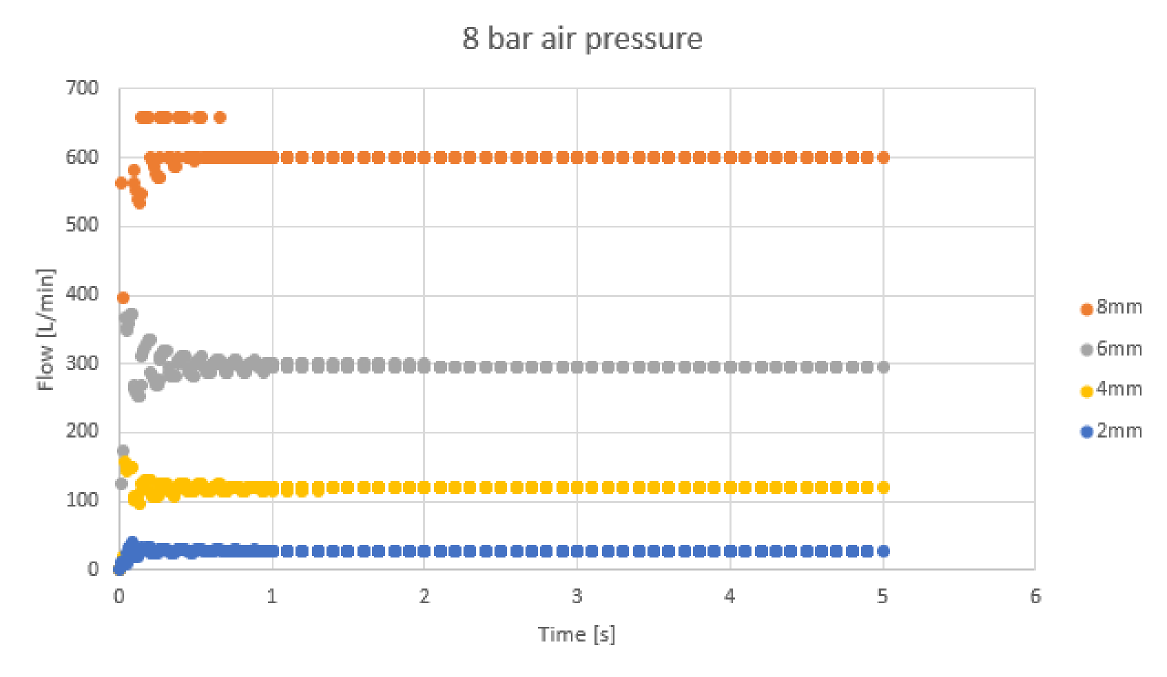
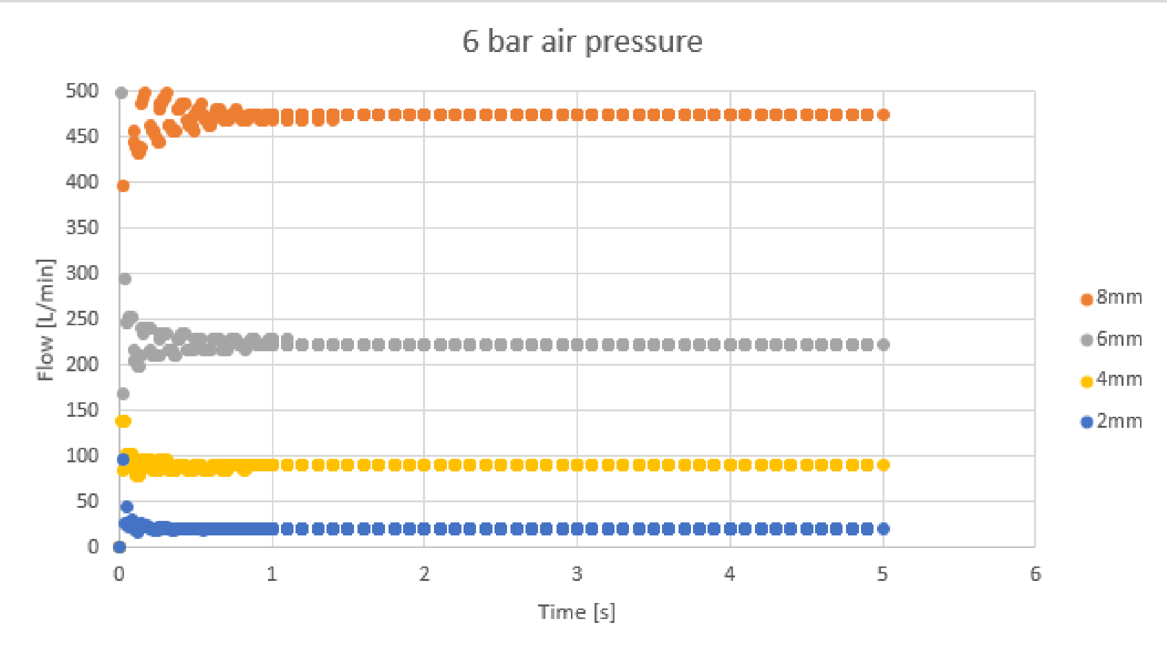
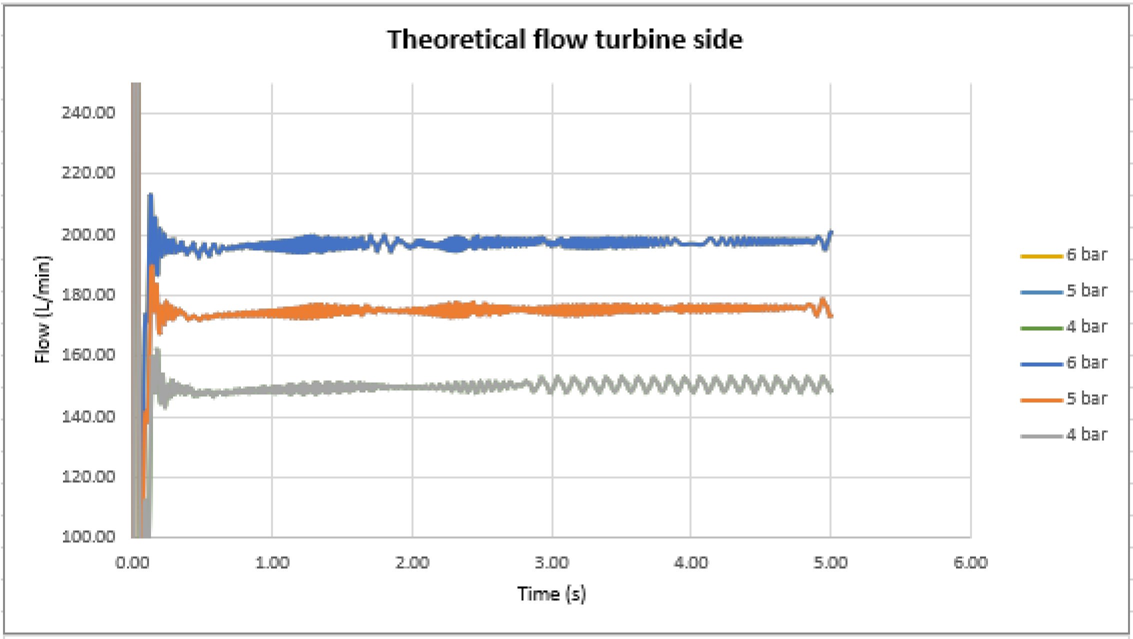
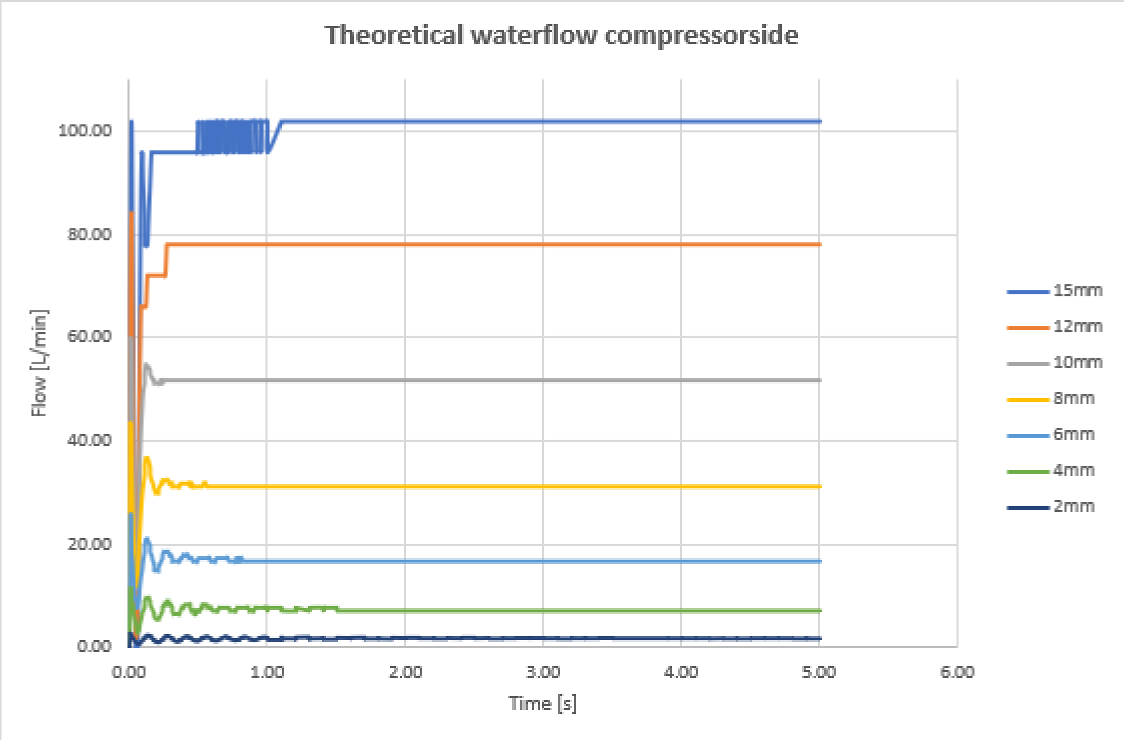
Appendix 1 Graph over purge airflow





Appendix 2 Graph over water flows





Appendix 3 Drawings ID: s for 2-stage wash unit

DRAWINGS

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