Design and development of a high pressure ED95 fuel delivery system for a single cylinder test cell engine

DAVID LAWRENCE
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David Lawrence

Master of Science in Engineering
Master programme in Vehicle Engineering
KTH Royal Institute of Technology

Supervisor at (AVL Motortestcenter AB): Daniel Danielsson
Supervisor at KTH: Andreas Cronhjort
Examiner at KTH: Mikael Nybacka

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KTH Royal Institute of Technology
School of Engineering Sciences
KTH SCI SE-100 44 Stockholm, Sweden
URL: http://www.kth.se/sci
Abstract

Bio-fuels, being the primary alternative to the fossil fuels, used in the internal combustion engines are subjected to constant development. The development of alternative Ethanol Diesel (ED95) formulations at AVL Motortestcenter AB has demanded a test facility capable of evaluating the combustion quality of these specimens. A test cell capable of evaluating fuels operating on the compression ignition concept was required for this reason. The aim of this thesis is to develop a high pressure fuel delivery system for a single cylinder test cell engine. The literature review conducted offered knowledge on stages involved in the development of the fuel and the operation of high pressure fuel systems for engines operating on the Diesel concept. Knowledge was acquired on phenomenon such as pressure fluctuations and information regarding engine test cells was familiarised. Scania’s XPI fuel system being the designated fuel system for the test cell was studied and adaptations required for its implementation in the single cylinder test cell was investigated. Based on the information acquired, recommendations for the setup of the high pressure fuel system for the single cylinder test cell engine are mentioned.

Keywords

Ethanol Diesel (ED95), Single cylinder test cell, Scania XPI system, Pressure fluctuations.
Sammanfattning

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Nomenclature

$BTDC$ Before Top Dead Center
$CFRE$ Cooperative Fuel Research Engine
$CI$ Compression Ignition
$CN$ Cetane Number
$DC$ Direct Current
$ECU$ Engine Control Unit
$ED95$ Ethanol Diesel
$FAME$ Fatty Acid Methyl Esters
$HFRR$ High Frequency Reciprocating Rig
$HVO$ Hydro-treated Vegetable Oil
$IC$ Internal Combustion
$PCV$ Pressure Control Valve
$RPM$ Rotations Per Minute
$SI$ Spark Ignited
$TDC$ Top Dead Center
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1 Introduction

1.1 Background

Contemporary challenges, such as climate change and global warming, threatening the condition of the planet has surged numerous solutions to combat them. The heavy-duty automotive sector, primarily equipped with internal combustion engines as powerhouses, employ the diesel combustion concept to provide them with the driving force. Fossil fuels and biofuels such as Ethanol Diesel (ED95), Fatty Acid Methyl Esters (FAME) and Hydro-treated Vegetable Oil (HVO) operate as fuels in the internal combustion engines. These Bio-fuels, the primary alternative to fossil fuels in the heavy-duty automotive sector, has been under consistent development to ensure its functionality as a replacement to fossil fuels. The incessant quest to develop efficient and cost effective bio-fuels reveals numerous possibilities to improve the current state of bio-fuels.

Ethanol Diesel (ED95), an alternative fuel, primarily used by Scania in the automotive industry constitutes of wet ethanol and a maximum of 10% of function enhancing additives by mass. The wet ethanol constitutes of approximately 95% ethanol and 5% water by volume. Combustion improvers and lubricity agents collaboratively comprise the function enhancing additives in ED95. ED95, when viewed from a fuel perspective, is not free from flaws and has the potential to be improved where combustion quality and lubrication property are the main areas in need of improvement. Scania, in association with Ethanol processors, AgroEtanol and SEKAB, collaborated with AVL Motortestcenter AB to improve the competitiveness of ED95 among bio-fuels. Figure 1 classifies fuel supplied in the year 2017 for the operation of the transport sector in Sweden.

![Supplies of transportation fuels in Sweden in 2017 (TWh)](image)

Figure 1: Transportation fuel supplied to vehicles operating in Sweden in 2017 [6].

AVL, a pioneer in development, testing and simulation of power-train systems offered their resources towards the development of ED95. AVL aimed to improve ED95 by enhancing its combustion and lubrication properties which consequently decreases the costs involved in operation and maintenance of engines utilizing this fuel. The primary stage involved screening of new components that could be added to improve the competitiveness of the fuel. By investigating possible improvements to the fuel, AVL aimed to enhance the quality of ED95 [3].
The second stage of testing involves evaluation of combustion quality in a single cylinder research engine and evaluation of lubricity of the developed ED95 fuel formulations. Testing the new ED95 fuel in the single cylinder test cell aids in determining the combustion quality of the new ED95 fuels. Considering the wear evaluation of the fuel system components, full engine durability tests should be performed to evaluate the wear in fuel pumps and fuel injectors [3].

The final stage of development involves full tests including the multi-cylinder tests in the test cell, road tests and tests required for emission evaluation [3]. On the completion of these three stages the performance of ED95 is evaluated based on the results from each stage.

1.2 Aim and objective

The aim of this thesis work is to develop a high pressure fuel delivery system for a single cylinder, test cell engine to perform the combustion evaluations required for the second stage development of the alternative ED95 fuel formulations. AVL currently has a test cell to perform evaluations on single cylinder, spark ignited (SI) engines [5]. These test cells hence operate on lower fuel pressure as compared to internal combustion engines running on the diesel combustion concept. Adaptations are required to facilitate high fuel pressure feed for the testing of fuels in single cylinder compression ignition engines. Additionally, it is essential to simulate conditions similar to real time running of engines to obtain accurate evaluations of the combustion quality.

1.3 Previous research and work

This thesis work, involving the development of a high pressure fuel delivery system for a single cylinder test cell engine, is a segment affiliated to a larger project. The project involves the development of ED95 to increase its competitiveness among renewable fuels. Figure 2 depicts the stages involved in the development of ED95 at AVL.

![Figure 2: Development stages of ED95.](Image)

AVL aims to develop this project with a three-stage approach. The primary stage involved the screening of new function enhancing additives to improve the economic and
technical potential of ED95. AVL approached several additive component suppliers in an attempt to acquire possible additives for testing. Nineteen function enhancing additives were acquired from the suppliers and sent in for initial lubricity and combustion evaluation. These nineteen function enhancing components comprised of seven combustion quality improvers and twelve lubricity agents. With the expertise of a technical veteran in fuel and lubes at AVL, a hundred and one test fuels were blended. Ninety out of these hundred and one test fuels were analysed for improvements in lubricity and combustion quality compared to the current ED95 fuel. The lubricity and the combustion quality was evaluated using the High Frequency Reciprocating Rig (HFRR) test and the Cetane engine test respectively. Promising results were obtained on two combustion improvers and four lubricity agents [3].

The second stage of development involves evaluations carried out in a single cylinder test cell engine and performing full engine durability tests. The assessment of combustion in the single cylinder test cell engine aids in determining the combustion quality of the fuel. A wear evaluating rig, including the fuel pump and injectors, simulating real conditions of running can provide information regarding the lubricating quality of the fuel. However, evaluation of wear of the components after performing full engine durability tests would provide more credible results. As per Scania’s test procedures, the durability test constitutes 1150 hours of transient engine running [3].

The development of single cylinder test cell to facilitate the flow, measurement and conditioning of the fuel has already been carried out by G. Glaad and C. Aksoy as a thesis work previously [12][16]. The development performed in the previous thesis provides us with numerous possibilities for the pumping of the fuel in the test cell. It provides insight on the accurate measurement of fuel and the devices required for fuel measurement. Additional components required for conditioning the fuel to simulate cold starts and different running conditions are also included in the thesis. The primary factor crippling the ability of the current test cell to evaluate the combustion quality of the alternative ED95 fuel formulations is its incapability to provide enough pressure required for the efficient combustion of the fuel. Parameters such as lower fuel flow to the single cylinder test cell engine as compared to the conventional five and six-cylinder inline engines need to be further investigated. Intrinsic behaviours like pressure fluctuations in the high pressure fuel line should be studied in order to reproduce such traits in the test cell to obtain accurate results.

2 Market analysis

2.1 Ethanol Diesel (ED95)

Ethanol Diesel, an ethanol based renewable fuel, is one among many renewable fuels used in internal combustion engines. It was primarily developed to be used in an engine employing the compression ignition principle [1]. Engines using ED95 as a fuel are required to have a higher compression ratio than engines operating on Diesel fuel to ensure efficient running of the engine [17]. ED95 and Diesel differentiate themselves in physical and flow properties.
Table 1: Relative comparison of properties of ED95 and Diesel [1].

<table>
<thead>
<tr>
<th>Property</th>
<th>ED95</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Content</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Density</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Viscosity</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Lubricity</td>
<td>lower</td>
<td>higher</td>
</tr>
<tr>
<td>Cetane number</td>
<td>lower</td>
<td>higher</td>
</tr>
</tbody>
</table>

Table 1 offers a relative comparison between the vital properties of ED95 and Diesel.

2.1.1 Current formulation

The formulation of ED95 is analogous in different regions of the world where they are manufactured. There is a standardised manufacturing formula for ED95 currently and a general specification provided by the Swedish fuel standard is followed to manufacture ED95 in Sweden. ED95 constitutes of wet ethanol, denaturants and up to 10% of function enhancing components by mass. Ethanol produced through standard procedures results in a final product constituting of ethanol and water i.e. wet ethanol. The wet ethanol used in the production of ED95 constitutes of ethanol, 95% by volume, and water, 5% by volume. The ignition improver and lubricity agent comprise of the function enhancing components of the fuel. The fuel also includes a minute amount of corrosion inhibitor to prevent unwanted reactions with the components of the fuel system. Identical function improving components are used globally while the denaturants are chosen based on local legislation. The current formulation of ED95 consists of approximately 6% of function enhancing components by mass and 2% of denaturants by mass [15]. Currently, components of fossil fuels serve as the source for certain elements used in the ignition improver and lubricity agents [3].

2.1.2 Current issues

Economical and functional issues arise as a consequence of significant amounts of function enhancing additives in ED95. Vehicles running on other renewable fuels offer lower maintenance costs compared to those running on ED95. High cost of fuel (per MJ) compared to other renewable fuels coupled with maintenance and service cost, escalates the running costs of vehicles operating on ED95 [3].

2.1.3 Areas of improvement

Albeit ED95 shows potential problems economically and functionally, it is a fuel whose potential has not been explored. Development of this fuel can unearth viable benefits, making ED95 a competitive fuel in the renewable fuel market. The aim of the development is to reduce deposit issues and wear issues which in turn reduces the maintenance cost of operation. Improved combustion quality can reduce the amount of unburnt fuel in the blow-by through the piston rings and cylinder, thereby reducing the contamination of the oil as well as increasing overall efficiency. Pragmatic development and choice of function enhancing components can be beneficial in the pricing of the fuel [3].
2.2 Standardised tests for fuel evaluation

Function enhancing components blended in ED95 in the screening stage of development needs to be validated to proceed to the second stage of development. The primary properties needed to be validated for the first stage of developing ED95 is the combustion quality and lubricating quality. The standardised test to evaluate these properties for diesel is the cetane test and high frequency reciprocating rig (HFRR) test. The cetane test evaluates the combustion quality whereas the HFRR test evaluates the lubricating quality of the fuel. Though ED95 and diesel are dissimilar these tests can be utilized to evaluate the properties of ED95. However modifications to the test procedures and test conditions are required to obtain credible results [3].

2.2.1 Cetane test

The cetane number (CN) of a fuel indicates its combustion quality. The cetane number is scaled from zero to hundred, with a higher number indicating a better combustion quality. The compression required by the fuel for ignition and the time required for the fuel injected into the combustion chamber to ignite determines the cetane number of a fuel [2]. Numerous factors can play a significant role in the combustion of a fuel in the engine. Pressure and temperature are primary factors which affect the ignition of fuel in the combustion chamber. Engine architecture such as combustion chamber design, air intake port geometry affecting the intake airflow can influence the combustion behaviour of the engine. Fuel pressure, temperature and injections techniques alter ignition times of the fuel [3].

![Figure 3: A F5 cooperative fuel research engine][7].

A Cooperative Fuel Research (CFR) engine with standardised boundary conditions is used to determine the cetane number of a fuel. Figure 3 shows a CFR engine used to evaluate cetane numbers of fuels. The engine has a variable compression ratio which can be altered to obtain a certain ignition delay between the injection of the fuel and its
ignition. Based on the compression ratio at the specific ignition delay of the engine, the cetane number is determined [2].

The primary modification in boundary conditions to accommodate the testing of ED95 fuels was to alter the fuel flow rates. ED95, having lower energy content than diesel would require a higher flow rate to satisfy the conditions established by Diesel fuels. Calculations based on energy content (lower heating value) established a new flow rate for ED95 to be used in the CFR. Cetane (CN 100) and isocetane (CN 15) used as reference fuels while evaluating combustion quality of Diesel were supplemented with ethanol (CN 11) and 1-Butanol (CN 17) to compensate for the changes made to the boundary conditions [3]. Table 2 shows the standard running parameters and the modified parameter value for testing ED95.

Table 2: Standard running parameters of the CFR engine test [2][3].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard value</th>
<th>Modified test value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio</td>
<td>variable</td>
<td>compression ratio</td>
</tr>
<tr>
<td>Engine speed</td>
<td>900 ± 9 RPM</td>
<td></td>
</tr>
<tr>
<td>Fuel injection timing</td>
<td>13° BTDC</td>
<td></td>
</tr>
<tr>
<td>Fuel flow</td>
<td>13 ± 0,2 ml/min</td>
<td>22 ± 0,2 ml/min</td>
</tr>
<tr>
<td>Inlet air temperature</td>
<td>66 ± 0,5°C</td>
<td></td>
</tr>
<tr>
<td>Required ignition delay</td>
<td>13° (ignition at TDC)</td>
<td></td>
</tr>
</tbody>
</table>

2.2.2 High frequency reciprocating rig

The high frequency reciprocating rig (HFRR) is a standardised test developed, as an outcome of wear issues in diesel fuel systems, to evaluate lubricity of the fuel. The HFRR is a specially constructed mechanism operating under standardised testing conditions and procedures [4]. The HFRR constitutes of an apparatus including a steel ball and a steel plate in contact with each other [18]. Figure 4a shows a schematic representation of the apparatus.

Figure 4: High frequency reciprocating rig.

The fuel to be evaluated occupies the region of contact between the steel ball and the steel plate. The steel ball is moved forward and backward on the steel plate causing
an abrasion on the plate. The force subjected to the steel ball and the reciprocating frequency of the steel ball is standardised. The fuel acting a lubricating film between the steel plate and the steel ball influences the abrasion produced on the steel plate. The test is carried out for a standard amount of time with controlled temperature conditions. The wear scar produced on the steel plate is co-relates to the lubricity of the fuel. The HFRR value, representing the mean value of the width and length of the scar is used as reference for comparing lubricity of fuels [18]. Figure 4b shows an example of a wear scar with an indistinct boundary.

Table 3: Standard running parameters of the HFRR test [4][3].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard value</th>
<th>Modified test value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample volume</td>
<td>2 ± 0.2 ml</td>
<td></td>
</tr>
<tr>
<td>Test time</td>
<td>75 ± 0.1 min</td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td>1 ± 0,02 mm</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>50 ± 1 Hz</td>
<td></td>
</tr>
<tr>
<td>Test temperature</td>
<td>60 ± 2°C</td>
<td>25 ± 2°C</td>
</tr>
<tr>
<td>Load</td>
<td>200 ± 1 g</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 shows the standard parameters of the test and the modified values required for testing ED95. ED95 being more volatile than diesel evaporates at 60°C and requires lower temperature conditions to provide accurate results. Hence the temperature during the test was lowered to 25°C. An additional modification to prevent this issue was to seal the fuel sample holder to decrease the evaporation of the fuel. An apparatus called the gasoline conversion kit, which is essentially a cover for the fuel reservoir, is used to curtail the evaporation [3]. Figure 5 shows a HFRR apparatus without and with a gasoline conversion kit.

(a) Standard HFRR. (b) HFRR with a gasoline conversion kit.

Figure 5: High frequency reciprocating rig and gasoline conversion kit.
2.3 High pressure fuel system - Common rail injection systems

Contemporary internal combustion engines primarily equip common rail direct injection systems to provide the conditions necessary for the efficient injection and burning of fuel in the combustion chamber. The fuel system constitutes of numerous components to filter the fuel and provide the required fuel pressure demanded by the engine at all working conditions. Common rail injection systems are advanced systems that have the ability to alter injection pressures and injection timings over an extensive range, portraying their dominance over other fuel systems. Independence between pressure generation and fuel injection made the development of the common rail injection system achievable. Albeit all vehicle employing a common rail direct injection system operate under the same principle, the components and its positions differ slightly while comparing passenger vehicles and heavy duty vehicles [8].

2.3.1 General operation

Pre-filtered fuel from the fuel tank is supplied to the high pressure pump by a pre-supply pump. The pre-supply pump in heavy duty vehicles, usually a gear-type pump, is often combined with the high pressure pump as a single unit unlike electric pre-supply pumps present in the fuel tanks of passenger cars. The primary objective of the high pressure pump is to maintain the pressures required in the fuel rail. The fuel rail channels the fuel to the injectors via short fuel lines which then inject the fuel into the combustion chamber. The injection timing and duration is controlled by the Engine Control Unit (ECU) based on numerous running parameters of the engine and driver input. Injection intervals and injector line pressures govern the amount of the fuel injected into the combustion chamber.

Figure 6: Common rail fuel system for heavy duty vehicles [8].

The pressure in the fuel rail is independent of the engine speed or the amount of fuel injected. The pressure in the fuel rail is maintained by pressure control valves (PCV) or is directly metered in the low pressure circuit of the system. The pressure control valves are usually connected to the fuel rail and releases high pressure fuel into the low pressure circuit to reduce rail pressures. Metering fuel in the low pressure circuit prevents the unnecessary working of the high pressure pump and pressurisation of the fuel in the
rail which is otherwise released by the pressure control valve into the return lines. This metering of fuel in the low pressure circuit reduces the thermal effects of pressurisation implying higher hydraulic efficiency in the system. Modern passenger car fuel systems pressurise the fuel in the range of 1600-1800 bar whereas heavy duty vehicles are capable of pressurising the fuel up to 2400 bars. The high pressure pump, the fuel accumulator and the injectors are the primary components of the common rail direct injection system differentiating it from other fuel systems [8].

2.3.2 High pressure pump

The high pressure pump is responsible for pressurising the fuel required for the efficient functioning of the system. It acts as a portal between the low pressure and high pressure circuits of the fuel. The high pressure fuel pumps are generally connected to the engine by a gear drive with a certain ratio. This constant ratio determines a proportional speed between the pump and the engine. The mechanical components in the high pressure pump require lubrication to prevent wear and contamination of the fuel. This lubrication is provided by the fuel itself or an external source which feeds oil to the required components. Heavy-duty commercial vehicles are generally lubricated by oil reducing the exposure of wear particles to fuel [9].

Numerous designs of high pressure pumps providing a wide range of pressure and flow rates are present in the market today. Radial piston pumps and in-line piston pumps are the most common types of high pressure pumps for heavy duty commercial vehicles [9].

![Exploded view of a radial piston pump.](image1)

![Schematic cross-sectional view of a radial piston pump.](image2)

Figure 7: Radial piston high pressure pump [9].
Radial piston pumps are high delivery pumps constituting of three pump chambers, offset from each other by $120^\circ$. Each pump chamber has a control volume and a plunger that moves along the axis of the chamber to compress and expand the volume in the chamber. An eccentric shaft coupled to a unit called an eccenter facilitates the upward and downward movement of the plunger. Figure 7a shows the exploded view of a radial piston pump and Figure 7b shows a schematic view of the cross section of a radial piston pump. Pre-supplied fuel with a pressure of $0.5 - 1.5$ bar is fed to the radial piston pump.

As the plunger moves down it performs an inlet stroke forcing fuel through the inlet valve into the chamber. Equilibrium of pressures between the pump chamber and inlet channel is achieved when the plunger exceeds the bottom dead center, compelling the intake valve to close. Fuel in the chamber is pressurised as the plunger is forced to move upwards by the eccentric shaft. The outlet valve is opened once the fuel in the chamber exceeds the pressure in the rail, passing the fuel to the high pressure circuit. Once equilibrium of pressures is achieved between the high pressure circuit and the pump chamber the outlet valve closes, until the pressure in the pump chamber is higher in the upcoming pressurising stroke. Three pump chambers feed the high pressure circuit with pressured fuel to maintain the requirements in the fuel rail [9].

In-line piston pumps are also high delivery pumps but have only two plungers that are placed in an inline orientation. These two plungers which are adjacent placed to each other are moved up and down by cam lobes which are attached to the drive shaft. The number of cam lobes and the drive ratio of the cam shaft may vary among manufacturers. Figure 8 shows a cross-sectional view of an in-line piston pump. The pump has an integrated low pressure pump connected to the camshaft with a high gear ratio to provide the high pressure pump with the fuel required at it its inlet. The in-line pump employs the same operating principle as the radial piston pump, providing high pressure fuel to the rail [9].

![Figure 8: An in-line piston high pressure pump](image-url)

The drive shafts of both the radial piston pump and the in-line pump are connected to the engine crankshaft by a gear drive. This ensures proportionality in the rotational speeds of the pump driveshaft and the engine. The drive ratio between the pump driveshaft and
the engine crankshaft is optimised to limit the quantity of pressurised fuel to the quantities required by the engine to be stored in the rail. However, since these pumps are built to deliver high quantities of fuel, the pump provides an excess of fuel to the rail at engine idle speed. This reduces the efficiency of the system as some energy is lost in pumping the fuel to the high pressure circuit to consequently be released back into the low pressure circuit. Another undesirable effect is increase of fuel temperature as a result of compression in the high pressure circuit followed by expansion in the low pressure circuit. A metering unit attached to the low pressure side of the pump can eliminate these undesirable effects by routing the fuel back to the low pressure circuit and supplying fuel based on the system demand [9].

2.3.3 Fuel rail or accumulator

The fuel rail is an accumulator or a storage unit for the pressurised fuel. Its primary function is to maintain the pressure of the fuel fed to it by the high pressure pump and to supply fuel to the injectors. The size of this accumulator plays an important role in its functionality. Pressure fluctuations as a result of the operating principle of the high pressure pumps can lead to oscillating pressures in the fuel rail. These oscillating pressures during injection intervals can lead to inconsistent injection volumes of fuel. The accumulator must be large enough to make these pressure fluctuations redundant. On the contrary, the accumulator should also be small enough to rapidly build the pressure requirements of the system. Simulations to obtain optimized sizes and shapes of fuel rails is a vital stage in its development [9].

Figure 9 shows a schematic view of the fuel rail and its components. The fuel rail is filled with fuel at all times. The pressure of the fuel rail, measured by the aid of a rail pressure sensor, is used to govern the pressure control valve. The pressure control valve opens and closes to release and build pressure in the fuel rail to meet the requirements of the system [9].

![Figure 9: Fuel rail and its components](image)

2.3.4 Fuel injectors

Contemporary fuel injectors are an integral part of the common rail injection system and its working principle has made it possible to employ them in the common rail system. The injectors on common rail diesel engines are attached to the head of the engine.
Short fuel supply lines from the rail provide high pressure fuel to the injector at constant pressure, independent of the engine speed and injected volumes. The injection opening and duration are governed by the fuel control unit with the aid of additional sensors [9].

Solenoid valve injectors or injectors with piezo actuators are used in electronically controlled fuel injection systems. Figure 10 shows the schematic, cross sectional view of a solenoid valve type injector. These injectors work on the principle of hydro-static equilibrium, depending on the imbalance of pressures to open and close the nozzle needle. Solenoid valves or piezo actuators facilitate the return flow of a certain volume of fuel creating an imbalance of pressure between the valve control chamber and the chamber volume in the injector. The direct actuation of the nozzle needle would demand high actuation forces which cannot be achieved by solenoid or piezo actuators [9].

2.4 Pressure fluctuations

Pressure fluctuations in high-pressure fuel systems are an inevitable phenomenon. The high pressure fuel pumps, due to their operating concept, are the primary sources of the fuel pressure fluctuations observed in the high pressure circuit of a fuel system. The consistent and powerful oscillations of the cavitation volume in the fuel injector, as a result of its construction geometry and operating principle also contribute to the pressure fluctuations in the high pressure circuit [20]. Though cavitation has ill effects on the fuel components, it also has some benefits. Sharp contours in geometry of the components, boosts the velocity of the fluid and shrinks the streamlines of the flow. This leads to the rise of vapor phase in the components, in regions where the flow is separated. The alternate growth and disintegration of the vapor phase produces the phenomenon of cavitation, leading to the birth of bubbles in the fuel. In the event of fuel injection, the explosion of bubbles helps in atomization of fuel [10]. However, the explosion of
bubbles inside the components of the fuel system can lead to erosion, noise and vibration. These negative effects can lead to physical damage to the structure of the components and contribute to pressure fluctuations in the system [21]. Figure 11 shows a schematic representation of cavitation in the injector nozzle.

Figure 11: Cavitation in the injector nozzle as a result of its geometry [10].

This pressure fluctuation can influence the quantity of fuel injected in a negative manner leading to a cyclic fluctuation in the quantity of fuel injected. The fluctuation of injected volumes is more significant in low load conditions where the injectors have short injection intervals. The spray tip penetration and spray angle of fuel from the injector into the combustion chamber is also affected. This affects the performance of the engine adversely as conditions deviate from the optimised injection conditions. Geometrical parameters such as pump cam profile of high pressure pump, length and diameter of pipes in the high pressure circuit, size and shape of fuel rail etc. govern the amplitude and frequency of the fluctuations in the high pressure fuel system [20].

2.5 Engine test cells

Engine test cells are special rooms or facilities housing sophisticated machines and instruments to evaluate performance of power-train and internal combustion engines. Development for numerous reasons such as fuel efficiency, cost reduction, design innovation, new technology and introduction of new materials in the components of the engine drives testing of engines in a controlled environment. Life expectancy and quality of the power-train is evaluated by manufacturers in full engine durability tests performed at such facilities. Additionally, restrictions imposed by current legislation require engine, power-train and vehicle developers and manufacturers to perform extensive testing and make the required modifications to conform to regulations. The controlled environments offered by test cells, provide data required for the observing the operation of the specimen and optimising its performance. High levels of accuracy and sensitivity is required by the components in the test cells to measure and produce credible data on the test events. Though the layout and capabilities of different test cells may differ, their primary objective is to provide data for the development of the specimen being tested [22].

Test cells can be used to perform evaluations on hybrid and electric vehicles, batteries, gearbox and transmissions, full power-trains and internal combustion engines. Though different test cells are designated for different purposes, all test cells are designed and constructed to act as a hazard containment box. The test cells are designed in this manner to protect the operators and employees in the test facility in case of a fire or gas
hazard. Operators of the test cell are seated in control rooms adjacent to the test cell. A glass window between the test cell and the control room aids the operators in observing the specimen and components in the test cell. Figure 12 shows adjacent test cells with a common control corridor. The test cells can be accessed by the operators from the front door. The rear doors offer access to the specimen being tested. Additionally, the test facility generally includes a storage area for support equipment and a support workshop.

![Schematic layout of a test facility with a common control corridor](image)

**Figure 12:** Schematic layout of a test facility with a common control corridor.

Test cells used for evaluating internal combustion engines require a supply of fuel and lubricating oil. Fuel storage in test facilities is an important factor which should not be neglected as they are capable of causing significant damage to property and personnel. Stringent regulations for the storage of volatile and gaseous fuels are present to prevent such catastrophes. Generally, fuel lines are placed above ground in regions least susceptible to damage. Test facilities with secure perimeters have fuel tanks above the ground. Placement of fuel tanks and fuel lines above the ground aids in easy detection of leaks in case of damage. Day tanks which store fuel required for a single test or series of tests are placed outside the test cell.

Ventilation and conditioning of the air inside the test cell is essential to maintain an acceptable environment in the test cell. Cooling water required for maintaining engine temperature must be provided to the test cell. Additional electric power should also be provided to ensure the functioning of auxiliary components required by the engine. Oxygen required for combustion in the engine is provided by air, either from the ventilation system of the test cell or an externally conditioning unit. Air properties such as pressure, temperature and humidity can affect the engine adversely and hence it is essential to provide conditioned air to the engine.

Dynamometers are an essential component in test cells. Engine and power-train test cells require dynamometers for evaluating the torque produced by the specimen. The measured torque is used to calculate the power characteristics of the specimen. Dynamometers used in engine or power-train test cells are directly coupled to the specimen. There are numerous types of dynamometers in a wide range of sizes which are used in different scenarios according to the setup of the test cell. To obtain credible and reliable
results it is essential to match the torque absorbing characteristics of the dynamometer to the torque producing characteristics of the specimen [24].

3 Discussions

The literature review performed in the previous section offers knowledge in the required areas, aiding in the development of the project. The knowledge acquired along with numerous meetings and discussions with personnel working in areas related to this project, helped in making advances in this project. This section involves the information acquired through meetings and reports directly linked with the development of single cylinder test cells.

3.1 Single cylinder test cell

A single cylinder engine offers numerous benefits over multi-cylinder engines while testing for combustion properties of an engine or a fuel. A single cylinder engine despite its compact size can provide information on the combustion properties which can be projected to deduce the combustion properties of multi cylinder engines. The single cylinder engine makes evaluation of combustion behaviour easier as there is no interference from other combustion pulses in the exhaust or inlet manifolds. A multi cylinder engine is often tuned for certain engine load or speed and that tuning can interfere with the ideal combustion behaviour making the evaluation more complicated [5]. The compact size of the engine reduces the requirements and the number of components needed for its functioning. The amount of resources such as fuel required for testing is significantly lower, impacting the economic figures of testing in a positive manner. The decreased requirement of fuel needed for testing makes single cylinder testing appropriate for testing the combustion properties of new fuels [3].

Albeit the observations made in the combustion properties of a single cylinder engine can be extrapolated to obtain information in multi-cylinder engines, there are few factors which cannot be duplicated and should be taken into consideration. The pulsating phenomenon of air in the exhaust and intake manifold is one of the prominent behaviours which cannot be replicated in the single cylinder engine’s gas exchange system. The single cylinder engine has more friction per cylinder than a multi-cylinder engine, making the internal friction losses, between a single cylinder engine and a multi-cylinder engine, an incomparable parameter [5].

3.1.1 Engine specifications

Since this project is designated to be developed for Scania engines it is essential to duplicate the conditions present in the OEM engine. This requirement will play an important role in the development of the single cylinder research engine. The single cylinder research engine is based on Scania’s latest five and six cylinder in-line ED95 engines [3]. The single cylinder engine will require a custom-built engine block with specifications identical to the OEM engine to accommodate the crankshaft and the piston. A shortened single cylinder specific crankshaft is required to be developed along with a connecting rod. The connecting rod should be built to accommodate the OEM piston which will be used
in the research engine. A standard mono-cylinder head used in Scania’s ED95 engines will be mounted on the custom engine block. Adaptations required for accommodating the shortened camshafts should be made to the cylinder head. An additional modification for the placement of a pressure sensor to measure cylinder pressure will be required in the cylinder head. It is essential to have a flush mounted pressure sensor to prevent alterations to the compression ratio and air flow in the combustion chamber. The OEM engines are direct injected, turbocharged engines. Single cylinder test cells at AVL have supercharged air to meet the requirements of the research engines. Hence an exhaust back pressure valve should be introduced in the exhaust manifold of the research engine to simulate the back pressure generated by the turbocharger [5]. Figure 13 shows a single cylinder research engine developed for testing at AVL.

![Figure 13: Single cylinder research engine at AVL [5].](image)

### 3.1.2 Dynamometer

A dynamometer is required to provide torque to the single cylinder research engine to simulate different loading conditions experienced in real time running of the engine. The single cylinder engine will be coupled to the dynamometer via a propeller shaft. In order to determine the torque in the system, a calibrated torque flange mounted between the dynamometer and the propeller shaft will be used. A Leroy Somer DC current dynamometer, previously used in single cylinder testing at AVL, will be used in the newly developed test cell [5]. Table 4 shows the specification of the Leroy Somer DC current dynamometer.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Torque</td>
<td>500 Nm</td>
<td>0-1850 RPM</td>
</tr>
<tr>
<td>Max. Power</td>
<td>100 kW</td>
<td>1850-4000 RPM</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>4000 RPM</td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>0-500 Nm</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>±1,2 Nm</td>
<td></td>
</tr>
</tbody>
</table>
3.1.3 High pressure fuel system in the test cell

This thesis, being a continuation of another thesis, adopts the high pressure fuel system developed in the previous thesis. However, the development of the high pressure fuel system in previous thesis was only in its initial stages, providing an outline to the components that are accommodated in the fuel system. Figure 14 shows an outline of the components and fuel lines in the fuel system of the test cell.

![Flow chart of the fuel system with the components and fuel lines](image)

This project, being directly linked to the Scania engine, will require original equipment manufacturer (OEM) components to evaluate the performance of the alternative ED95 formulations. Hence it is necessary to accommodate the high pressure pump, the fuel rail and the injectors from the Scania XPI system [3]. An electric low pressure pump supplies fuel to the high pressure pump from the fuel tank. The low pressure pump generates the inlet pressure required for the efficient functioning of the high pressure pump. A pressure limiting valve releases pressure of the inlet pressure circuit in occasions when the pressure in the inlet circuit exceeds the recommended value. The pressurised fuel from the high pressure pump is conveyed to the fuel rail and eventually to the fuel injector via the high pressure circuit. Return flows from the high pressure pump, fuel rail and the injectors are directed to the low pressure circuit which is then recirculated to the low pressure pump or the fuel tank. In situations when the pressure in the low pressure circuit exceeds the recommended value, another pressure limiting releases the pressure of the circuit, ensuring appropriate functioning of the components. A drainage valve present in the low pressure circuit aids in flushing the system during change of test fuels [12]. An AVL PR3 pressure factory acts as the fuel tank in the test cell. This device, installed as close as possible to the engine can adjust the fuel feed pressure to the low pressure pump and the fuel return from the engine close to zero bar, simulating the conditions imposed by a fuel tank in a vehicle [26].

3.2 Scania’s XPI system

The XPI System developed in collaboration with Cummins is an advanced fuel system providing significantly high pressures compared to other common rail fuel systems. The system with its advanced fuel pump and injectors, function at pressures required for the operation compression ignition (CI) engines [12]. These high pressures supplied by the XPI system provides new opportunities in the development of CI engines operating on alcohol-based fuels. Additionally, this broadens the spectrum of possible fuels that can be
used in such CI engines [17]. The XPI system being the OEM fuel system in heavy duty Scania’s five and six cylinder in-line engines should be implemented in the single cylinder research engine. It is imperative to duplicate the injection conditions imposed by the fuel system in Scania engines to the conditions established in the single cylinder research engine. This is necessary to obtain a credible evaluation of the new ED95 formulations and obtain comparable combustion parameters such as combustion speed, ignition quality and ignition delay. Figure 15 shows the XPI system in Scania’s heavy duty engines.

Figure 15: Schematic representation of the XPI system present in Scania’s engines [12].

Data on Scania’s advanced XPI pump and injector developed in collaboration with Cummins is confidential and information on these products are not available. However, these components are advanced versions of models developed by Cummins. The common rail fuel pump and injector used in Scania engines are the developed version of the Cummins XPI OLP3 pump and CRFI5 injectors. The two-cylinder, oil lubricated pump is capable of generating a rail pressure of 2600 bar [13]. A 1:1 connection to the crankshaft of the engine via a gear drive provides the pump with the power required for its operation. The fuel feed pressure required for the operation of the high pressure pump is provided by a mechanical gear type, low pressure pump. The low pressure pump requires an inlet pressure of 5-15 bar, which is provided by the electrical pump at the fuel tank [12]. An inlet metering valve ensures that the pump is fed with only the required amounts of fuel to prevent unnecessary pressurisation of fuel. The electronically controlled fuel injectors are developed to operate at the high pressures provided by the system. Scania’s fuel management system governs the injection times and injection quantities based on numerous parameters. The return fuel from the injector and pressure accumulator is conveyed to a return rail in the system [3]. This return circuit from the pump and the injector requires a pressure below 1 bar for its operation [12]. The return rail functions as an expansion chamber to ensure that the conditions required in the return circuit are satisfied. Figure 16 shows the Cummins pump and injector which serve as base components in the XPI system.
3.3 Pressure fluctuations

Pressure fluctuations in the fuel system play an important role in combustion and performance of the engine. Significant research and development is carried by manufacturers to ensure the fuel system provides consistent conditions for combustion in the engine. It is vital that the conditions established by the XPI system and the effect of pressure fluctuations in Scania’s full sized-engine is replicated in the single cylinder research engine. Identical injection quantities and behaviour assures that the combustion evaluation will be performed in desirable conditions and will provide credible results.

To replicate the pressure fluctuations in the single cylinder research engine a deeper understanding of the pressure fluctuations in the full-sized engines was required. Testing of fuel systems by manufacturers is confidential and intricate details on properties such as pressure fluctuation is not available. AVL Gmbh, headquartered in Graz, being pioneers in the development, simulation and testing of power-trains were able to offer assistance in this matter. A thorough discussion with G. Heimel, a technical expert in fuel injection, provided insight on the pressure fluctuations in a fuel system. Detailed testing carried out in AVL Graz showed that injection delays can have significant effect on fuel quantities as a result of pressure fluctuations [27]. Full load tests at 1200RPM were performed to study the effect of pressure fluctuations and cycle variations in fuelling with injection delay. The tests performed on a six-cylinder heavy duty engine with a two cylinder high pressure pump recorded pressures in the fuel line on the injector side as well as on the pump side of the system. The pressures were recorded with extremely responsive pressure sensors placed in close proximity to the pump and injector, which recorded values every 0.1° rotation of the crankshaft [14]. Figure 17 shows information specific to a single cylinder and its corresponding injector over 360° of crank rotation.

Figure 17 provides data on the current supplied to the injector, the pressure in the fuel line close to the injector being studied and pump torque of the high pressure pump providing the fuel system with the required pressure. A high current is required for initially opening the injector and approximately half the magnitude of current is required to ensure the injector remains open. Since the high pressure pump has two cylinders with a three lobed cam actuating the piston in each cylinder, there are six pumping events for every 360° of crank rotation. The pump torque indicates the torque required for each pumping event.
The rise in pressure in the fuel line as observed in the graph is a result of the pumping event and the drop in pressure is a consequence of injection events. The six-cylinder engine has six injection events over two complete rotations of the crankshaft, corresponding to one injection event from each injector every 120° of crank rotation. Results obtained from the test show that a cyclic pressure fluctuation repeating every 120° of crank rotation is present on the injector side and the pump side of the fuel line [27]. The cyclic pressure fluctuation on the injector side can be observed in Figure 17. The maximum deviation between the maximum pressure and the minimum pressure on the pump side was double the maximum deviation in the injector side [27]. In the test performed, the pressure sensor is placed in the fuel line of the injector responsible for the third injection event in Figure 17. Injection events from other injectors lead to a drop in pressure in the line being observed but did not induce any pressure oscillations in the line. The fuel accumulator plays an important role in dissociating the pressure waves, as a result of injection events, between the injector side and the pump side and also between the different injector lines in the system. The oscillations caused as a result of the injection event lasts only for an inconsiderable amount of time, only in the line corresponding the injection event. The pressure fluctuations resume to follow its cyclic variation before the next injection event, ensuring that identical pressure values are obtained in all injector lines of the system. This guarantees that the fuelling will remain consistent and will not be affected by the oscillations caused by injection events.

4 Design considerations

The XPI system designed to provide fuel to full-size heavy-duty engines has a high fuel flow rate. Adaptations and modifications will be required to integrate the XPI system to the single cylinder research engine as flow rates provided by the XPI system is significantly
higher than the demands prescribed by the single cylinder research engine. The XPI system will require the inlet metering unit to meter a majority of the inlet fuel and will provide the minimum required fuel for the operation of the high pressure pump. However, this would still provide the system with a high fuel flow rate and demand the pressure control valve in the fuel accumulator to dump the excess fuel to the return rail. To prevent the unnecessary pressurization of fuel, leading to the rise of fuel temperatures in the system, adaptations are required to be implemented in the high pressure pump. Disabling one of the pistons of the two-piston pump is a viable option to reduce the flow rate of the pump. This will provide the system with a flow which is pragmatic and will reduce the fuel metered by the inlet metering unit. Adaptations will also be required to prevent the flow of fuel to the disabled cylinder of the high pressure pump [3]. Additionally, based on input from the manufacturer, the high pressure pump will be able provide fuel pressures up to 3500bar with some modifications [12]. This could be beneficial for the combustion evaluation of the alternative fuel formulations.

To mimic the cyclic pressure fluctuations present in Scania’s full sized engine’s fuel system, it is necessary to employ the same system and include all the components present in the XPI system [27]. Initially, it was decided to modify the fuel rail to accommodate the attachment of the input line from the high pressure pump and provide an output line for one injector that will be attached to the single cylinder engine. Information obtained from the tests performed on the evaluations of pressure fluctuations and discussions with fuel injection technical expert, G. Heimel, implied that modifications on fuel rail and removal of output lines to the injectors can have detrimental effects in the duplication of the cyclic pressure fluctuations. As a result, it is necessary to include the complete rail with all the lines to the numerous injectors to ensure that the pressure fluctuations are mimicked in the single cylinder research engine [27]. The removal of one piston from the high pressure pump will reduce the frequency of the cyclic pressure fluctuations by half, while having no effect on the behaviour of the pressure increments as a result of pumping events. It is crucial to eliminate the right piston and ensure a right synchronization is obtained between the pump and the crankshaft in order to obtain a pumping event just before an injection event as seen in Figure [17].

Albeit the entire XPI system is required to replicate the pressure fluctuations, it is advantageous to eliminate the injectors which do not supply fuel to the single cylinder research engine. This can be beneficial economically as well in terms of fuel measurement. The elimination of one piston in the high pressure pump halves the number of injection events required to maintain the cyclic pressure fluctuations i.e. one injection in the single cylinder engine and two additional injections to maintain the pressure fluctuations. The two additional injections can be simulated by the discharge of identical quantities of fuel by the pressure control valve in the fuel accumulator to the return rail of the XPI system. Additionally, clamps provided to aid in the fastening of the different fuel lines to and from the pump and the rail cannot be omitted and must be located in points recommended by the manufacturer. Based on information logged in test cell reports at AVL, failure to do so has resulted in damage in the fuel lines as a result of vibrations from the engine [28]. Hence, the entire XPI system devoid of the redundant fuel injectors is required to be implemented in the single cylinder engine to duplicate the conditions in a full engine and obtain credible results in the combustion evaluation.

The powering of the pump via a 1:1 gear connection to the crankshaft can be replaced
by an electric motor to offer more freedom in varying the operating speeds of the pump. This can aid in studying the effects of operation speed on the pressure fluctuations by observing the combustion parameters and can also be employed to obtain an ideal fuel flow rate for testing in the single cylinder engine. However, the addition of another component to facilitate the operation of the pump can increase the complexity of the system and increase the costs of the project. Since the primary focus is to obtain the same conditions in the full sized engines and not to study the effect of varying running conditions of the high pressure pump, it is plausible to power the high pressure pump via a gear connection to the crankshaft. Additionally, the risk of error during testing requiring a re-run of the test makes the powering of the high pressure pump by an electric motor undesirable.

Scania’s fuel management system is required for the operation of the fuel system according to the conditions required by the OEM. However, if it is not possible to obtain this management system, an ECU programmed to provide the same injection parameters as the OEM will be required to perform the combustion evaluation.

5 Conclusions and future work

This thesis aimed at providing a high pressure fuel delivery system for a single cylinder, test cell engine to perform the combustion evaluations required for the development of the alternative ED95 fuel formulations. The project being a continuation of a previous thesis focused on the integration of a system to pressurize fuel for the functioning of a single cylinder test cell engine. Critical properties in the fuel system to provide optimum conditions required for the operation of the single cylinder research engine were analysed.

Recommendations for the implementation of a high pressure fuel system was established based on the information acquired through literature review, discussions with company personnel and meetings with technical experts at AVL. The literature review section offered information on Ethanol Diesel (ED95), fuel systems in heavy duty commercial vehicles, pressure fluctuations in high pressure fuel systems and engine testing in controlled test facilities. The discussions section addressed matters directly linked with this project and factors which play an important role in obtaining credible results. The design considerations section gives recommendations for the set-up of the high pressure fuel system and the adaptations required to ensure it’s efficient functioning.

Based on knowledge obtained, a complete XPI heavy duty fuel system is recommended to be integrated in the single cylinder research engine to obtain conditions identical to the Scania’s full sized ED95 engine. Modifications are required to be made to the high pressure fuel pump to provide appropriate fuel flow rates required for the single cylinder research engine. Information obtained on pressure fluctuations in identical systems offers clarity regarding potential issues that can arise as a consequence of integrating the XPI heavy duty fuel system, designated for a full sized engine, into a single cylinder research engine. Justification for powering the high pressure fuel pump by the crankshaft is included. The recommendations and information included in this thesis coupled with the information provided in the previous theses sets the foundation for reconstruction of the single cylinder test cell.
Although recommendations for the set-up and reconstruction of the single cylinder test cell are mentioned, further investigation and adaptations can be made after the construction of the test cell to improve its competence and credibility. It is vital to scrutinize the pressure fluctuations in the system and compare it to observations made in Scania’s full size ED95 engines to ensure correlation between the two systems. The pressure control valve’s capability to discharge fuel, to simulate injection events, should be evaluated and an alternate relief valve must be accommodated in case of unsatisfactory performance. Investigating the effect on pressure fluctuations as a result of eliminating components from the XPI system, such as redundant injector lines, can aid in minimizing the components required in the system. In the future it might be beneficial to couple the high pressure pump to a electric motor to study the effect of different operating speed of the pump.
Bibliography


