Pressurizing of high-pressure fuel system for single cylinder test cell

Trycksättning av högtrycksbränslesystem för encylindertestcell

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Abstract

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This master thesis covers the development of a high-pressure fuel system for compression ignited fuels such as diesel and diesel-like fuels that will be deployed into a single cylinder test cell at AVL MTC Södertälje, Sweden. The test cell is used by AVL to conduct research and testing of new fuels for their customers and this new fuel system will widen the span of fuels able to be tested by the equipment.
This thesis focuses on pumping and pressurizing of the fuel, ensuring that all ingoing materials are non-corrosive in this environment and compatible with the necessary fuels and lastly a safety analysis of the system with respect to operator and process safety. Other aspects of the project such as mass flow measurements and fuel conditioning is covered in a sister thesis *Mass flow rate measurement of compression ignition fuels in high-pressure stand-alone pump unit for single cylinder test cell* written by C. Aksoy [1].

The goal of this thesis project was to deliver a finished manufactured fuel system and if the time allowed for it, also validate its performance and finally installing and incorporating it into the single cylinder test cell. The development process started with the writing of a product specification outlining the requirements and request on the product in a specification of requirements matrix and relate these to product properties of the system using a quality function deployment (QFD) matrix. This document was then used as a base for further advancement in developing concepts to solve each product property and weighing these concepts against each other using Pugh's matrices. The chosen concepts were then further developed, a flow chart for the system was developed as well as fuel lines and other supporting components were analyzed and chosen.

In the end the high-pressure fuel pump from Scania's XPI fuel system were chosen as well as a pressure transducer in the HP1000 series from ESI. Within the time frame of this thesis, the project did not end up getting finished to the degree planned, but due to time constraints were halted before starting manufacturing of the system. Some minor component choices remained as well as documentation such as drawings and finalizing the physical layout of the system remained. All information regarding the remaining work needed to finalize the project and deploying the system in the test cell were outlined and with more time, the fuel system should fulfill its purpose of allowing testing and research of compression ignited fuel to be possible in the test cell.

Sammanfattning

Kontentan för denna mastersavhandling är utvecklingsprocessen för ett högtrycksbränslesystem för kompressionsbränslen såsom diesel och diesellika bränslen som kommer att installeras i en encylindertestcell hos AVL MTC Södertälje, Sverige. Testcellen används av AVL för forskning och testning av nya bränslen åt deras kunder och detta nya bränslesystem kommer att utöka typerna av bränslen som kan testas med utrustningen till att inkludera kompressionsantända bränslen.

Denna avhandling fokuserar på utvecklingen av tillförseln och trycksättnigen av bränslet, säkerställnigen av att ingående material är icke-korrosiva i den avsedda miljön och kompatibla med alla nödvändiga bränsletyper och slutligen en säkerhetsanalys av systemet med avseende på operatörs- och processäkerhet. Andra aspekter såsom massflödesmätning och bränslekonditionering presenteras i systeravhandlingen *Flödesmätning och konditionering av högtryckantända bränslen för encylindertestcell* skriven av C. Aksoy [1].

Målet med denna avhandling var att leverera ett färdigtillverkad bränslesystem och om tiden tillät, även validera systemets prestanda och slutligen integrera och installera systemet i testcellen. Utvecklingsprocessen inleddes med att skriva en produktspecifikation som innehöll en sammanställning av kundens krav och önskemål för produkten och relaterade dessa till produktegenskaper med hjälp av en *quality function deployment* (QFD) matris. Detta dokument användes vidare som en bas för fortsatt utveckling av produkten i konceptgenereringsprocessen och för att väga de olika koncepten mot varandra med hjälp av Pugh's matriser. De valda koncepten blev sedan analyserade ytterligare, ett flödesschema för de ingående komponenterna framtaget och övriga sekundära komponenter analyserade och valda.

Till slut valdes högtrycksbränslepumpen från Scanias XPI system och en tryckgivare från HP1000-serien från ESI. Inom tidsramen för avhandlingen färdigställdes aldrig projektet till den grad som hade planerats, men blev istället avbrutet innan tillverkningen av systemet han påbörjas på grund av tidsbegränsningar. Vissa sekundära komponentval, dokumentation såsom ritningar och färdigställning av den fysiska layouten av systemet kvarstod vid avhandlingens slut. All information angående allt nödvändigt fortsatt arbete för att färdigställa projektet och integrera systemet i encylindertestcellen dokumenterades och med mer tid borde bränslesystemet kunna uppfylla sitt syfte att möjliggöra testning och forskning av kompressionsbränslen i testcellen.

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1 INTRODUCTION

In this thesis, one of two perspectives of the product development of a high-pressure fuel system for a single cylinder test cell is presented. The other perspective can be read in the thesis by C. Aksoy [1]. Where appropriate the thesis is divided into the sub-sections product specification, concept generation, concept selection and detail engineering for clear separation and easy reading. Used abbreviations are explained in appendix A.

1.1 Background

Because of the problems associated with fossil fuels, there has been a rise in interest and effort regarding the research and development of alternative energy sources to power the transports that we, as a society, rely on. When it comes to fuels for combustion engines, different variants and combinations of fuels such as ethanol, ED95, biogas, biodiesel and hydrogenated vegetable oil (HVO) are being developed and refined to compliment and eventually replace fossil fuels all together.

Various fuels sets different requirements on the engine which they will be used in and therefore require the engine to be set up specifically for the type of fuel intended to be used. Modern combustion engines can be divided into two different types, spark ignited (SI) and compression ignited (CI) engines. SI engines works on a constant volume heat addition cycle, known as the Otto cycle. As the name ”spark ignited” implies, this type of combustion engine depends on a spark to ignite the fuel and is used for highly volatile fuels with a high self ignition temperature, such as petrol. CI engines work on a constant pressure heat addition cycle, known as the diesel cycle. This type of combustion engine uses the high temperature of highly compressed air to ignite the fuel and therefore doesn’t require a spark plug. This type of engine is used for non volatile fuels with low self ignition temperatures, such as diesel. Because of this fundamental difference of the two main types of engines, one can’t use the same engine, associated components and operating conditions for all types of fuels. [2]

One general trend in the development of CI fuels seems to be to increase the injection pressures of the fuels to achieve higher efficiency and lower emissions.

1.2 Literature

In this section, some useful concepts for understanding this thesis are presented. For more information on each concept, refer to the references.

1.2.1 Common rail direct injection fuel system

A common rail direct injection (CRDi) system is a type of direct injection fuel system used for CI engines. An example schematic of a CRDi system can be seen in figure 1. The fuel is usually pumped from a fuel tank, where a heat exchanger is usually located and through filters that together conditions the fuel before reaching a high-pressure pump. The high-pressure pump delivers the fuel to a fuel rail shared by the engines injectors and maintains a precise pressure, determined by the engine control unit (ECU). The rail pressure is monitored by a pressure sensor and there are many strategies for maintaining the pressure in the fuel rail. One is to to supply the rail with an abundance of fuel and allow the excess to flow through a high-pressure regulator or pressure control valve back to the fuel tank. Another is to meter the fuel at the high-pressure pump and only provide the amount of fuel needed by the injectors [3]. The later approach improves the hydraulic efficiency and develops less heat than the other method described. From the rail, the fuel continues to the injector nozzles which are controlled by the ECU to supply the engines combustion chambers with a precise amount of fuel at specific timings. Because of how the injectors valves are designed, there is also a leak flow from each injector that is returned to the fuel tank. The entire process is controlled by the ECU with the input from a number of sensors (some mentioned above) and engine parameters such as accelerator pedal position and engine speed.

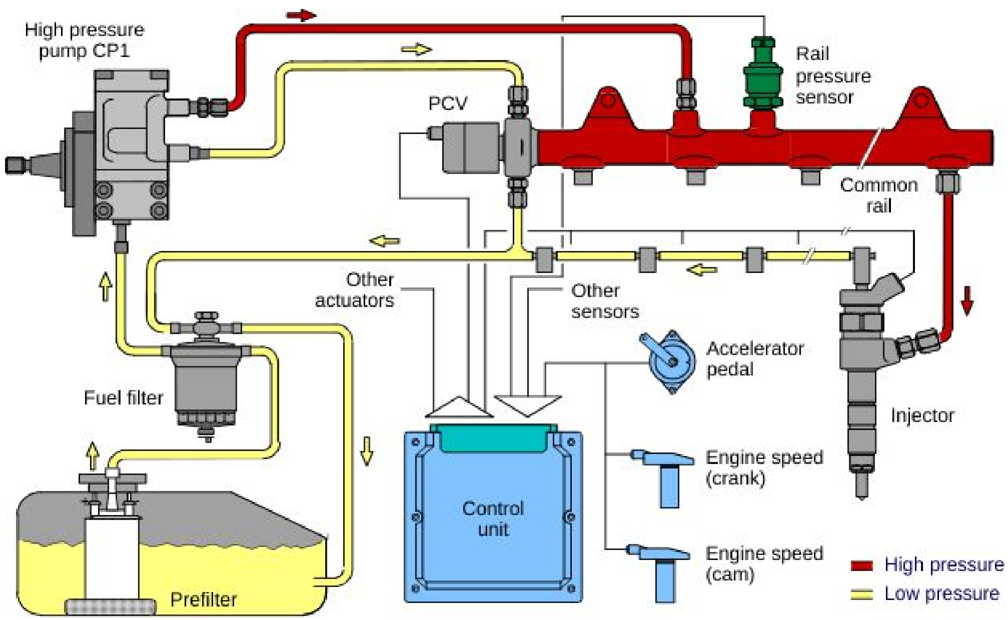


Figure 1: Schematic image of common rail diesel fuel injection system from Bosch [**?**].

1.2.2 Pump types

There are numerous types of pump types with various working principles. They can be categorized by the way in which they move and pressurize the fluid into rotodynamic pumps, more commonly known as centrifugal pumps, and Positive displacement pumps (PDP). Both categories can be further broken down in to subcategories based on their working principles. Centrifugal pumps, as the name implies, use centrifugal force produced by an impeller to move fluid. The fluid enters the fast rotating impeller through its axis and exits along the circumference, thus accelerating the fluid. This results in a controlled discharge and pressure. In general, centrifugal pumps are designed to operate at higher flow rates and lower pressures when compared to PDP. They also have some inherent limitations, for example when it comes to operation at a large pressure range. This is because their efficiency has a quite sharp maximum with varying pressure. The efficiency of PDP on the other hand are not as affected by pressure variations by comparison. Centrifugal pumps will also provide flow rates which vary with pressure as opposed to PDP which can deliver constant flow regardless of the pressure. [4, 5]

PDP operate by moving a fixed amount of fluid by enclosing it and mechanically moving it through a system of check valves. The action is cyclic and can be driven by a plethora of mechanisms such as pistons, plungers, diaphragms and gears. PDP are divided into two group, reciprocating PDP and rotary PDP. In figure 2 schematics of different PDP working designs can be seen. Reciprocating pumps work by moving a piston, plunger or diaphragm back and forth in a linear motion, sucking in fluid from the inlet and emptying it into the outlet as it oscillates. Rotating PDP works by trapping fluid between rotating cogs or gears and the pump housing, creating a suction at the inlet and transferring the fluid to the outlet. By adjusting the stroke speed and length, reciprocating can achieve a repeatable and predictable action, which is useful when accurate metering of the pumped fluid is desired. Because of how PDP operates, using seals and valves to move fluids, they are generally able to achieve greater operating pressures than centrifugal pumps. Of the different PDP types, plunger reciprocating pumps can achieve the highest working pressure. This is because reciprocating pumps have less leakage than their rotary counterpart and the fact that plunger pumps, as opposed to piston pumps, use a static seal instead of a seal moving with the reciprocating piston (refer to figure 2), which is an easier way to create an effective high-pressure seal. A drawback of PDP is that they generate a pulsing flow, especially reciprocating pumps because of their oscillating working principal. [6]

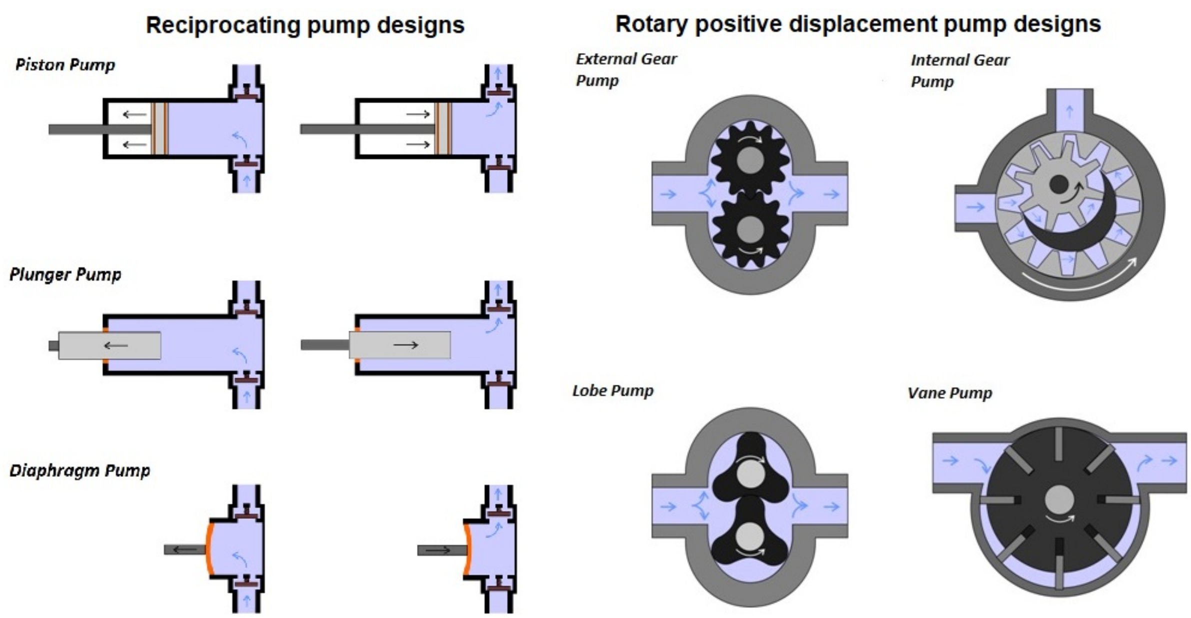


Figure 2: Positive displacement pump designs. Modified by author [6].

1.2.3 Fuel interaction with metals and sealing materials

If two different metals are connected by an electrically conducting path, there is an electrolyte present and the metals have a galvanic incompatibility, they will form a composition cell. This will cause the metal acting as the cells anode to corrode. This type of corrosion is commonly referred to as dissimilar metal corrosion or galvanic corrosion [7]. However, not all combinations of metals form a electrolytic cell that will result in corrosion. To do this, the metals much have a difference in nobility, also referred to as galvanic incompatibility, to create the necessary voltage for the chemical reaction to occur. To determine whether a specific combination of metals are compatible with each other, meaning they will not corrode when a composition cell is formed, a galvanic compatibility chart may be used (see figure 3). This chart however, does not always tell the full story, since the phenomenon depends on many aspects such as on the type of electrolyte used and its concentration on polarization and alloying elements in the metals as well [7]. The chart will however give a good indication as to whether the metal combination will be suitable to use in an otherwise corrosive environment as described.

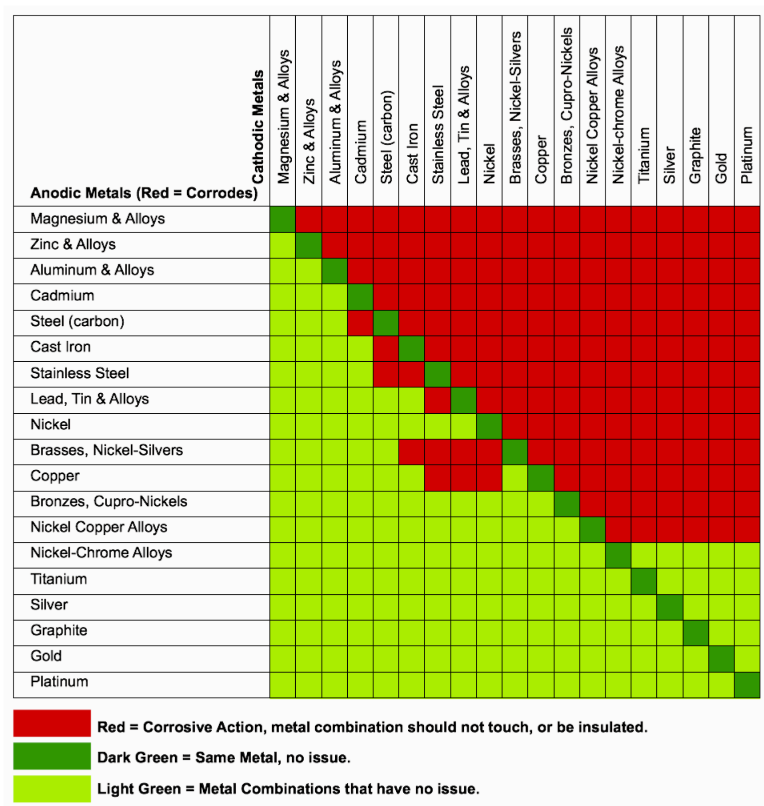


Figure 3: Galvanic compatibility chart. [8]

When choosing a polymeric sealing material for a combustion fuel application one must take into consideration that polymers can suffer damage and/or degradation when exposed to certain types of fuel compositions [9]. For example, when some polymers are exposed to ethanol-blended fuels they may react with oxygenated hydrocarbons which can cause swelling, alter tensile strength and break elongation, cause weakening, cracking, leakage and brittle behaviour [10]. New sealing materials are always being developed to better suit existing, as well as new operating conditions [9, 11]. For applications such as the one in this project, where the type of fuel used will vary frequently it is also important to consider that a sealing material can react differently to exposure of a certain type of fuel, before and after exposure to a second type of fuel [11]. This happens because although nothing bad might happen to the seal when exposed to a first type of fuel, the seal might alter its chemical composition when exposed to a second fuel type. This change in chemical composition doesn't necessary influence the seal in such a way that the sealing performance of the material is directly altered, but rather can make it so that the sealing material reacts differently when exposed to the first fuel type again. Compared to how it reacted before exposure to the second fuel type, this might lead to a damaged seal in any of the aforementioned ways.

1.3 Problem description

This thesis was assigned by AVL, who is an international automotive consulting firm with their own independent research institutes where development, testing and simulation of power train systems are conducted. With their many years of experience AVL has become one of the leading companies within the automotive industry. One of their areas of research is on fuels in a single cylinder test cell. The equipment can test combustion parameters such as combustion speed, ignition quality, ignition delay, pre-ignition, as well as fuel emissions and efficiency. AVL uses their expertise to develop their own power trains, including SI, CI and electric power trains. They also sell their expertise as a consulting firm, where they help the automotive industry in the development of their power trains as well as assist governments in certification tests of vehicles and alike.

As of the start of this project, the equipment in the test cell in AVL's facility in Södertälje is only set up to test SI fuels and there are a need for the cell to be able to test CI fuels for upcoming research projects. The current SI fuel pump is powered by pneumatic pressure and a basic schematic of the current system can be seen in figure 4. The main thing that is needed to be able to run the equipment on CI fuels, is a new fuel system capable of delivering the fuel from the fuel tank to the engines injection nozzle under high-pressure and at a given temperature, the development of which is the topic of this thesis. The current SI system is designed to operate under steady state flow conditions and the new CI system is supposed to operate in the same way.

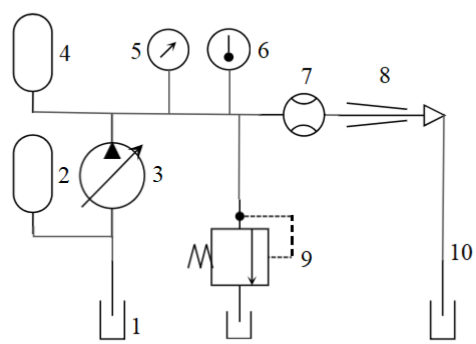


Figure 4: Basic flow chart of the SI fuel system currently used in the test cell in AVL's facility in Södertälje. 1: Fuel tank, 2: Low pressure accumulator, 3: high-pressure fuel pump, 4: high-pressure accumulator, 5: Pressure sensor, 6: Temperature sensor, 7: Mass flow rate sensor, 8: Engine injector nozzle, 9: Pressure relief valve, 10: Injector low pressure return line, leading to a fuel tank.

1.4 Goals & demarcations

This master thesis part of a larger project, which has been divided into two theses. This thesis and a sister thesis written by C. Aksoy [1], the separation and goals of which is described below. The mutual purpose of both these theses is to design and build a CI fuel system to be integrated into AVL's single cylinder test cell in Södertälje, Sweden. Which will later be used for research and testing of diesel-like fuels by AVL.

Goals

- **Fuel pressurizing** – The main functions and goal of the system to be designed and built as part of this thesis are pumping and pressurizing the fuel to be delivered to the engines injection nozzle accurately and at specified flow rates.
- **Material selection** – Evaluate the materials to be used in the system (metal components and seal materials) and determine their compatibility with each other and the fuels that will be used in the system.
- **Safety** – Conduct a failure mode and effects analysis (FMEA) of the system and its components. This will be done in collaboration with C. Aksoy [1] and safety representatives from AVL, where this thesis will focus on the analysis of the parts of the system that is related to the aforementioned goals.

Demarcations

- **Mass flow measurement** – The system will be able to measure the mass flow rate of the fuel to determine the engines fuel consumption. This aspect of the system will be handled by C. Aksoy [1].
- **Fuel conditioning** – Ensure that the fuel system has the ability to monitor and adjust the temperature of the system to parameters set by the operator. As well as bleed the system of any unwanted gases. This aspect of the system will be handled by C. Aksoy [1].
- **Fuel tank and injector nozzle** – These components represent the endpoints of the scope of the system that is to be designed and are not included in this system.

Optional goals

Below follows goals which will only be included in the thesis if they fit within the time frame of the project. These goals addresses the system as a whole, including the aspects discussed in the thesis by C. Aksoy [1] and will be collaborative goals, where this thesis focuses on the aspects that relate to its main goals.

- **Validation** – After the system is designed, some stand-alone validation tests will be conducted to evaluate the function of the system.
- **Installation** – The final goal of the project is to install and integrate the system into the test cell engine and evaluate the performance of the system in the test cell.

2 METHOD

At the start of the thesis the structure and time frame of the project was outlined in a project plan that can be seen in its entirety in appendix B. This was done together with C. Aksoy [1], the client company and the thesis supervisor to get input from and ensure conformity between all involved parties. The project plan outlined, among other things, the organization, project model, time plan in the form of a Gantt chart and risk evaluation of the project. The risk evaluation of the project was done in the form of an FMEA which can be seen in table 1 in appendix B.

2.1 Product specification

Together with C. Aksoy [1] and the representatives from AVL a product specification document was written with methods inspired by R. Andersson [12]. In which the requirements and request regarding the final system were outlined and used to break down and facilitate the systems functions and properties to simplify further work. This document can be read in its entirety in appendix C.

The first step in defining the product was to create a table containing the requirements and request that the client had on the product. The importance of all requests was weighted as low, medium or high priority and every criteria was categorized as either a function or a limitation, depending on its nature and how it impacted the product. The goal of this process was to define the product as generally as possible as not to limit or influence the concept generation process. This table was then used to create a Quality function deployment (QFD) matrix, where the criteria of the specification of requirements were related to product properties. An example of a QFD matrix can be seen in figure 5.

In field I of the QFD matrix, see figure 5 all the criteria from the specification of requirements were listed and assigned an importance value. The requests were numbered 1 for low, 2 for medium and 3 for high, while requirements were assigned the value 4. In field II the product specifications were listed. These were brain-stormed to relate the clients criteria to technical properties of the product that was to be developed. Care was taken to keep the criteria somewhat global and general as to not lead the concept generation into any particular solution in this stage of the process. Field III is called the correlation matrix and was used to identify and quantify the relationship between the product properties and the clients criteria. This was done by discussing the correlation of the properties and criteria column by column and assign values to each cell of 1-3, depending on how strong the correlation was. Cells indicating no correlation was left blank. Following this, the matrix was examined for empty rows and columns. This was done to ensure that all criteria was related to a property of the product and that no property was obsolete. The last step of the creation of the QFD matrix was to fill in field IV. Here, the row ”Expected difficulty” indicated how hard the development of each product property was expected to be. This was marked with a value between 1-3. 1 indicating an easy development and 3 a difficult development. The row ”Weighted importance” was used to get a sense of what properties will require the most attention in the development process. This was done by multiplying the importance value of each criteria with its correlation valuem, column by column and adding them together according to equation 1. The higher the value, the more demanding the property was expected to be.

$$\text{Weighted Importance} = \sum \text{Importance} \times \text{Correlation} \quad (1)$$

The last row, "Weighted Importance w.r.t. Difficulty" took the weight importance of each property and related them to the expected difficulty to get another perspective of the needed attention for each property, where difficulty was taken into consideration. This was calculated according to equation 2.

$$\text{Weighted Importance w.r.t. Difficulty} = \sum \text{Weighted Importance} \times \text{Expected Difficulty} \quad (2)$$

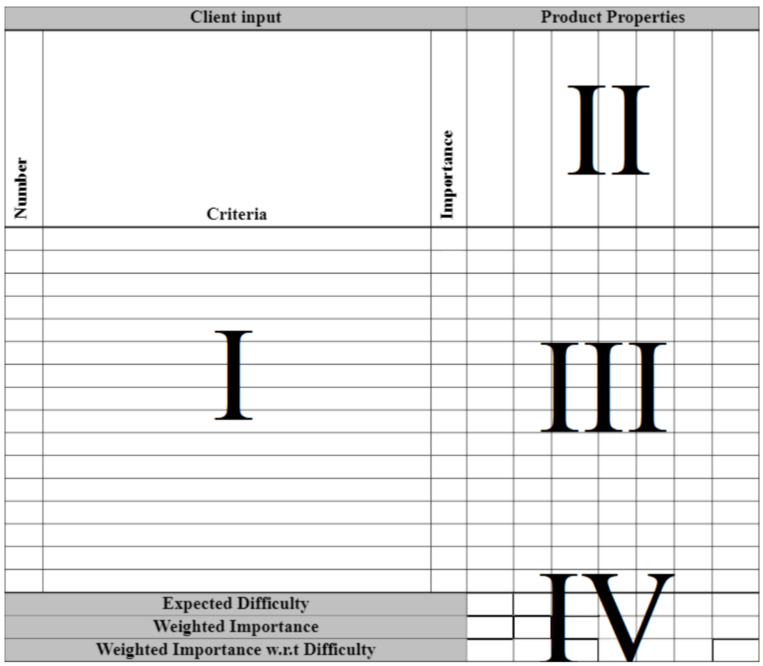


Figure 5: Quality function deployment matrix relating the requirements and requests of the client to the planned product properties.

2.2 Concept generation

To be able to generate plausible solutions for each aspect of the system that could function with each other with minimal obstacles, a basic flow chart containing the identified essential components for the systems function were created. A priority list was also created, before the actual concept generation ensued. The priority was based on what components and aspects of the system would be reliant on other system functions. Thus identifying the most important components for the main systems ability perform its task and what components it relied on to do so. Doing this helped dictate what parameters and attributes the less important components would need to perform and adhere to in order to support the more vital components and making the system as a whole function as intended. The QFD matrix described in section 2.1 was used as a base for this prioritizing.

Following this ranking, concepts for each major sub-system were generated by brain storming and analyzing the available selection of components on the market that could possibly fulfill the basic requirements outlined by the client, either off-the-shelf or after some modification. Solutions that plainly fell short on too many points were discarded at this stage and were not carried forward to the main concept selection phase. Work on the lesser sub-systems were left until the detail engineering phase.

2.3 Concept selection

The generated concepts were ranked and compared with the use of a variation of a method called Pugh analysis [13], where the concepts were lined up i a matrix together with the criteria that the concepts were intended to satisfy. This was done in two steps. First a matrix where the concepts were weighted against the clients requirements were created. The concepts were given a ”+” if they met the requirement and a ”-” if they didn’t. The values were then summed up for each concept to get a score showing how well the concepts met the requirements of the end product. Secondly a similar matrix, weighing the concepts against the clients requests were created. Here the concepts were given scores from zero to three depending on their potential to meet the requests. A column with the importance score of the requests from the QFD matrix was also included in the table and used as input in the summation of the total score of the concepts in the same way as in equation 1 for the QFD. Both matrices were accompanied by a written explanation of why the concepts were awarded their individual scores.

Based on the scores in these two matrices, together with an examination of how the shortcomings of each concepts could be countered and/or ignored and still deliver a satisfactory final result, were used to make a final decision on what concept was best suited for this project. This decision was then presented to the client to ensure their approval before continuing with the detail engineering of the chosen concept.

2.4 Detail engineering

After the selection of the most crucial components, a more complete flow chart for the fuel system was created based on the one created in the concept generation phase (figure 6). This was done by reviewing what requirements each of the major components put on the system. These requirements determined the layout of the flow chart as well as what extra components were needed for the system to operate as intended. The extra components that were needed were in turn analyzed and their individual requirements identified before a concept generation and selection process similar too, but not as in depth as the ones described in section 2.2 and 2.3 were performed for each component. This process was then iterated until all components needed for the complete system to operate as intended was identified and chosen.

At this point, a concept sketch for a physical layout of the system was created using 3D computer aided design (CAD) software. This sketch was then analyzed together with the clients internal safety department to make sure that the system would meet the company’s safety policies. The risk analysis was done in the form of a FMEA matrix outlining the observed risks with the system, an explanation of what each problem could result in and a suggested solution to take each problem into account in further development, manufacturing and later operation of the equipment. The possibility of the risks to occur were evaluated and each risk given a value between 1 and 4 (1 representing a low possibility and 4 a very high possibility). The gravity of the risk were evaluated in a similar way and marked with a value between 1 and 4 (1 representing a low gravity and 4 a very high gravity). These two values were then multiplied into a risk value, to get an idea of the severity of each identified risk.

3 RESULT

In this section all the results from the initial product specification to the final concept are presented.

3.1 Product Specification

For convenience of the client, from whose perspective this thesis and the one written by C. Aksoy [1] were a single project that would deliver one combined result, the product specification, which can be read in its entirety in appendix C, was a collaborative effort between both theses. This means that the result presented in this section include portions not directly related to this thesis, all of which are clearly specified.

The specification and requirements and requests are summarized in table 1 and are elaborated on in appendix C. Criteria 5-6 concerning fuel consumption were, for the purposes of this thesis, interpreted as ”The pressurizing system must be developed in such a way as to enable fast and accurate measuring of the fuel mass flow”. Criteria 12 was, for the purposes of this thesis, interpreted as ”The pressurizing system must be designed in such a way as to allow for components for conditioning of the fuel to be installed”. Criteria 1-4 concerned the project, rather than the product and were therefore not taken directly into account in the product development process in the same way as the other criteria.

The QFD matrix can be seen in table 2 and for the purposes of this thesis, the product properties B and C were not of interest. All product properties are explained in appendix C. Based on the weighed importance (with and without respect to difficulty) the product properties that were expected to need the most attention in this thesis were: A. Pressure control, D. Connections and G. Material selection.

3.2 Concept generation

The component deemed of highest priority for the function of the system was the high-pressure fuel pump followed by the pressure sensor needed to control the pump. Other components were left to be worked on in the detail engineering phase of the project, since they would depend heavily on these two aforementioned components (mainly the pump). A basic flow chart, containing the essential components needed for the fuel system to function was created and can be seen in figure 6 (note that the fuel tank and fuel injector were already in place in the test cell and therefore not included in the system designed in this thesis). Note that components, such as flow measuring

Table 1: Specification of requirements and requests for the entire product, outlined by the client. Elaboration on the table can be seen in appendix C

Criteria number	Category	Criteria	Requirement /Request	Function/ Limitation
1	Documentation	Documentation for implemented components	Requirement	-
2	Documentation	2D drawings of manufactured parts	Request, mid	-
3	Documentation	Assembly drawings	Requirement	-
4	Documentation & Safety	Risk assessment	Requirement	-
5	Fuel consumption	Evaluation of fuel flow measurements	Requirement	Function
6	Fuel consumption	Implementation of flow measurement components	Request, mid	Function
7	Fuel consumption	Take return flow into consideration	Requirement	Limitation
8	Fuel supply	Adjustable pressure range	Requirement	Function
9	Fuel supply	Run on a range of liquid fuels	Requirement	Function
10	Fuel supply	Mass flow	Requirement	Function
11	Fuel supply	Constant fuel pressure	Requirement	Limitation
12	Fuel supply	Fuel conditioning	Requirement	Function
13	Operation	Stand-alone	Request, high	Function
14	Operation	Flexible	Request, high	Limitation
15	Operation	Compatible with other equipment	Requirement	Limitation
16	Operation	OEM Components	Request, low	Limitation
17	Operation	No mixing of fuels	Requirement	Limitation
18	Operation	Possibility to run system with an auxiliary fuel tank	Request, high	Function
19	Operation	Fuel drainage & pressure relief	Requirement	Function
20	Safety	Meet safety regulations	Requirement	Limitation

and conditioning components, that indeed were essential for the function of the system are not included in the flow chart. These components have been left out, since they first of all are not included in the scope of this thesis, but are the subject of the thesis written by C. Aksoy [1], and secondly because their position in the flow chart would be determined based on the position of the components covered in this thesis and not the other way around.

Since the remaining components needed in the system would depend heavily on these two main components, they were left to be analyzed in the detail engineering phase in section 3.4.

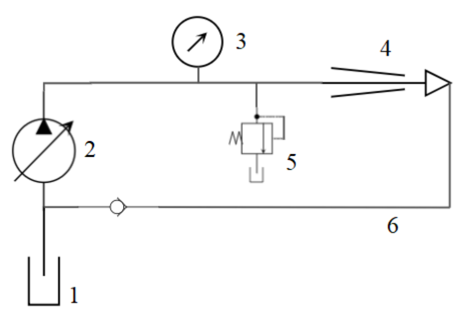


Figure 6: Basic flow chart of the fuel system. 1: Fuel tank, 2: high-pressure pump, 3: Pressure sensor, 4: Injection nozzle, 5: Pressure relief valve, 6: Injector low pressure return line.

Table 2: Quality function deployment matrix relating the requirements and requests of the client from table 1 to the planned product properties. More information about the table can be seen in appendix C

Client input			**Product Properties**						
Number	**Criteria**	**Importance**	**A. Pressure control**	**B. Temperature control**	**C. Flow measurement**	**D. Connections**	**E. Layout**	**F. Size**	**G. Material selection**
5	Evaluation of fuel flow measurements	4	2		3				
6	Implementation of flow measurement components	2			3				
7	Take return flow into consideration	4	1		3		2		
8	Adjustable pressure range	4	3		2				2
9	Run on a range of liquid fuels	4	2	1	1				3
10	Mass flow	4	3		1				
11	Constant fuel pressure	4	3		2				
12	Fuel conditioning	4		3					
13	Stand-alone	3				3			
14	Flexible	3					3	3	
15	Compatible with other equipment	4	3	3	3	3		1	1
16	OEM components	1	3	1					
17	No mixing of fuels	4				3	3		
18	Possibility to run system with an auxiliary fuel tank	3				3			
19	Fuel drainage & pressure relief	4	2			2	1		
20	Meet safety regulations	4	2	2		2	1	1	3
Expected Difficulty			2	1	3	1	1	2	3
Weighted Importance			87	37	66	58	37	17	36
Weighted Importance w.r.t Difficulty			174	37	198	58	37	34	108

3.2.1 High-pressure fuel pump

After scouring the limited market for this type of application with extreme pressures and low flow, three candidates were found that might be suitable for this application. Today's high-pressure fuel systems appears to top out at around 2500 bars and operate under higher flow rates, since most CI engines have more than one cylinder and therefore require more fuel than the single cylinder test cell engine that this fuel system is intended for. In other applications such as water cutting, pumps able to operate at high enough pressures were found to be fairly common. However, pumps with low enough flow rates appeared to be few or non-existent in this market. The concepts deemed potential candidates for this project are listed in table 3 and described in further detail below.

I. Pneumatic piston pump

Haskel DXHF-602 is a 2 hp pneumatic piston pump (see figure 7), which was of the same type as the one used in the current SI fuel system in the test cell, although rated for higher pressures. It had a stroke volume of 2.3 ml capable of delivering 0.28 l/min (16.8 l/h) at 3500 bars operating pressure

Table 3: Viable concepts for fuel supply and pressurizing to be carried forward to the concept selection phase

No.	Concept name	Brand	Model	Pump type	Power source
I.	Pneumatic piston	Haskel	dxhf-602	Piston pump	Pneumatic
II.	Hydraulic plunger	Haskel/Hydmos	Custom	Plunger pump	Hydraulics
III.	OEM fuel pump	Scania/Cummins	XPI	Piston pump	crankshaft/ Electric motor

and a driving pneumatic pressure of 8.5 bar, expending 2.5 Nm/min. Using two of these pumps in parallel gave a high enough maximum flow rate of 0.56 l/min (33.6 l/h) at 3500 bar. Since this pump was driven by pneumatic power, the stroke speed couldn't be accurately controlled, which meant that there would be large pressure pulsations in the high-pressure fuel lines when the pumps completed a stroke. To circumvent this problem, an accumulator acting as a pulse damper would be needed. In the current SI fuel system an accumulator was used for this purpose, which can be seen in figure 4. The accumulator would help to minimize the pressure spikes by expanding in volume when the pumps delivered more fuel to the high-pressure lines, thus increasing the volume of the system rather than the pressure to accommodate the extra fuel. This expanded volume would then gradually decrease as the fuel entered the combustion chamber through the fuel injector. By doing this, the pressure could be kept closer to constant than without the use of an accumulator. Usually, a membrane accumulator is chosen for this task, because of its low moving mass (referring to the membrane), meaning that it can respond to pulses quickly and thus dampen the pressure pulses effectively. However, there are seemingly no membrane accumulators capable of operating at the pressures needed for this system. Accumulators capable of operating at the pressures required were found to be mostly piston accumulators, which has a larger moving mass (the piston) and thus a slower response time, which is not enough to effectively dampen pressure pulses. A piston accumulator is therefore generally not used for this application. Furthermore, the use of an accumulator would negatively impact the ability of accurately measure mass flow, since some of the fuel would go to charging the accumulator instead of continuing directly through the system to the injector.

A pressure limiting valve could also be used as a mean to dampen pressure pulses. This option was discarded on the basis that it was an inefficient method, resulting in extra heat in the fuel that would need extra cooling capacity, as described in section 1.2.1.

The wetted materials of the pump are *Stellite 15-5PH SS* and the seals are made of *ultra-high-molecular-weight polyethylene* (UHMWPE), which according to the manufacturer should be compatible with all CI fuels.

Figure 7: Haskel DXHF-602 pneumatic pump [14]. Modified by author.

II. Hydraulic plunger

The second concept was to convert a pneumatic pressure amplifier (PA) pump from Haskel to be driven by hydraulics. The PA is essentially a plunger pump with a stroke length of 75 mm and a stroke volume of 84 ml. By using this pump, the stroke speed could be accurately controlled, thus keeping the pressure in the system very accurate without the use of an accumulator. A picture of a fuel system using a similar system to the one described here can be seen in figure 8 However, if a simple single acting cylinder was used, the pressure and flow fluctuations during the backstroke (when the pump chamber is refilled with fluid) would be significant and occur under an unacceptably long time. This could be solved in a few ways. One being the use of a double-acting PA, where one pump chamber is refilled while the other discharges and vise versa. This would shorten the time of the pressure and flow fluctuations considerably, but not eliminate them. Since the pump would still have to stop to change direction at the end of each stroke, thus halting fuel delivery for a split second. The manufacturer of the custom pump (Hydmos Industriteknik AB) estimated the pressure fluctuations for this configuration to be in the neighborhood of around ± 100 bar at 3500 bar operating pressure ($\pm \sim 3\%$).

Figure 8: Fuel system using one single acting PA pump, complete with hydraulics and control system, manufactured by Hydmos to another costumer. Picture courtesy of Hydmos Industriteknik AB.

Another solution to this problem, and the one proposed for this concept, was to use two single acting PA from Haskel, and customized by Hydmos Industriteknik AB, to work in unison as shown in figure 9. From a to b, pump 1 would operate at full speed and supply the entire flow needed at the pressure requested. From b to c, pump 2 would be started and both pumps would operate at half speed, thus delivering half the needed flow each at the pressure requested. At c pump 1 would have completed its stroke and would complete its backstroke and recharge between c and d, while pump 2 would operate at full speed, delivering the entire needed flow at the pressure requested. At time d, the pumps would be in the same state as in time b (but their roles would be reversed) and the operation between b and d would repeat. In this configuration the manufacturer estimated that the pressure fluctuations could be kept within ± 10 bar at 3500 bar operating pressure ($\pm \sim 0.3\%$). The stroke position would be monitored by position sensors mounted onto the pumps.

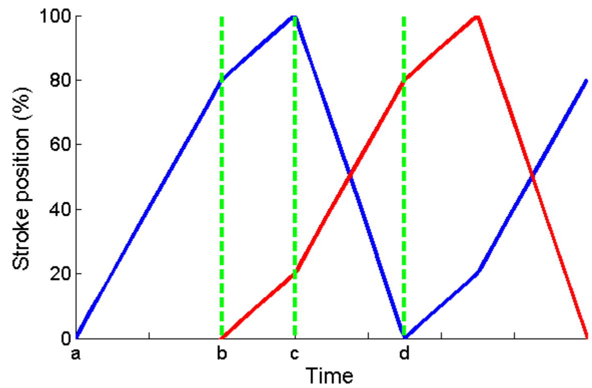


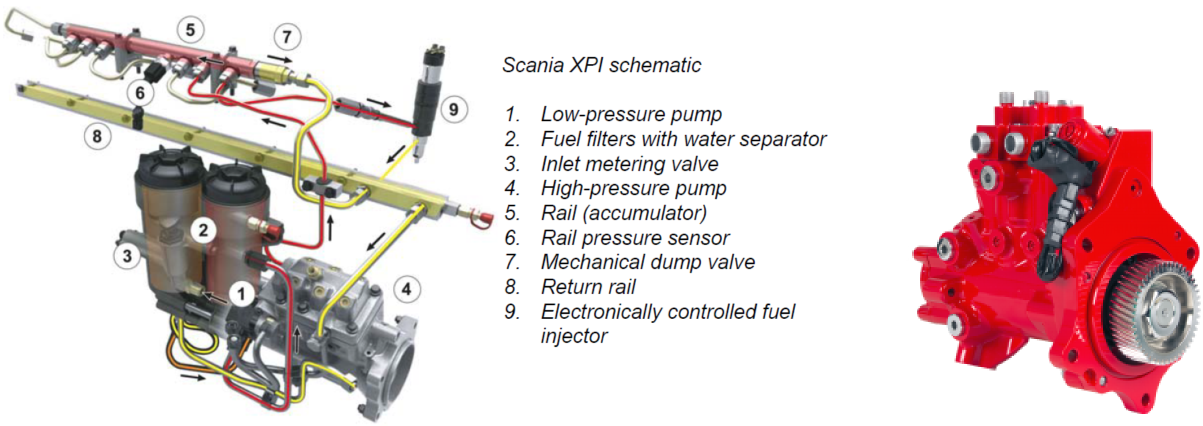
Figure 9: Plunger stroke positions to achieve steady flow and pressure with hydraulic plunger pumps. The blue curve represents plunger 1 and the red represents pump 2.

This concept needed an associated hydraulic system to power it. This was not, as opposed to pneumatic or electric power, already available in the test cell and thus would need to be designed and built together with the rest of the fuel system. Although not impossible, this would require more available space in the facility. Something that was a limited asset, thus making the addition of a hydraulic system a minor inconvenience. Because of the large stroke volume of this concept, the flow in the inlet of the pump would fluctuate significantly. At a flow of 30 l/h the two pumps would complete the cycle b-d in figure 9 a total of around 6 times per minute. This fact would make mass flow measurements in the low pressure side of the system extremely inconvenient or impossible without unreasonably long measuring times to achieve sufficient mean mass flow rate measurements. Because of the high accuracy of the intended position sensors of 0.02-0.05% (quoted by the Hydmos Industriteknik AB) the possibility of using the pumps themselves as the means of measuring mass flow rate (in conjunction with a pressure sensor) would also be a possibility. This would in that case be done by calculating the mass flow based on the output of the position sensors for volume output (stroke volume was a known constant) and a pressure and temperature sensor to determine the fuels density.
The wetted materials of the pump are the same as for concept I, which according to the manufacturer should be compatible with all CI fuels.

III. OEM fuel pump

The final viable concept composed in this thesis was to use an original equipment manufacturer (OEM) fuel pump. A dual piston pump from Scania's XPI common-rail fuel injection system, a schematic of their common rail system and the pump can be seen in figure 10. The pump has been specially developed for Scania's trucks together with Cummins. The pump is designed to operate at a maximum pressure of 2400 bar [15], but is capable at operating at 3000 bar and with some modifications also at 3500 bar (see section 3.4). All data of the pump is not public, therefore the following specifications are from another of Cummins XPI pumps, OLP 3, of similar size [16]. As standard, the pump has two pistons that are capable of supplying up to around 5 l/h. By disabling one of the pistons the flow should be reduced to numbers that better suited the intended application. The pump is designed to be mounted to the engine and driven by the crankshaft at 1:1 speed com-

pared to the crankshaft, but it could also be powered externally by an electric engine. The inlet of the pump has a metering valve to regulate the flow and pressure supplied to the high-pressure side of the system [15]. According to the manufacturer, the pressure should be able to be kept within $\pm$ 40 bar of a requested operating pressure of 3500 bar ($\pm \sim 1\%$).
The wetted materials of the pump consists of an *undisclosed stainless steel alloy* and an *undisclosed sealing material* intended for use with diesel-like fuels.



(a) **(b)**

Figure 10: (a) Schematic of Scania's XPI system [15]. (b) Cummins XPI fuel pump [16].

3.2.2 Pressure monitoring

As an input parameter to be able to control the high-pressure pump a device to monitor the pressure in the high-pressure lines of the system was needed. Numerous ways of measuring pressure exists. The method deemed best suited for this application was a pressure transducer, which for high-pressure applications for example can use Silicon-on-Sapphire technology to translate pressure into an electrical signal [17]. In table 4 the viable options found for this application are listed and was carried forward to the concept selection stage and in figure 11 a picture of the candidates can be seen.

Table 4: Viable concepts for pressure monitoring in on the high-pressure side of the system to be carried forward to the concept selection phase

No	Brand	Model	Pressure range (bar)	Accuracy	Wetted materials	Signal type(s)
a.	Applied Measurements LTD	DMP 304	0-4000	$\pm$ 0.25%	SS 1.4548 17-4 PH	4-20 mA/0-10 V
b.	Omega	PX91N[*]-60KS5T	0-4137	$\pm$ 0.35%	SS 17-4 PH	0-5 V
c.	ESI	GS4200-USB	0-4000	$\pm$ 0.15%	Unspecified titanium alloy	USB
d.	ESI	HP1103EX-4000DE	0-4000	$\pm$ 0.1%	Unspecified titanium alloy	4-20 mA

Concept a. from Applied Measurements LTD was a pressure transducer which used a compensated strain gauge bonded onto a hardened stainless steel diaphragm to measure pressure. It came with several options for rated nominal pressures, physical and data connection types and had a response time of less than 2.5 ms. Concept b. from Omega was a pressure transducer which used an undisclosed measuring technique in a stainless steel housing to measure pressure. It came with several options for rated nominal pressures, physical and data connection types and the response time was undisclosed. Concept c. and d. from ESI were pressure transducers which used silicon-on-sapphire technology to measure pressures. They were both made of an undisclosed titanium alloy with several physical connection types. Concept c. used USB to transfer measurement data, while concept d. transmitted data via a 4-20 mA signal. The response time of concept c. was undisclosed, while concept d. had a response time of 1 ms.

Figure 11: Pressure transducer from ESI from the HP1000 series [18].

3.3 Concept selection

In this section the results from the concept selection process is presented for the high-pressure pump, as well as the pressure monitoring component.

3.3.1 High-pressure fuel pump

In table 5 the concepts have been weighed against the requirements on the product. Motivations for whether or not the concepts was found to meet the requirements are provided below.

- **Criteria 5** – Concept I did not meet the requirement on the basis that it would need pulse dampeners to operate within specifications. Which in turn would have made mass flow measurements slower and less accurate. Concept II did not meet the requirements on the basis that the flow on the inlet side of the pumps would be extremely irregular, making mass flow measurements on the low pressure side of the system extremely slow and less accurate. Measuring flow on the high-pressure side would still be possible, but more complex. The pressure

Table 5: Pugh's matrix, showing if and how well the concepts meet the requirements outlined in table 1

Criteria	**Concepts**		
	I. Pneumatic piston	**II. Hydraulic plunger**	**III. OEM fuel pump**
5	-	-	+
7	+	+	+
8	+	+	+
9	+	+	+
10	+	+	+
11	-	+	+
12	+	+	+
15	+	-	+
17	+	+	+
19	+	+	+
20	+	+	+
+	9	9	11
-	2	2	0
Total	**+7**	**+7**	**+11**

and flow fluctuations in concept III were considered low enough as to enable sufficiently fast and accurate mass flow measurements.

- **Criteria 7** – Neither concept would hinder the return flow from the injector to be integrated into the fuel system.
- **Criteria 8** – All concepts were deemed able to operate within the requested pressure span.
- **Criteria 9** – Neither concept had any restraints making them unable to work with the different fuel types intended to be used.
- **Criteria 10** – All concepts, with suggested modifications, would be able to supply flow rates spanning the requested range.
- **Criteria 11** – None of the concepts were found able to meet the target value for maximum pressure fluctuations. Concept I was found to not be able to operate with small enough pressure fluctuations. Concept II was found to have the potential for lowest pressure fluctuations of the three, with values well within acceptable levels. Concept III's pressure fluctuations was found to be small enough on the basis that they were comparable to the fluctuations found in Scania's XPI system, thus making it acceptable and competitive.
- **Criteria 12** – None of the concepts were found to inhibit accurate fuel conditioning.
- **Criteria 15** – Concept II did not meet this requirement on the basis that its power source was not already available in the test cell. The other concepts met the requirement.
- **Criteria 17** – Neither concept were found to be unable to be designed as a separate system from the existing SI fuel system.
- **Criteria 19** – Neither concept were found to be unable to be designed with pressure relief and fuel drainage in mind.
- **Criteria 20** – All concepts were found to be able to meet all necessary safety requirements at this stage. (Discussed in more detail in the detail engineering phase in section 3.4.7).

In table 6 the concepts have been weighed against the requests on the product. Motivations for how well the concepts was found to meet the requests are provided below.

Table 6: Pugh's matrix, showing if and how well the concepts meet the requests outlined in table 1

Criteria	Importance	Concepts		
		I. Pneumatic piston	II. Hydraulic plunger	III. OEM fuel pump
6	2	-	-	-
13	3	3	3	3
14	3	2	2	3
16	1	0	0	3
18	3	3	3	3
Total		**24**	**24**	**30**

- **Criteria 6** – This criteria was not related to this aspect of the project and was therefore not taken into account.
- **Criteria 13** – All concepts were deemed able to be designed as a stand-alone system. Concept III also had the possibility to be mounted directly to the engine. Doing this would classify concept III as not stand-alone, but this did only offer extra flexibility in the design.
- **Criteria 14** – All concepts were found to satisfy this request to varying degrees. Concept I got a lower score because of its high-pressure fluctuations hindering flexible operation. The concept should however be very small and portable, thus the final score. Concept II were deducted score because of its increased size associated with the hydraulic system. In other aspects it would still be flexible in regards to maintenance, repairs and portability. Concept III were awarded the highest score, because it were deemed to satisfy the request without fault.
- **Criteria 16** – Only concept III were considered to meet this request, since it was the only concept that used the requested OEM components.
- **Criteria 18** – None of the concepts were deemed to hinder the use of an auxiliary fuel pump, thus all earned full score.

As is evident from reviewing tables 5 and 6, concept III was the option that showed the highest potential and thus was the concept and approved by the client for further development.

3.3.2 Pressure monitoring

The criteria that the pressure sensor would need to meet to be viable for this application were not all directly specified in table 1, therefore they are all clarified here for convenience.

I. The sensor needed to be able to measure pressures from 500 to 3500 bar, with an additional safety margin in both directions. Corresponds to criteria 8 of table 1.

II. The accuracy of the sensor should be as high as possible and should at the very least be accurate enough to measure the fluctuations caused by the high-pressure pump. Corresponds to criteria 11 of table 1.

III. The sensors output had to be of a type that the test cells systems could read. Those were: 0-5 V, 0-10 V, 4-20 mA and pulse width modulation (PWM). Corresponds to criteria 15 of table 1.

IV. The wetted materials of the sensor should be compatible with the rest of the system and all CI fuel types. Corresponds to criteria 9 of table 1.

V. The sensor should be able to operate within the necessary temperature range, i.e $\sim 20-70°C$.

Concept c. from ESI failed on the basis that it did not meet criteria III, while all other solutions offered compatible signal types. All sensors met criteria V with a wide enough margin as to not be considered an issue, had wetted materials deemed suitable and had operating pressure ranges spanning the required range. Of the four, concept d. from ESI became the choice best suited for this application because it offered the best accuracy of $\pm 0.1\%$ and as a not necessary, but welcome bonus, also the shorted response time of 1 ms, which offered the possibility of a greater resolution of pressure readings over an ignition cycle compared to the other options. For example, at an engine speed of 7000 rpm, ~ 17.1 pressure readings per ignition cycle (four stroke ignition cycle, i.e. 2 full rotations per cycle) was made possible with its response time of 1 ms. The only other candidate with a known response time (concept a.) in turn would only produce ~ 6.8 readings under the same conditions.

3.4 Detail engineering

In this section, the results from further development of the chosen concept from section 3.3 are presented.

3.4.1 Flow chart

In figure 12 the proposed flow chart for the fuel system can be seen. Not included are the components needed for fuel consumption measurements and fuel conditioning, which are covered in the thesis by C. Aksoy [1]. An explanation as to why the flow chart looks as it does follows below.

The high-pressure pump was observed to have three connections. An inlet that needed a feeding pressure of around 5-15 bar, a high-pressure outlet to be connected to the fuel rail and a low pressure return line for the overflow from the in-pump metering system. The use of an OEM fuel rail from Scania's XPI designed for several cylinder operation system was chosen firstly because of convenience of assembly, since its connecting components already were designed with it in mind, and secondly to have a convenient place to mount components such as the pressure transducer and pressure relief valve, where in the intended configuration on a Scania truck, the fuel injectors for the remaining cylinders were supposed to be connected. The fuel rail also had a pressure limiting valve and thus needed a return line connection to the low pressure side of the system. The low pressure return line from the fuel injector and high-pressure pump were observed to need a maximum pressure just under 1 bar to be able to operate correctly. Thus, a regulator or pressure limiting valve would be needed to be placed in fuel line 6 and 7 in figure 12 to ensure that even if the rest of the low pressure lines exceed this pressure value, the components could still function as intended even under maximum operating pressure (3500 bar) in the high-pressure fuel lines. This was necessary

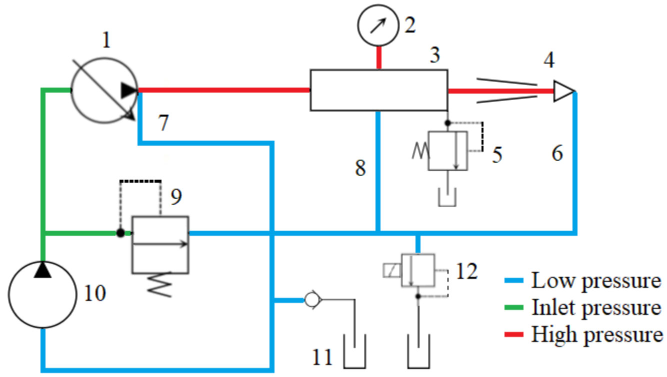


Figure 12: Flow chart for the CI fuel system. 1: high-pressure fuel pump, 2: Pressure sensor, 5: Fuel rail, 4: Engine injector nozzle, 5: Pressure relief valve, 6: Injector low pressure return line, 7: Pump metering low pressure return line, 8: Fuel rail low pressure return line, 9: Pressure limiting valve, 10: Low pressure fuel pump, 11: Main/Aux fuel tank, 12: Drainage valve.

since there was a possibility for the pressure in the low pressure fuel lines to exceed this value under maximum working pressure in the high-pressure fuel lines caused by the other return lines.

With the suggested flow chart and its ingoing components, the choice of placement for the mass flow measuring and conditioning components would not be limited to any single location within the system. The fluctuations in flow and pressure throughout the system, in the suggested configuration, should be low enough to achieve satisfactory measuring times regardless of the placement of the measuring equipment. No apparent obstacles for the placement of the conditioning components could be identified either.

3.4.2 Power source for the high-pressure pump

As can be seen in figure 10(b), the fuel pump is driven by connecting a power source to the gear visible in the figure. The pump is normally mounted to the side of the engine and the gear is directly connected to the crankshaft of the engine with a 1:1 rotation ratio compared to the crankshaft. This option was also available in AVL's test cell engine. A second option of powering the high-pressure fuel pump was to use an electric engine. Doing this would satisfy criteria 13 of table 1 better. However, since no major modifications would be needed to mount the pump to the engine and power it with the crankshaft, it was decided to design the system to enable both options, thus giving the system more flexibility (criteria 14 of table 1). This way the operator was given the choice of two ways of powering the engine depending on what type of tests would be conducted and what method was most beneficial for that operation.
The choice of electric motor for powering the high-pressure pump was left for future work due to lack of knowledge of the required power and torque output of the electric motor that was needed, as well as limited available time.

3.4.3 Fuel lines

To connect the components of the fuel system together a combination of flexible hoses and rigid tubing were chosen. The flexible tubing was necessary because of the vibrations from the engine during operation. Therefore, the connection between the engine (or the high-pressure pump mounted to the engine) and the other components could not be mounted rigidly for obvious reasons. For all other connections, rigid tubing with quick disconnection points at strategic locations for maintenance, general convenience and flexibility of disassembly was chosen. The use of rigid tubing for these applications was chosen because it would require less space due to smaller minimum bend radious and accompanied lower complexity of the system compared to if flexible hoses would have been used.
The options for fuel lines presented below have been chosen to withstand the pressures after the high-pressure pump in the system. The choices could be used for the entire system, but similar fuel line options rated for lower pressures could be used for the parts of the system where high-pressure ratings were not needed. In this thesis, the assumption that high-pressure rated fuel lines would be used for the entire system has been made.

The flexible tubing chosen for this system was the *high-pressure hose* from KMT shape technologies group (figure 13(a)) made from *316 stainless steel mesh* and an interior liner of *Acetal* (polyoxymethylene). Both of these materials should be compatible with the intended fuels for this system [19] and the hose is rated to a maximum pressure of 4000 bar. The hose's dimensions had an inner diameter of 4.5 mm and an outer diameter of 15.3 mm with a minimum bend radius of 250 mm. The rigid tubing chosen for this system was the high-pressure tubing *TU-HP4-60K* from Spir Star (figure 13(b)) made from *316 stainless steel* and rated for 4140 bar. As mentioned earlier, 316 stainless steel met the material compatibility requirements for this system. The tubing had an outer diameter of 6.35 mm and an inner diameter of 2.1 mm.

(a) **(b)**

Figure 13: (a) high-pressure hoses from KMT Shape technologies group [20]. (b) high-pressure tubing from Spir Star [21].

3.4.4 Remaining components

As mentioned in section 3.4.1, the high-pressure pump was observed to require the fuel to be pressurized at the inlet to be able to operate as intended. To do this a inlet pressure fuel pump would be needed. Because of the lower pressure rating needed for this component compared to the high-pressure pump, the available selection of pumps on the market was much larger. Also, because of the lower pressure in this part of the system and accompanied lower complexity, more solutions for keeping the pressure within the required range was available, thus expanding the available options of inlet pressure pump even further. Because of lack of time, the selection process of the inlet pressure pump was not as in-depth as for choosing the high-pressure pump, but a basic recommendation was made.
The recommended inlet pressure pump chosen was the 0.33 hp pneumatic pump *Haskel MS-21*. Which was rated for a maximum working pressure of 179 bar, had a maximum flow rate of 2.13 l/min (127.8 l/h) and was made of *316 stainless steel* and *UHMWPE* (same materials as Haskel DXHF-602 mentioned in section 3.2.1). This pump was chosen because it was powered by pneumatic power, which was already available in the test cell and therefore didn't require any extra equipment to be deployed. To counter the associated pressure pulses that comes with using this type of pump, which was discussed in section 3.2.1 a pressure limiting valve was added to the system (9 in figure 12). The purpose of this valve was to allow excess fuel to circulate back to the low pressure fuel lines and thus made the use of an accumulator to counter the pressure pulses redundant.
To control the inlet pressure pump, the use of a pressure transducer was not deemed necessary between the inlet pressure pump and the high-pressure pump. The pump could be set up to operate at a constant speed and the pressure to be controlled by the pressure limiting valve (9 in figure 12). If a pressure transducer was for some reason deemed necessary at a later date to improve the systems performance, the selection of components for this purpose on the market was found to be wide and therefore not analyzed further in this thesis because of lack of time.

Other components such as valves, fittings and quick disconnects necessary for this system was not analyzed and chosen in this thesis due to lack of time. The choice of these components was therefore left for future work.

3.4.5 Material selection

The metallic materials of the above chosen components are *316 stainless steel* and an *undisclosed titanium alloy*. According to the galvanic compatibility chart in figure 3, these two metals are not compatible with each other and might cause galvanic corrosion to occur. However, as mentioned in section 1.2.3, the galvanic compatibility chart does only provide an indication as to the corrosive potential of two metals. Several sources have found the combination of titanium with stainless steel to be a compatible pair in a galvanic corrosion situation [22, 23, 24] and galvanic corrosion in the system should therefore be a non-issue.

To ensure that the sealing materials of the system would be compatible with all the necessary fuel, the manufacturers documentation for compatible fluids were used. Detailed analysis where frequent fuel type changes were taken into account were not conducted. This was neglected for two reasons, firstly because of time constraints and secondly since the equipment would be used for development of new fuel types, not all variables were known to accurately conduct the investigation fully. Instead, caution when changing fuel types and regular inspections of the seals were suggested to ensure that the seals would work as intended.

3.4.6 Physical layout

The available space in the test cell chamber where the new fuel system was intended to be installed was a square section with side lengths of roughly 5-7 dm next to a wall. To utilize this space efficiently it was decided that the equipment should be mounted to a frame of extruded aluminum similar to the one shown in figure 14, that could in turn be mounted to the wall. The components within the frame could then be connected to the rest of the test cell with quick disconnects located in the edges of the frame for easy access. Within the frame, the components should be arranged as to easily be able to access each component without hassle when needing maintenance. Note that the high-pressure fuel pump would be able to be mounted both within this frame as well as on the engine.

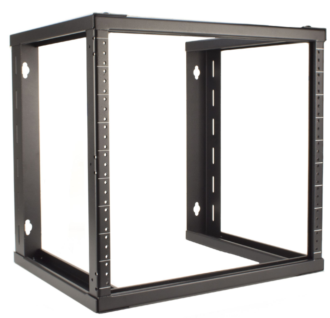


Figure 14: Wall-mountable extruded steel frame. [25]

3.4.7 Safety analysis

To establish that the fuel system would operate safely and correctly, in the validation phase mentioned in section 1.4 the systems safety features should be tested thoroughly by pressure testing the system to ensure that all components work as intended and that the pressure relief valves are triggered when they are supposed to. During the safety analysis it was also observed that it would be beneficial to install pressure sensors in more parts of the system, namely the low and inlet pressure fuel lines. This would help the operator to troubleshoot the system in the event of any mishap. In table 7 below, the FMEA constructed during the safety analysis of the system can be read.

Table 7: FMEA for fuel supply system

Risk	Possibility (P:1-4)	Gravity (C:1-4)	Risk value (P*C)	Effect	Solution
System leaking fuel (low pressure).	2	3	6	Fire hazard. Inaccurate fuel consumption measurements.	Monitor fuel flow for unexpected deviations in fuel consumption. Install a floor in the extruded aluminum frame to catch any leaks as to not spill any fuel and to easily see if any fuel has leaked.
Hose or pipe bursting or coming loose, leaking fuel (high-pressure).	2	4	8	Fire hazard. high-pressure fuel could cause injury to operator or damage to other components.	Never enter the test cell chamber when the system is pressurized. Install shielding around high-pressure components and fuel lines to stop high-pressure jet streams from spreading. Do regular checks to ensure no components have come loose.
Small debris come loose inside the system.	1	3	3	May clog the fuel system, ceasing operation. Could cause damage to pumps or other components.	Do regular maintenance on the system and assess wear. Evaluate if extra filters are needed.
Pressure relief valves fails to release pressure.	2	4	8	May cause damage to components and or bursting hoses/tubing.	Perform regular pressure tests of the system to validate that it is safe and ensure that components work as intended. Program the system to cease operation if the measured pressure exceeds acceptable values.
System runs out of fuel.	3	2	6	May cause cavitation in pumps.	Monitor the fuel flow rate and program the system to shut down if the flow becomes irregular or stops. Check the amount of fuel in the fuel tank before operation.
System still pressurized when operator enters the test cell chamber.	2	4	8	Unsafe working conditions for operator. May cause injury.	Ensure that the pressure can be validated from outside the test cell chamber.
Pressure release vale leaks fuel.	1	2	2	Fire hazard. Inaccurate fuel consumption measurements.	Connect a reservoir to all pressure relief valves to easily spot a leak and keeping the fuel contained. Test the system regularly to validate that it works as intended.

4 DISCUSSION

In this section both the methodology and results of this thesis are discussed. Included is also a summary of the remaining work needed to finalize the product.

In the planning of the project, a risk analysis of the project was made (table 1 of appendix B). In which, *Ordered components do not arrive on time* was observed to be the greatest risk of the project. This assessment has throughout the project been found to be accurate and has been the main culprit in the project not being finished to the degree that was planned. To be more specific, because this risk was found to be the greatest of the project, care was taken to minimize it in every step of the project. Despite this, with the limited time available, the manufacturers were not given enough time to deliver their products in order to reach all the goals of the project and finishing the system to the degree that was planned within the time frame of the thesis. Besides not being able to start the manufacturing phase and succeeding phases in the project, this delay also affected the documentation of the system (drawings, PBS etc.), since not enough information could be gathered before receiving the components for these documents to be of any help at this stage in the project.

4.1 Product Specification

Given the fact that this has been the first project in this field for the author, the product specification could have been formulated as to better predict and plan for the type of issues and challenges that were encountered during this project and that in hindsight were quite obvious. That being said, although the product specification could have been improved on, it has been a sufficient and helpful tool for the project and it has predominantly served it purpose well. An example of one of the sections that could have been improved upon was the expected difficulty row in the QFD matrix (table 2). Which, because of limited prior knowledge on the subject of the thesis, was somewhat inaccurate. In hindsight, product property *A. Pressure control* for example should definitely have been evaluated as harder (value 3) to better reflect the challenges faced regarding it throughout the project.
All in all, despite these flaws, the product specification has served as a great tool to both ensure a mutual understanding between the author and the client regarding the project and as a starting document to base the development process on.

4.2 The concept generation process

The concept generation process adapted in this thesis differs from what is usually used in a construction concept generation process. This was a conscious decision made on the basis that the end goal worked towards in this thesis was always inherently a single specimen product as opposed to a mass produced product. Because of this fact, the time and cost associated with designing custom components outweighed the more tailored functionality possible with starting from a clean sheet. This meant that, instead of strictly trying to develop concepts for each product property individually, the project focused on identify the systems main functionality and define the dependence of all sub-functions of the system. Thus creating a logical order of attack based on the dependence

of the sub-functions. Following this, concepts for each sub-system could be developed and OEM components and solutions prioritized to save time and money.
However, if all the components needed to produce a system meeting all the demands outlined by the client already existed on the market as a finished system, this thesis would have been obsolete. Therefore, custom components and modifying existing products to better suit the intended applications was taken into account in the concept generation process as well as already existing solutions. But as mentioned, components not needing modification were prioritized.
At the initial concept generation stage following the sub-system ranking, no consideration of whether the concepts for each subsystem would be able to be used together with each other was taken into account, instead each sub-system was only evaluated individually until a later stage. This was done to minimize an unnecessary bias process and prematurely discarding possibly viable concept. This way, the process would be as general and open to different solutions as possible.

4.3 The concept selection process

In table 5, a scale of only 2 values were chosen to weigh the concepts against each other (+ for pass and - for fail). This was done on the basis that a requirement only could be met or not, therefore breaking the problem down to a yes or no question for each requirement. In table 6 on the other hand, because of the nature of some of the requests outlined in the specification of requirements in table 1, a larger scale of 0 to 3 was chosen to specify how well the concepts met the requests. An example of when this was beneficial was when evaluation how well the concepts met criteria 14 of table 1, *flexible*. Which, at this early stage in the development process, is a quite subjective decision compared to when evaluation if a concept is, for example, able to supply the engine with fuel at up to 30 kg/h (as criteria 10 of table 1 states). Thus, a larger scale made it possible to show what concepts showed the greatest potential in these scenarios when needed.

As mentioned in section 3.3, none of the concepts for high-pressure fuel pump met the target value for maximum pressure fluctuations of $\pm 0.1\%$. At the high operating pressures at which this value would need to be met, factors such as volume change due to strain in pressure lines due to the high-pressures starts to become large enough to not be neglected. This means that reaching this level of consistency in the pressure is extremely difficult and in the end deemed impossible in this system without sacrificing other vital functionality of the system. However, the estimated maximum pressure fluctuation value of $\pm 1\%$ should be sufficient to enable the operators to obtain reliable data and a be competitive option for high-pressure CI fuel research.

4.4 Detail engineering

In section 3.4.2 two possible choices for power sources were chosen, electric motor and mounting the high-pressure pump directly to the engine and powering it via the crankshaft. This was chosen on the basis that, when consulted, the client found it beneficial to be power the pump via the crankshaft for its simplicity and to accurately emulate the operation of a normal powertrain. However, for some types of testing, this would mean that more hassle when changing engine components between tests, since the fuel pump also would need to be removed. If instead, the high-pressure pump would be mounted in the frame mentioned in section 3.4.6 and powered by an electric motor, there would be more upfront work to tune the electric engine to run in a satisfactory was, but would then not need any attention. Because of this, when this project is continued, the decision of power source for the high-pressure pump should be evaluated once again to see if two possible power sources is worth it. Or if instead only the electric engine should be chosen.

4.5 Final Product

Below are all criteria from table 1 listed with descriptions of whether or not they have been met by the system designed in this thesis. Note that criteria 5-6 were for the purposes of this thesis interpreted as ”The pressurizing system must be developed in such a way as to enable fast and accurate measuring of the fuel mass flow” and criteria 12 as ”The pressurizing system must be designed in such a was as to allow for components for conditioning of the fuel to be installed”.

1. *Documentation for implemented components* – As mentioned in the beginning of section 4, the project has not been finalized to a point in which these documents could be written in a way that would be of any benefit.

2. *2D drawings of manufactured parts* – At the state in which the project is in at the end of the scope of this thesis, no custom components have been designed or found to be needed as of yet.

3. *Assembly drawings* – At the state in which the project is in at the end of the scope of this thesis not all necessary information is known in order to create assembly drawings. Nor has the system been assembled, for explanatory pictures to be taken.

4. *Risk assessment* – A detailed risk analysis in the form of an FMEA has been conducted and presented in section 3.4.6.

5. *Evaluation of fuel flow measurements* – The system has been designed as to give several possible options for positioning of fuel mass flow measuring components.

6. *Implementation of flow measurement components* – See criteria 5.

7. *Take return flow into consideration* – Return flow from the fuel injector has been taken into account when designing the system.

8. *Adjustable pressure range* – The high-pressure fuel pump chosen is able to operate within the entire pressure span required.

9. *Run on a range of liquid fuels* – The materials chosen for each components should be compatible with all necessary fuel types. Note that further research and/or testing of compatibility when changing fuel type frequently is still advised.

10. *Mass flow* – The high-pressure fuel pump, after the mentioned modifications, is able to operate within the required span of mass flow.

11. *Constant fuel pressure* – Although not meeting the target value, the pressure fluctuations of the fuel system should be within acceptable values, namely $\pm 1\%$ of the operating pressure.

12. *Fuel conditioning* – The fuel system has been designed in such a way as to easily be able to incorporate fuel conditioning components.

13. *Stand-alone* – The system has been designed to meet this criteria, but also enables the operator to chose to mount and power the high-pressure fuel pump with the engine.

14. *Flexible* – The physical layout of the system is not yet finalized. Therefore this criteria has not yet been met, however when finished, the system should meet this criteria with the preparations and suggestions made in this thesis.

15. *Compatible with other equipment* – This criteria is partially met by the system. All data connections and signal types has been chosen to be compatible with the rest of the test cell equipment. However, not all physical connections between components, both within and outside the fuel system have been evaluated as of yet. With further work and possible adapters, this criteria should be met in the future.

16. *OEM Components* – The concept selection process showed that the use of Scania's XPI system components were the best option, thus this criteria has been met.

17. *No mixing of fuels* – The new CI fuel system has been designed independent of the existing SI fuel system without any mutual components or fuel lines.

18. *Possibility to run system with an auxiliary fuel tank* – The designed system will be able to be connected to an auxiliary fuel tank.

19. *Fuel drainage & pressure relief* – The system has been fitted with both a drainage system and a pressure release valve.

20. *Meet safety regulations* – After a final evaluation of the system in the validation phase, the system should meet all necessary safety requirements.

In the product specification under the heading ”FINAL PRODUCT”, which can be found in appendix C, a list of what would be delivered to the client at the end of the thesis was stated. Unfortunately, none of the listed points have been finalized. However, the results of this thesis could be used as a base for further work on the fuel system and with more time, all points should be fulfilled.

4.6 Future work

To finalize the CI fuel system designed in this thesis some further work is needed. As mentioned in the results, some minor components choices remain, the physical connections between the components needs to be evaluated and necessary adapters designed and manufactured (or bought if available). The physical layout needs to be finalized together with C. Aksoy to ensure that the components needed for mass flow measurements and fuel conditioning fits as well. When these things have been finished, the necessary drawings and other documentation can be finished and the manufacturing of the system can begin. After which, the last two goals of the thesis can be undertaken, validation and implementation of the system in the test cell.

5 CONCLUSIONS

In this master thesis project a concept for a CI fuel system for AVL's single cylinder test cell in Södertälje has been presented. The choice of major components such as a high-pressure fuel pump and a pressure sensor have been evaluated in detail to ensure that the end system can deliver fuel to the engines fuel injector at the required pressures and flow rates. Other necessary components, such as fuel lines have also been touched on. A flow chart for the included components have been created with consideration taken to the components needed for mass flow measurements and fuel conditioning, the choice of which are covered in the thesis by C. Aksoy [1]. The materials of the fuel systems included components have been taken into consideration to ensure that no corrosion will occur and that the materials will be compatible with diesel and diesel-like fuels. A safety analysis of the system has been conducted in collaboration with C. Aksoy [1] and a representative from AVL to ensure that the fuel system will be safe and meet AVL's safety standards.

Throughout this master thesis, the project developed from a construction project where a physical finalized product was the end result to a concept selection project. This was done because of the limited available time to prepare for the future work needed to finalize the project. Before the system is ready for manufacturing and later validation and implementation into the test cell some work remains. Including finalizing the physical layout of the system, select the remaining minor components and ensure that all connections between components are of the right type to fit together. With these things done, together with the results from this thesis, the CI fuel system should be able to be manufactured and eventually be used for future fuel research and testing by AVL.

6 ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to AVL MTC Södertälje for allowing me to be a part of this project and write my master thesis in their facilities and to all the helpful and inviting employees there. This project has taught me much and has been a great way to finish my studies. I am also grateful that this project has given me the opportunity to accept a working position as a test cell engineer at AVL Södertälje going forward.

I would also like to take the opportunity to thank some people individually that has helped me throughout this project. Thanks to Daniel Danielsson, Johannes Andersen and Lars Westerlund from AVL Södertälje and Anders Biel from Karlstad University for valuable supervision during the project and to Henric Ericsson, also from AVL Södertälje, for giving me the opportunity to me a part of this project and hiring me as a result of it. Thanks to Olle Ljungberg from Hydmos industriteknik and Martin Gidewall from Scania for excellent help regarding the choice of high-pressure fuel pump.

Lastly a special thanks to C. Aksoy for all your treasured input and discussions and for completing this project together with me.

Gustaf Glaad

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A List of Abbreviations

CAD	Computer aided design.
CI	Compression ignition.
CRDi	Common rail direct injection.
ECU	Engine control unit.
ED95	Ethanol mix containing 95% ethanol and other additives to improve ignition.
FMEA	Failure mode and effects analysis.
HVO	Hydrogenated vegetable oil. A type of biodiesel produced from vegetable fats and oils.
OEM	Original equipment manufacturer.
PA	Pressure amplifier pump.
PBS	Product breakdown structure.
PDP	Positive displacement pump(s).
PWM	Pulse width modulation.
QFD	Quality function deployment.
SI	Spark ignited.
UHMWPE	Ultra-high-molecular-weight polyethylene.
W.R.T	With respect to.

B Project plan

Can Aksoy, Gustaf Glaad

Faculty: Faculty of Health, Science and Technology

Subject: Degree Project for Master of Science in Engineering, Mechanical Engineering

Points: 30 hp

Supervisor KAU: Anders Biel

Supervisors AVL: Daniel Danielsson, Johannes Andersen, Lars Westerlund

Date: 2019-01-31

BACKGROUND

AVL is an international automotive consulting firm with their own independent research institute, where development, testing and simulation of powertrain systems are conducted. With their many years of experience AVL has become one of the leading companies within the automotive industry when it comes to drivetrains. At their facility in Södertälje they offer engineering, testing and simulation solutions for drivetrain solutions. At this facility AVL currently has a single cylinder test cell with two engine units at its disposal. The two engines are both currently set up for spark-ignited fuels (gas and petrol-like fuels), but upcoming projects will need to be run with compression-ignited fuels e.g. diesel and diesel-like fuels. The oil, fuel and water pumps are currently separate stand-alone units in the test cell as opposed to being directly connected to and powered by the engines crankshaft as is normally the case. The idea is to solve the high-pressure diesel pump unit in a similar way, i.e. a stand-alone unit that is easily connected to the current system, making it possible to run compression ignition tests. As the entire project is relatively large and complex, it is intended for two persons and thus separated into main parts, namely mass flow measurements and conditioning, and fuel supply and pressurizing.

PURPOSE & OBJECTIVE

The purpose of the project is to implement a fuel system for tests of compression-ignited fuels in AVL's single cylinder test cell. The system will additionally be validated and integrated in AVL's single cylinder test cell. To accomplish this, the requirements and relevant regulations that the product will need to meet will be identified. By these means, the product will be designed, constructed and then tested to make sure that the obligations are met.

ORGANIZATION

Project members: Gustaf Glaad, Can Aksoy
Supervisors: Anders Biel (KAU), Johannes Andersen (AVL), Daniel Danielsson (AVL), Lars Westerlund (AVL)

Responsibilities
The project will be divided into two separate master theses. Gustaf Glaad's main responsibilities will be pressure regulation, fuel supply and material selection. Can Aksoy's main responsibilities will be mass flow measurements and conditioning. New unforeseen tasks will be divided evenly among the project members with regards to time and relevance to the members other responsibilities.

PROJECT MODEL

The project will be carried out in several stages listed and described below.

- **Project plan**
  The project will start of with the planning of the projects structure and schedule, outlined in this document.

- **Product specification**
  In this section, the requirements and request regarding the end product outlined by the client will be specified and broken down. The purpose of this is to get a clear picture of what is expected and agreed upon to be accomplished by the end of the project. This document will be used as a base for the rest of the project.

- **Concept selection**
  After the product specification has been agreed upon by all involved parties the development process will begin with research on relevant information and inspiration needed for the project. Based on this, concepts to solve all problems and preform all functions of the product will be generated, analyzed, weighed against each other in terms of how well they meet the requirements of the product. This ranking will be used to determine which solutions to move forward with and incorporate in the product.

- **Detail engineering**
  In this part of the project, when the final concepts for creating the product has been finalized, the design and construction of the entire system will be finalized.

- **Manufacturing and assembly**
  When the development of the product has been completed, it will be manufactured and assembled in this section of the project.

- **Validation**
  In this part of the project, the functionality of the product will be tested and validated to ensure that the system works as intended.

- **Integration**
  The last part of the project, not counting documentation and presentation of the project, will be to integrate the product into the single cylinder test cell for deployment.

RISK EVALUATION

In the planing of the project, potential risks and how to avoid and/or deal with them were discussed and outlined in table 1.

Table 1: FMEA outlining the risks of the project

Risk	Possibility (P:1-4)	Gravity (C:1-4)	Risk value (P*C)	Solution
End product does not meet the clients requirements	2	4	8	Have regular meetings with the client to discuss the state and direction of the project and be transparent.
Schedule is not followed	2	3	6	Plan the project thoroughly and far ahead of time. Exaggerate the time needed for each task whenever possible. Record progress using tools such as PBS to have a clear picture of how far the project have come and a explicit picture of what to do next.
End product does not meet necessary regulations	2	4	8	Do thorough research into the relevant regulations and laws that the product needs to follow beforehand and evaluate the system and its components compliance regularly throughout the process.
Project members do not fulfill their obligations	1	4	4	Have a dialogue between the members, together with the supervisors if necessary, to ensure that the cooperation works and is in accordance with the schools directives.
Ordered components do not arrive on time	4	3	12	Decide as early as possible which components will be ordered and which will be manufactured in-house. Prioritize the selection of off-the-shelf components and order them as early as possible.

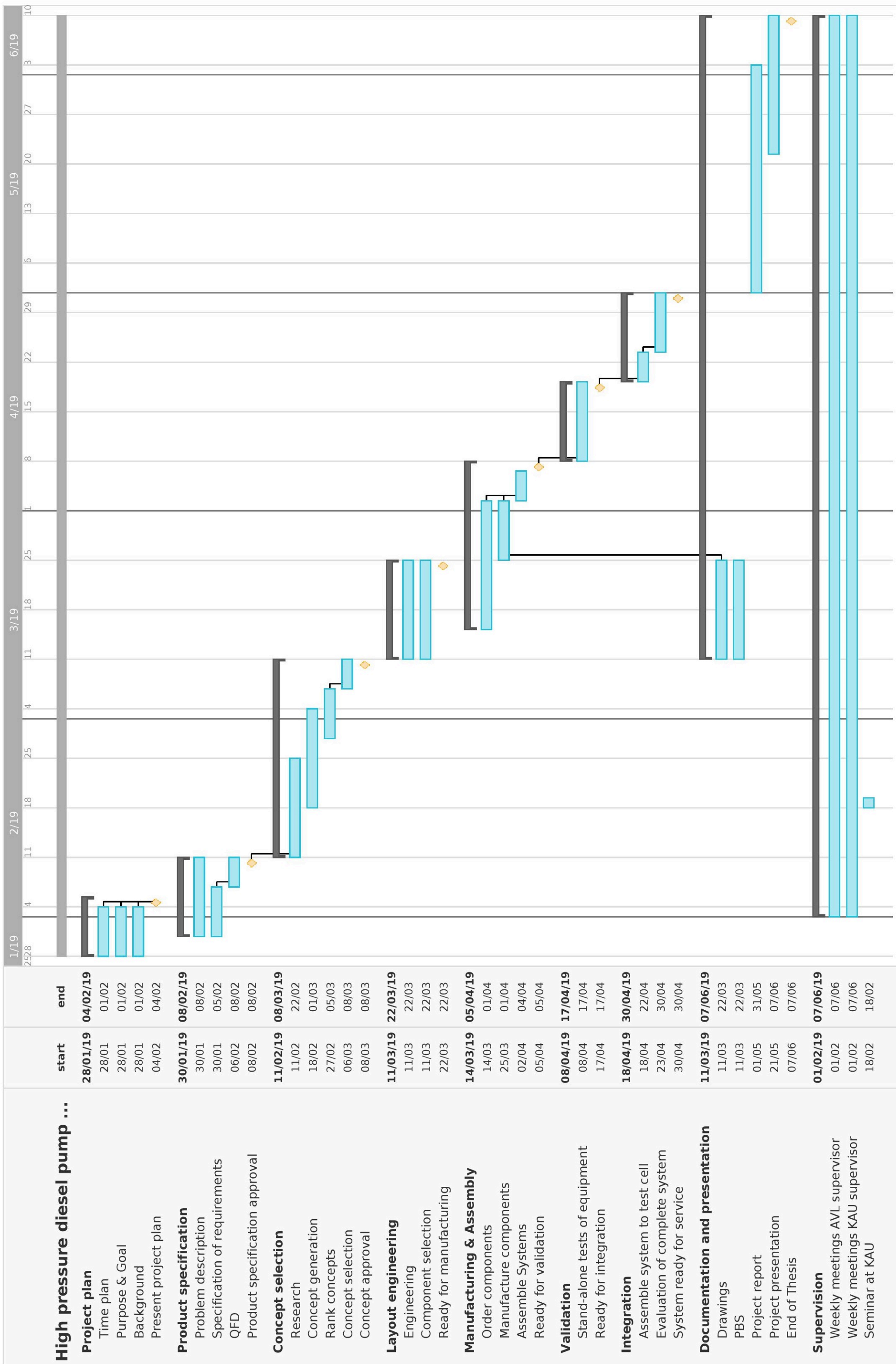
DOCUMENTATION

Documents and files related to the project will be saved to the specified folder on *dropbox.com*, with the exception of the PBS-file, which will be accessible at *drive.google.com*. Technical reports used as references will be uploaded to the project folder on *mendeley.com* for easy referring in correlation with *overleaf.com*. Access links to the specified folders will be sent to the affected parties email addresses. This is to ensure that proper backup practises of the data is followed.

All documents shall be named according to the format *yymmdd_DocumentName_version*. File names of 2D-drawings and 3D-models should be the same as the PBS number of the component or assembly that they are associated with.

All in-going components and assemblies should be listed and their progress recorded in a PBS document. The parts and assemblies should be named according to the format *XY-ZZZ*. Where *X* denotes the assembly to which the item belongs to, *Y* denotes the sub-assembly to which the item belongs to and ZZZ is the part number.

PROJECT OUTLINE



C Product specification

Can Aksoy, Gustaf Glaad

Faculty: Faculty of Health, Science and Technology
Subject: Degree Project for Master of Science in Engineering, Mechanical Engineering
Points: 30 hp
Supervisor KAU: Anders Biel
Supervisors AVL: Daniel Danielsson, Johannes Andersen, Lars Westerlund
Date: 2019-02-26

PROBLEM DESCRIPTION

Currently AVL has a dedicated single cylinder test cell with two engine units at its disposal. The two engines are both currently spark-ignited (gas and petrol-like fuels), but upcoming projects will need to be run with compression-ignited fuels e.g. diesel and diesel-like fuels. The oil, fuel and water pumps are currently separate stand-alone units in the test cell as opposed to being directly connected to and powered by the engines crankshaft as is normally the case. The idea is to solve the high-pressure diesel pump unit in a similar way, i.e. a stand-alone unit that is easily connected to the current system, making it possible to run compression ignition tests.

METHOD

To quantify what will be delivered and ensure a mutual understanding of the product's specification between the client and the contractors, a list of the requirements and requests concerning the product has been constructed in collaborations between the client and contractors, which can be seen in table 1. This table will be the foundation on which the development and design of the product will rely on to satisfy the clients needs. From this table a *Quality function deployment* matrix has been constructed, which can be seen in table 2. This matrix translates the requirements and requests of the client to products properties and enables the contractors to plan the development process and easier develop a suitable solution to the clients needs.

Specification of requirements

Each requirement and request outlined by the client was numbered and sorted by its applicable category in table 1. Each criterion was expressed in detail while keeping them solution-independent and finally denoted as either a function or limitation to the products use where applicable.

Elaboration on requirements and requests

1. *Documentation for implemented components* – All off-the-shelf components should be documented. Information about supplier, product number, number of components, theoretical life time and possible long delivery times should be available in the documentation. In addition a rough cost assessment for each component should be included.

2. *2D drawings of manufactured parts* – All relevant components not acquired from an outside-supplier should have a 2D drawing with necessary manufacturing information.

3. *Assembly drawings* – Clear instructions of which components are included in the system, their output-signals, how they are controlled and how they are assembled should be documented. Depending on time available this will either be delivered as a document with pictures and descriptive text, or a conventional assembly drawing.

Table 1: Specification of requirements and requests for the product, outlined by the client.

Criteria number	Category	Criteria	Requirement /Request	Function/ Limitation
1	Documentation	Documentation for implemented components	Requirement	-
2	Documentation	2D drawings of manufactured parts	Request, mid	-
3	Documentation	Assembly drawings	Requirement	-
4	Documentation & Safety	Risk assessment	Requirement	-
5	Fuel consumption	Evaluation of fuel flow measurements	Requirement	Function
6	Fuel consumption	Implementation of flow measurement components	Request, mid	Function
7	Fuel consumption	Take return flow into consideration	Requirement	Limitation
8	Fuel supply	Adjustable pressure range	Requirement	Function
9	Fuel supply	Run on a range of liquid fuels	Requirement	Function
10	Fuel supply	Mass flow	Requirement	Function
11	Fuel supply	Constant fuel pressure	Requirement	Limitation
12	Fuel supply	Fuel conditioning	Requirement	Function
13	Operation	Stand-alone	Request, high	Function
14	Operation	Flexible	Request, high	Limitation
15	Operation	Compatible with other equipment	Requirement	Limitation
16	Operation	OEM Components	Request, low	Limitation
17	Operation	No mixing of fuels	Requirement	Limitation
18	Operation	Possibility to run system with an auxiliary fuel tank	Request, high	Function
19	Operation	Fuel drainage & pressure relief	Requirement	Function
20	Safety	Meet safety regulations	Requirement	Limitation

4. *Risk assessment* – A risk assessment of the system should be conducted and well documented in the form of a FMEA with respect to safety of operation and personal.

5. *Evaluation of fuel flow measurements* – An evaluation of how fuel mass flow measurements could be carried out and what components could be used and where they should be placed in the system.

6. *Implementation of flow measurement components* – Depending on available time the flow measurement components should be implemented into the system.

7. *Take return flow into consideration* – The return flow from the fuel injector must be accounted for in the system.

8. *Adjustable pressure range* – The system should be able to operate at pressures in the range of 500-3500 bar (exact values may change).

9. *Run on a range of liquid fuels* – Be able to run on diesel and alternative diesel-like fuels, such as ED95, biofuel and HVO.

10. *Mass flow* – The system should be able to operate with a mass flow between 0-30 kg/h (exact values may change).

11. *Constant fuel pressure* – The fuel pressure must be able to be kept near constant with a target value of fluctuations being less than 0.1% of the requested system pressure.

12. *Fuel conditioning* – The system should be able to accurately condition the fuel in terms of temperature and bleeding of gases. Filtering will be handled by components outside of the scope of this project.

13. *Stand-alone* – The system should be powered separately and not depend on the operation of the engine for energy.

14. *Flexible* – The system should be flexible and easy to operate in regards to installation, maintenance and repairs. The system should also be portable in the sense that it should not be permanently mounted in the lab.

15. *Compatible with other equipment* – The system should be compatible with the test cells existing control systems, other test equipment and the existing control systems *Raptor, Labmeas and Puma*.

16. *OEM Components* – If possible and in other aspects advantageous, the system should be composed of, or compatible with OEM components from existing fuel systems, for example Scania's XPI system. This is to enable other types of tests in the cell, such as wear testing of these OEM components.

17. *No mixing of fuels* – The new system for combustion-ignited fuels should be separate from the existing system for spark-ignited fuels.

18. *Possibility to run system with an auxiliary fuel tank* – The system should be able to be connected to a smaller auxiliary fuel tank to enable testing of lesser amounts of fuel easier.

19. *Fuel drainage & pressure relief* – The system should be able to be emptied of fuel through some type of drainage mechanism. An estimate of the amount of fluid that will be drained from a full system should be done, as well as an estimate of how much and where in the system there will be fluid left after draining it. There should also be a pressure release valve that lowers the pressure of the high-pressure lines at shutdown and in the event of failure.

20. *Meet safety regulations* – The system and its components should meet all necessary safety regulations concerning for example high-pressure fuels to ensure the safety of personal and equipment during operation.

Quality function deployment

To relate the clients inputs on the product to product properties a QFD matrix was constructed and attached as table 2. The requests in table 1 were weighted between 1-3, based on their importance (low, mid or high), where 3 is the most important. The product requirements, also from table 1 were weighted as 4 since they were regarded to be of highest importance for obvious reasons. The correlation of each product property in relation to the client input criteria were graded between 1-3, where 3 denotes highest correlation. Cells which corresponds to non-correlative combinations were left empty. The grade of difficulty for each property to be brought to completion was ranked 1-3, where 3 represents the most difficult.

To get a better understanding of which of the product properties that will require the most attention throughout the project, a weighted importance was computed by using equation 1.

$$\text{Weighted Importance} = \sum \text{Importance} \times \text{Correlation} \tag{1}$$

Finally the expected difficulty was incorporated by using equation 2, further clarifying which product properties presumably will be the most resource-heavy. The three properties with the highest values based on equation 1 and 2 has been marked red, orange and yellow in table 2.

$$\text{Weighted Importance w.r.t. Difficulty} = \sum \text{Weighted Importance} \times \text{Expected Difficulty} \tag{2}$$

Table 2: Quality function deployment matrix relating the requirements and requests of the client to the planned product properties.

Client input			Product Properties						
Number	**Criteria**	**Importance**	**A. Pressure control**	**B. Conditioning**	**C. Flow measurement**	**D. Connections**	**E. Layout**	**F. Size**	**G. Material selection**
5	Evaluation of fuel flow measurements	4	2		3				
6	Implementation of flow measurement components	2			3				
7	Take return flow into consideration	4	1		3		2		
8	Adjustable pressure range	4	3		2				2
9	Run on a range of liquid fuels	4	2	1	1				3
10	Mass flow	4	3		1				
11	Constant fuel pressure	4	3		2				
12	Fuel conditioning	4		3					
13	Stand-alone	3				3			
14	Flexible	3					3	3	
15	Compatible with other equipment	4	3	3	3	3		1	1
16	OEM components	1	3	1					
17	No mixing of fuels	4				3	3		
18	Possibility to run system with an auxiliary fuel tank	3				3			
19	Fuel drainage & pressure relief	4	2			2	1		
20	Meet safety regulations	4	2	2		2	1	1	3
Expected Difficulty			2	1	3	1	1	2	3
Weighted Importance			87	37	66	58	37	17	36
Weighted Importance w.r.t Difficulty			174	37	198	58	37	34	108

Product properties

A. *Pressure control* – Refers to the systems ability to pressurize the fuel and accurately regulate and maintain the pressure level.

B. *Conditioning* – Denotes the systems ability to, if deemed necessary, regulate the fuels temperature before entering the combustion chamber in accordance with the directions outlined by the operator or at the very least monitor it, as well as bleeding the system of any gases.

C. *Flow measurement* – Refers to the systems ability to accurately measure and monitor the fuel consumption of the system in real time.

D. *Connections* – Refers to the types and positioning of the systems in- and outputs, including fuel-lines and control signals, sensors and others.

E. *Layout* – Denotes the components positions relative to each other within the system, i.e. the arrangements, with respect to accessibility, safety, and sequence of the components.

F. *Size* – The unit should be as small as possible, without losing flexibility in operation, maintenance, installation and repairs.

G. *Material selection* – Refers to the material selection for each component in the system, which will influence for example corrosive resistance against the fuels used in the system.

Planned procedure

The next step in the development process will be to distribute the work load and responsibilities between the contractors in more detail. Thereafter the research and concept generation will begin. Followed by ranking the concepts and, together with the client, choose a final concept for further development and deployment.

FINAL PRODUCT

At the end of the project this is what will be delivered to the client:

- A system capable of conditioning and supplying a variety of diesel-like fuels from a fuel tank to a combustion chamber under high-pressure. The fuel tank and the injection nozzle are not included in the system, but all other components that connects the two are. The system should meet all requirements and regulations outlined by the client and also aim to fulfill as many of the clients requests as possible. The system should also be able to run separate from an engine.

- Detailed documentation of the product and its components containing 2D-drawings of custom manufactured components, article numbers and suppliers of off-the-shelf components, a list of all in-going components, a diagram of the system layout and a risk analysis of the product and its operation.

- Depending on available time, documentation from test results from validation of the systems capability and operation.

- Depending on the available time in the outlined project, implementation of the product in the existing test cell.