Norway grants

Ammonia as carbon free fuel for internal CombusTion engIne driVen AgriculTural vEhicle

Work Package 1
Deliverable Report

David Emberson (NTNU)
david.r.emberson@ntnu.no

Topic: D1.1

Injection system details, first non-optimized engine results with NH3 as a fuel

Work Package 1 leader	**Project Promoter**
David Emberson	Wojciech Adamczyk
Date	Date ....

Programme operated by: The National Centre for Research and Development

Project consortium: Silesian University of Technology, NTNU Norwegian University of Science and Technology, LOGE, University of Agriculture in Krakow

07.07.2021

1 Injection system Report

1.1 Introduction

The ACTIVATE NTNU engine will operate with a pilot diesel fuel, injected using a common rail system, detailed in the milestone report. Primary fueling of the engine is by a direct injection of liquid ammonia. The deliverable report outlines the details of the injection system produced to meet this requirement.

1.1.1 Handling ammonia for injection

One of the main outcomes of ACTIVATE is the successful operation of a compression ignition engine using liquid ammonia injections as the primary fuel. To achieve the injection and formation of a spray in the engine combustion chamber, injection must occur at high pressure. For this project, the ammonia is being used from a pressure vessel (ammonia bottle, or ammonia tank), with liquid ammonia stored at room temperature at around 8-10 bar pressure. This option is chosen as it seems the most likely to be used on an agricultural vehicle as opposed to cold storage in a vessel at -34 °C. While diesel injectors have increased in operation to very high pressures, over 1000 bar, gasoline injection has also moved from quite low pressure, port injection to high pressure direct injection (GDI). Over recent years the pressure of these systems has increased and is now operating in the 200-300 bar range. Initially, a decision needed to be made to choose the type of injection system to be used for the liquid ammonia. This was relatively simple- as a direct injector was required.

1.1.2 Injector choice

A direct injector is one in which the needle (that moves up and down to open the nozzle holes to allow fuel flow) is moved directly by the electrical actuator, either a solenoid or a piezo crystal. In most diesel, common rail type injectors, the needle motion is achieved by the hydraulic pressure of the fuel in a small control volume inside the injector, which is controlled by the motion of small needle valve which are controlled by the electrical actuator. This type of design necessitates a small volume of fuel to flow from the control volume and leaves the injector at low pressure and is termed return fuel, as it returns, unused to the fuel tank. For normal liquid fuels this is not a problem, but for ammonia in a liquid state, the drop in pressure associated with the fuel return would mean that the ammonia changes state, from liquid to gas. To return the ammonia to the tank would require a compressor.

GDI injectors are generally direct injecting, with no return fuel flow rate. Hence a the decision to use a GDI injector was made. This then has a cascade effect in terms of decision making. The injection pressure was then know to be in the range of 200-300 bar max, so a target upper pressure of the system is determined. This pressure range then lead to the choice pumps, pipes and connections.

1.1.3 Pump choice

Based upon experience over previous years of engine and fuel testing in an academic environment, it was known that the choice of pump is critical. Although these are generally off the shelf items, in a lab environment they are often being used outside of their design envelope, mainly by pumping fluids that they are not always intended for. Also, they can go for long periods of inactivity in between campaigns, rarely have a regular serving schedule and can lead quite short but hard lives. Having a stoppage of an experiment that has taken some time to setup due to a pump issue is an extremely frustrating and ultimately time consuming experience. The decision was made early on to choose the pump wisely, or if possible remove the pump from the system.

The system must provide highly predictable injections, with little variation between injections, provide liquid ammonia at around 200bar, and operate for long enough that the engine can be operated at a number of operational points and conditions for long enough to reach a stable measurement point.

Based upon previous designs employed elsewhere, a system was decided upon that does away the pump completely, and uses high pressure gas to pressurize the system, essentially removing all moving parts (only vales) and providing a stable system for experiments. Fuel lubricity, pump surface wear, pump sealing, pump power, pump vapour lock- all of these issues were solved on one go by the system choice. Flow rate is essentially limited by the pressure of the system, (and pipe diameters) while running time would be limited by the size of the pressure vessel used to pressurize the ammonia in.

The choice of 200 bar injection allowed for the use of Swagelok parts, which further simplified the process, as the team at NTNU building the system has many year experience using Swagelok parts.

1.1.4 System design

At the outset, safety and flexibility were a goal. Hence the design was initially intended to be a form of ”skid” with the majority of the system on a euro pallet, in an enclosure, which could be easily moved from rig to rig or across institutes. The system design is shown Fig.1 with the parts used in the system detailed in Table.1

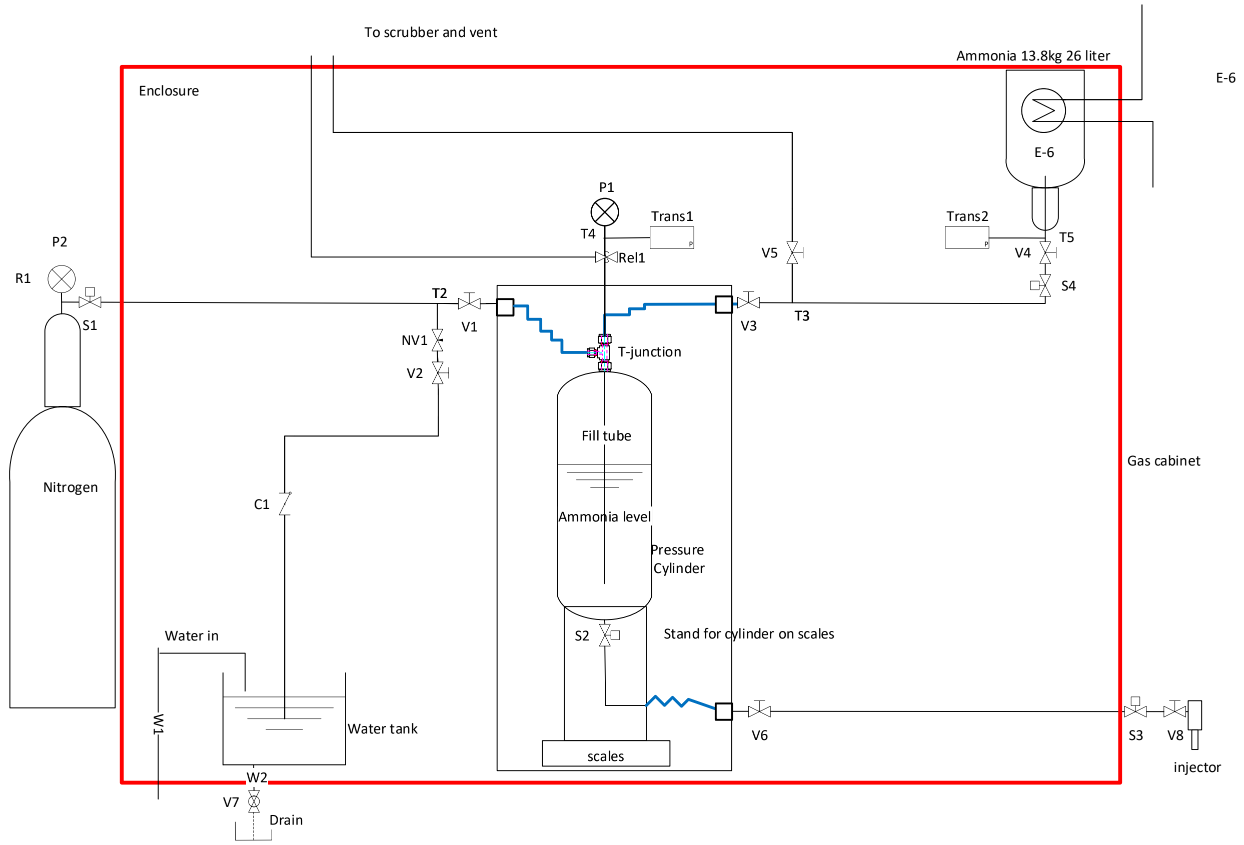

Figure 1: Scheme of fuel injection system for ammonia injection liquids, parts in Table.1

Table 1: Table of injection system parts

Scheme Number of parts	Description	Part number, supplier etc.
R1	Regulator	AGA Pro 300 bar,
P2	General Purpose Gauge, B Series, swagelok 6mm, 400bar	PGI-63B-BG400-L-ASX
W1, W2, SV1, DV1	Pressure Ball Valve Stainless Steel	RS Stock No. 764-4256
T-Junction	Bore thru male run tee, 6mm OD x 1/4” NPT BT	SS-6M0-3-4TMTBT
T2, T3, T4, T5	Stainless Steel Swagelok Tube Fitting, Union Tee, 6 mm Tube OD	SS-6M0-3
Rel1	High-Pressure Valves (R3A, Ethylene propylene -EP Spring kit (206 to 275), white	SS-6R3A-MM-EP Spring kit 177-R3A-K1-F
S1, S2, S3, S5	Stainless Steel 1-Piece 40G Series Ball Valve, 1.4 Cv, 6 mm Swagelok Tube Fitting	SS-43GS6MM
	Actuator-5519871	5519871
	End switch 24v -5520891	5520891
NV1	SP Needle Valve GU-Series, 1/4” NPT,Anti Tamper , Male Connector, 6 mm Tube OD x 1/4 in. M	SS-4GUF4-AT
	Male Connector 6 mm Tube OD x 1/4 in. M	SS-6M0-1-4
C1	Check valve, Stainless Steel Poppet 6000 psig (413 bar) Check Valve, 6 mm Swagelok Tube Fitting, 1 psig (0.07 bar)	SS-CHS6MM-EP-1
V1-V9	Stainless Steel 1-Piece 40G Series Ball Valve, 1.4 Cv, 6 mm Swagelok Tube Fitting	SS-43GS6MM
Pressure cylinder	316L SS Double-Ended DOT- 1/4” FNPT	316L-50DF4-500
Hose	SM6- 6mm Swagelok tube fitting, 213 bar metal hose FM series	SS-FM 4 SM6 60CM SS-FM 4 SM6 100CM
tube	316/316L Stainless Steel Seamless Tubing, 6 mm OD x 1.0 mm Wall x 6 Meters	SS-T6M-S-1.0M-6ME
Water pump	Xylem Flojet Diaphragm Electric Operated Positive Displacement Pump, 19L/min, 3.1 bar, 12 V dc	RS Stock No. 667-9093
Trans 1, Trans 2	Pressure Transducer	

1.2 System description and operation

The system works by first purging the system of all air, to remove all water vapor. The high pressure sample cylinder (HPS) is then filled with liquid ammonia from the ammonia tank. When full, the nitrogen bottle is then opened and the nitrogen is used to pressurize the ammonia in the HPS, via a bored though T section in the top of the HPS cylinder. Pressure in HPS cylinder, as well as ammonia mass are measured. High pressure ammonia then flows out of the bottom of the cylinder to the injector. To fill the cylinder with ammonia, the gas in the cylinder must be vented, this is achieved through a needle valve and water trap, to remove any ammonia present.

The system is to be operated as follows:

- The system is first purged with nitrogen at low pressure, with all valves open apart from V4 on the ammonia tank.
- The fuel injector is also removed or at least the connection is loosed to allow nitrogen through that portion of the system. The purge is stopped, and all valves closed.
- Check valve closure in this order, V1- V2- V3- V4 -V5 - V6 - V8
- Check emergency shut-off circuit by opening S1, S2, S3 and S4 and then depressing the emergency shut off button, re-open S valves after test.
- Turn on scales that measure mass in HPS cylinder. Start-up procedure:
- Check gas alarms are working and check gas levels.
- Check closure of injection rig cabinet, switch on local hand heled NH3 detectors.
- Recharge procedure
  1. Switch on local water system, W1 and W2 through V7
  2. Open V4, V3
  3. Open V1 and V2
  4. Controlled venting of top gas (see recharge in attachment) form HPS through NV1
  5. Ensure liquid flow of ammonia, Open water circuit E6 (25°C max)
  6. When desired mass is reached close NV1, V2 and V1 and E6 circuit.
  7. Close V4 and V3, open V5.
  8. Leave HPS for 10mins until temperature is stable.
- Pressurise system- Open R1 to system pressure of 10bar. Open V1, V6 and V8- ammonia vapour in fuel injection line will condense under pressure to liquid as pressure R1 is increased. Increase nitrogen pressure incrementally until desired injection pressure is reached. Check fuel injector is sealing correctly visually. If suspected leak of seal fail, shut of nitrogen and close V8.
- Injection system is now ready to use for injection experiments.

Safety shut off is achieved by air operator actuators, which are electrically controlled connected to a number of emergency buttons around the lab. Upon pressing of the button, the valve is closed and ammonia flow is stopped.

1.3 System production

As the technical staff actually started to construct the rig the design changed somewhat. It is envisaged that in the second iteration, the design points and operational points learnt here will be applied to a more modular, palletised version.

A large, heavy platform to hold the pressure HPS and scales, to avoid vibrations in the mass measurement was added. The enclosed volume was shrunk, with the ammonia tank now external. An aluminum cabinet has been made to house the ammonia tank, with a flexible extraction hood system placed over the cabinet. After some experimentation which required the filling of a small pressure vessel with liquid ammonia, it was found that the tank would not require any assistance to make the ammonia flow to the HPS, a tank fitted with a dip tube will work very well The water tank for the venting is also external to the enclosure. It was found that the flexible Swagelok hoses added too much tension when coiled and the scales would not have worked, so they were replaced with length of 3mm tube coiled to provide a spring type tube connection, this has found to work well with the scales.

The system so far has been pressurised and tested with water, up to 240 bar. The system cannot yet be tested with ammonia until the labs ventilation and control systems are complete. The completed system is shown in Fig.2

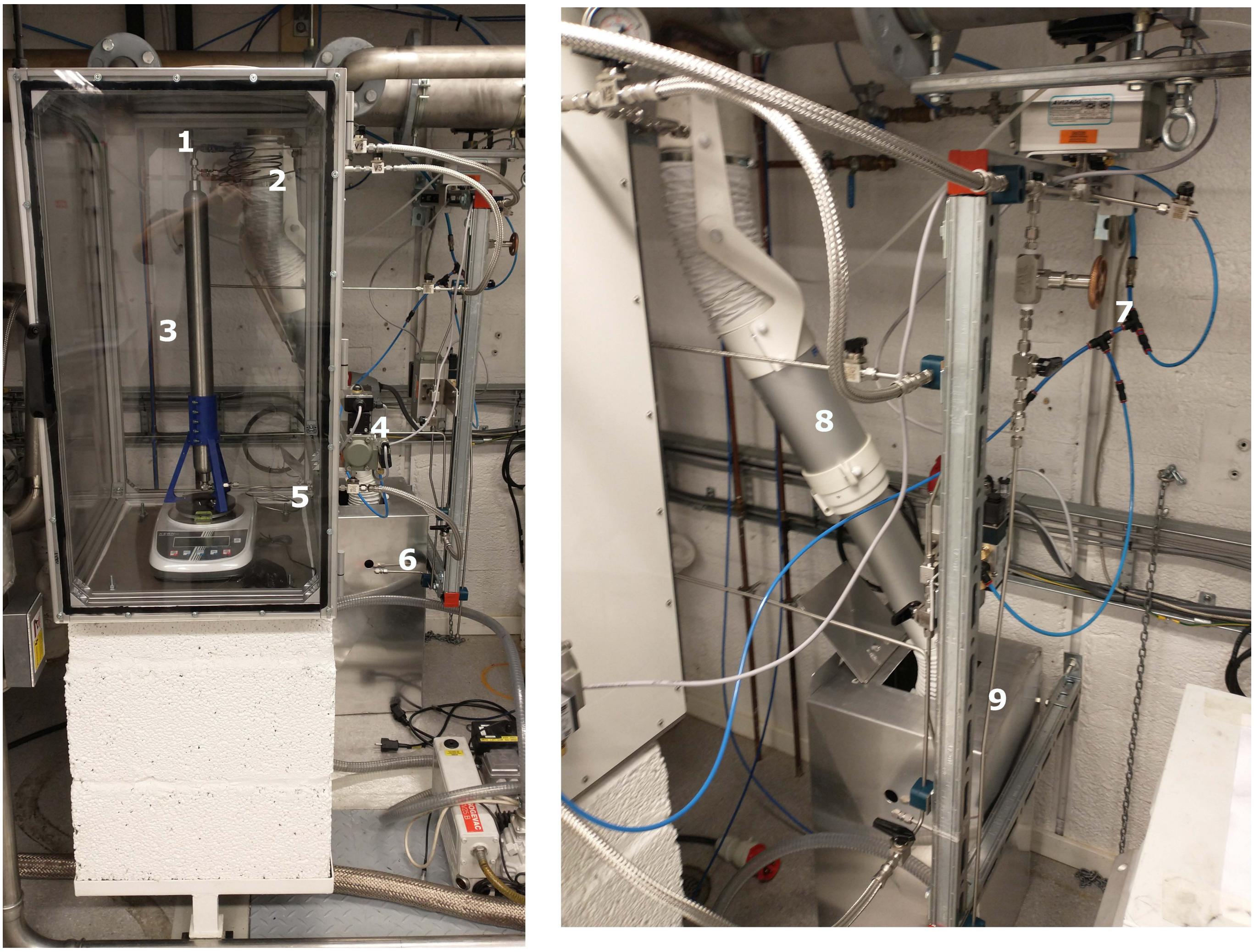

Figure 2: Fuel injection system. Left hand side-enclosure with high pressure ammonia cylinder, right hand side, exterior of the enclosure, with supporting pipe work an, venting control and ammonia fuel tank cabinet and extraction hood. Parts: 1 Nitrogen and ammonia inlet through bored though T section; 2. Ammonia coiled line input ; 3 High pressure cylinder; 4 High pressure put to injector safety shut off solenoid; 5 High pressure injection coiled line to injector; 6. Ammonia line from ammonia tank; 7 Needle valve control for venting cylinder; 8 Extraction to room exhaust; 9 Aluminum cabinet for ammonia fuel tank.