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AMMONIA AS CARBON FREE FUEL FOR INTERNAL COMBUSTION ENGINE DRIVEN AGRICULTURAL VEHICLE

Work Package 1
Deliverable Report

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Topic: D1.3

REPORT ON ACTIVITIES UNDERTAKEN IN WP1

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Introduction

A summary of all activities in ACTIVATE WP1 is reported in this report. The report is structured as a summary of all Milestone and Deliverable reports delivered. The reports are listed in chronological order.

Milestone Report 1.1 - Instrumented engine equipped with ammonia injection system, running and ready for optimization

A highly instrumented single-cylinder engine has been constructed for the development of an agricultural vehicle in the ACTIVATE project. The engine has been modified to accommodate a diesel common rail injector (DI) and a gasoline direct injection injector (GDI). It is installed on a test trolley with a shaft coupling to an AC motor acting as a dynamometer. The air intake system allows for accurate measurement of air mass flow rate, compression, and heating. The engine exhaust is equipped with a particulate analyzer and a gaseous emissions analyzer. This engine will serve as the core component for a testing campaign focused on optimizing the operation of a diesel-ammonia liquid direct injection engine. The report provides a detailed description of the engine, intake system, test trolley, and instrumentation, while a separate deliverable report covers the injection system for liquid ammonia.

The engine is designed to operate using a pilot injection of diesel fuel followed by a main injection of liquid ammonia. Two separate injectors were installed in the engine cylinder head to accommodate this injection strategy. The engine's original design, which used mechanical jerk-type injectors, did not provide control over the timing of the diesel injection. Therefore, modifications were made to enable precise control of the diesel injection, similar to modern diesel engines. The specific engine used is the Hatz 1B30, a single-cylinder engine commonly used in applications such as small generators, pumps, and compressors.

The chosen engine, Hatz 1B30, offers several advantages for the project. Its compact size closely resembles the engine used in the agricultural vehicle being developed. This smaller engine size is beneficial as it reduces the amount of ammonia required for testing, minimizing risks associated with handling larger quantities of ammonia in the lab. The engine's high compression ratio makes it well-suited for igniting ammonia, and its robust design ensures durability during testing. With a camshaft-operated two-valve configuration, the engine's simplicity facilitated the necessary modifications. Notably, the engine head had an unfinished cast feature, a hole at an angle of approximately 32 degrees, that appeared suitable to accommodate an injector for liquid ammonia. By selecting the appropriate liquid ammonia injector and machining the cast feature, it could be utilized for ammonia injection. On the other hand, the diesel injection would be accomplished by installing a standard common rail injector with minor modifications to fit it into the original injector's hole.

The selection of injectors for the engine modification followed a straightforward process. Since a direct-acting injector was required for liquid ammonia, a gasoline direct injector (GDI) was chosen. The target injection pressure of 200-250 bar further narrowed down the options to the Bosch HDEV5 series injectors. Among the available options, a long body type was selected for ease of fitting. An existing injector that could be modified was chosen for the diesel injector. The selected injectors are the Bosch GDI injector (part number: 0 261 500 063) and the Common Rail injector (Bosch 0445110 202). To install the GDI injector, the unfinished hole in the engine head was machined according to the requirements specified in ISO 22561, which provides guidelines for installing injectors in gasoline engines with direct fuel injection. This standard specifies the bore size, tolerances, and the use of a small sealing ring near the nozzle end to ensure adequate sealing of the GDI injector. The standard also provides recommendations for clamping the injector into position.

The common rail diesel injection system consists of an automotive common rail pump driven by an AC motor and is installed on a trolley. The trolley includes a common rail with a pressure sensor and a pressure control valve (PCV) solenoid valve to regulate the pressure. The fuel tank, made of a glass beaker on a set of scales, measures the mass of fuel used over time. Fuel is pumped from the tank to the high-pressure pump using a low-pressure 12V pump. The high-pressure pump pressurizes the fuel to the rail, and any unused fuel is returned to the tank. The PCV controls the pressure in the rail, which releases excess fuel. The rail pressure is measured by a sensor and regulated by an Arduino connected to a solid-state relay. Unused fuel from the rail and injector is passed through a heat exchanger before returning to the tank. The fuel mass flow is determined by the balance of fuel flowing out of the tank and return fuel flowing into the tank, which is measured by the scales. The scales are placed on a heavy steel plate with rubber feet to minimize vibrations. An Arduino controls the PCV and communicates with a computer running LabView software to log various parameters. Injection control is achieved using an NI 9751 module, and the system is designed for autonomous operation. Once the trolley is powered and the pump is running, the pressure is set by adjusting the pump speed and the PCV duty cycle.

The intake system includes a large wooden air box with an orifice plate and a manometer to measure the air-flow rate into the engine. The purpose of the air box is to dampen flow fluctuations caused by the engine's reciprocating motion. The air then passes through a roots compressor driven by a 230V AC motor. Steel pipe work is used to connect the compressor to an inline air heater, which is powered by a 1.5 kW 230V unit. From the heater, the air is directed to the engine through a custom intake connection that replaces the original setup. This custom coupling section is equipped with an absolute pressure transducer (Kistler type 4011A) and a K-type thermocouple. The pressure transducer is used to maintain a fixed cylinder pressure during inlet valve opening (IVO). The maximum operating pressure of the intake system is approximately 1.7 bar, and the maximum temperature is 130 degrees.

The engine is equipped with various measurement and control equipment. It is mounted on a modified engine test stand called the test trolley, which features a control and load unit. The trolley is designed for engines up to 7.5 kW and includes an asynchronous motor with an energy recovery unit acting as a brake. The engine is started by the asynchronous motor, and once running, the motor and energy recovery unit act as a brake to apply load. The torque and speed of the engine are controlled by a frequency inverter. The test trolley has been modified to accommodate the ACTIVATE engine. A shaft encoder was installed between the engine and the brake to measure speed and identify compression top dead center (TDC). A hall effect sensor was installed on the camshaft, which rotates at half engine speed, to identify compression TDC and assist with injector control and signal referencing. Various sensors are used to measure parameters such as air intake pressure and temperature, in-cylinder pressure, engine speed, and IMEP (indicated mean effective pressure). The air intake pressure is measured using an absolute pressure transducer, while the in-cylinder pressure is measured with a Kistler transducer installed in the glow plug fitting of the cylinder head. All sensor outputs are connected to National Instruments modules mounted in Compact RIOs, and the data acquisition and control are performed using LabView software.

Deliverable Report 1.1 - Injection system details, first non-optimized engine results with NH3 as a fuel

The injection of liquid ammonia is necessary to create a spray in the engine's combustion chamber, requiring high-pressure injection. The project utilizes liquid ammonia stored in a pressure vessel at room temperature and around 8-10 bar pressure, a choice suitable for agricultural vehicles. Diesel injectors have seen increased operation at pressures over 1000 bar, while gasoline injection has transitioned from low-pressure port injection to high-pressure direct injection (GDI), operating in the 200-300 bar range. Due to project requirements, the decision to use a direct injection system for liquid ammonia was straightforward.

The selection of the pump for the ACTIVATE project was considered crucial due to previous experiences with pump issues in academic testing environments. To avoid potential problems and interruptions in experiments, it was decided to choose the pump carefully or eliminate it from the system altogether. The goal was to achieve highly predictable and consistent injections of liquid ammonia at approximately 200 bar pressure, allowing the engine to operate under various conditions until reaching a stable measurement point. A system design that utilized high-pressure gas instead of a pump was chosen, minimizing the number of moving parts and addressing issues related to fuel lubricity, wear, sealing, power, and vapour lock. This system also allowed for the use of Swagelok parts, which simplified the process due to the team's experience with them at NTNU.

The fuel system used in ACTIVATE involves purging the system of air and water before filling the high-pressure sample cylinder (HPS) with liquid ammonia from the ammonia tank. Nitrogen is then introduced to pressurize the ammonia in the HPS cylinder. The pressure and mass of ammonia in the cylinder are measured. The high-pressure ammonia is then directed from the cylinder to the injector. To fill the cylinder with ammonia, any existing gas in the cylinder is vented through a needle valve and water trap to ensure the removal of ammonia.

During the construction of the rig, design changes were made to improve its functionality. The lessons learned from this iteration will be applied to a more modular version in the future. A platform was added to hold the pressure high-pressure sample (HPS) and scales, reducing vibrations during mass measurements. The enclosed volume was reduced by placing the ammonia tank externally and housing it in an aluminium cabinet. An extraction hood system was installed over the cabinet. It was discovered that the ammonia tank with a dip tube does not require assistance for ammonia flow to the HPS. The water tank for venting was also positioned outside the enclosure. Swagelok hoses were replaced with coiled 3 mm tubes to alleviate tension and ensure compatibility with the scales.

Milestone Report 1.2 - Fuel injection strategy established

Initial engine tests were conducted using diesel fuel injections, which highlighted issues related to the common rail injector. As a result, the work on WP1 was temporarily halted due to personnel changes. While M1.2 has been partially achieved in optimizing the injection strategy for diesel fuel, this report focuses on developing the diesel injection strategy and the methodology for running the engine on the test stand.

The diesel injection system described in M1.1 includes a common rail fuel pump driven by an electric motor and an automotive common rail with a pressure control valve. The return fuel is cooled and directed back to the tank through a heat exchanger. Initial tests were conducted to assess the accuracy and precision of the fuel injection system, using an unmodified 6-hole fuel injector. The maximum stable injection pressure achieved was 680 bar, limited by the electric motor and system specifications. To ensure accurate mass measurement, a test was conducted with 1000 injections in a cooled flask, comparing the mass measured by the fuel tank scales to the actual mass of the injections. The results showed a maximum error of approximately 2%, which was considered acceptable.

After confirming the accuracy and precision of the injection trolley scales for measuring fuel usage, engine testing with the standard injector began. The engine test stand, which underwent modifications outlined in report M1.1, operates with manual speed and load control using potentiometers. The AC motor acts as the dynamometer, and its speed is set as a fixed point during testing. Fuel injection timing is adjusted based on engine speed, and injection duration is varied to increase fuel volume and indicated mean effective pressure (IMEP). The AC motor adjusts its braking torque to maintain a constant speed in response to increased fuel. However, the initial testing with the unmodified 6-hole injector resulted in excessive fuel volume, surpassing the highest IMEP of the original engine at maximum load. To address this, a test program was implemented to modulate the injection pressure and the number of holes in the nozzle to reduce fuel mass. A detailed map of the engine was constructed, considering various injection hole configurations (3, 2, and 1) and pressure ranges (550 to 650 bar) at different engine speeds (1500, 2000, 2500, and 3000 rpm) with corresponding injection timing adjustments.

The injector holes were modified by laser welding the holes of an unmodified, 6-hole nozzle closed. The results include cylinder pressure for 100 consecutive cycles, heat release rate, P-V diagram, and IMEP and CA50 (crank angle of 50% burn) map for the three-hole injector with a minimum injection duration of 1 ms. The injection pressure used was 550 bar, which was found to provide highly repeatable injections. However, the IMEP obtained with this minimum fuel quantity was too high, making it impossible to achieve the required engine speed-load map defined by the project partners.

The single-hole injector did not meet the required IMEP for all conditions. While increasing the injection duration led to a small increase in IMEP, there was a reduction in the maximum IMEP as engine speed increased. The two-hole injector showed more promising results, with the target IMEP being reached for some conditions. However, testing was halted due to the departure of the researcher from the project.

To further analyze the suitability of the injectors, the mass of injections with different hole configurations and injection durations was collected. This data and engine air flow rate measurements were used to determine the equivalence ratio for the various injections. However, data processing for the two-hole injector has not been completed due to the researcher's departure. It should be noted that all tests were conducted without applying intake pressure from the supercharger and without intake air heating, which could provide some control over the equivalence ratio and fuel volume injected.

Milestone Report 1.3 - Dual fuel composition optimized

The focus of M1.3 was on studying ammonia and diesel combustion in the ACTIVATE engine rig. However, the report does not include the measurement of gaseous emissions using FTIR (Fourier Transform Infrared Spectroscopy) as the measurement routines were still under development. The results presented in the report consist of measurements of O2 and CO2 gas concentrations in the exhaust.

The engine rig at NTNU has undergone improvements in the ammonia fuel system, including the addition of an extra nitrogen bottle for purging and pressurization. Valve leakage issues have been addressed by ensuring proper temperature and clearance specifications. The room ventilation system has been upgraded to include a manual switch with normal and experiment modes, maintaining negative pressure and facilitating quick air exchange in case of ammonia leaks.

The engine head has been modified to accommodate both a Bosch common rail diesel injector and a gasoline direct injection (GDI) injector. The diesel injector allows for high-pressure injections of diesel-like fuels, while the GDI injector injects ammonia through six holes at a maximum pressure of 200 bar. A new diesel injector with smaller hole diameters was chosen to enable higher ammonia energy shares or shorter injection durations. Three injector nozzles with varying hole configurations (1, 2, and 3 holes) were welded and tested. The maximum achieved ammonia energy share was estimated at 86% with a 4 ms injection duration, while the maximum achieved thermal efficiency was 37% with an estimated engine output of 8.7 kW. The maximum ammonia energy share achieved with the updated setup was 54.4% using the 2-hole diesel injector. Further adjustments, such as increasing intake pressure or decreasing intake temperature, are planned to optimize compression ignition conditions for leaner mixtures in the next campaign.

The hydraulic delay of the gasoline direct injection (GDI) injector was examined using a high-speed camera. The investigation involved injecting ammonia into a constant volume chamber at 2 bar and 16C. The injection duration was set to 1 ms with an injection pressure of 200 bar. The injection signal triggered the camera, capturing the first image immediately upon the trigger. The camera's frame speed was set to 200,000 frames per second. Analysis revealed that the observable ammonia injection began 330 s after the start of energizing. The first indication of injection ending occurred at 1390 s after the start of energizing, resulting in a total injection period of 1060 s.

The motored pressure of the engine under specific intake air conditions results in a peak pressure of 46.64 bar. Based on numerical simulation, the in-cylinder pressure trace is adjusted in post-processing to align the motored peak pressure position at -0.5 CAD ATDC. The timing of the in-cylinder pressure is synchronized with the intake valve opening and closing, which is determined by the engine manufacturer's valve lift curves. The inlet valve begins to open at -405 CAD ATDC and reaches full opening at -257 CAD ATDC. As the piston approaches bottom dead center (BDC) at -180 CAD ATDC, the gas exchange through the inlet valve decreases, and the pressures in the cylinder and intake port equalize. The inlet valve closes completely at -105 CAD ATDC. To ensure pressure matching, the pressures are synchronized at -170 CAD ATDC.

The engine's air mass flow rate is measured using an orifice plate meter placed inside a wooden box to minimize pressure oscillations caused by downstream components. The differential pressure across the orifice plate and the pressure and temperature of the incoming air are measured. However, suspicions arose about the accuracy of the air mass flow rate measurements during post-processing. To investigate this, a manual manometer was employed to verify the pressure transducer used in the measurement system. It was discovered that the range of the pressure transducer needed adjustment, as it had previously been set for a higher flow rate. This adjustment led to higher air mass flow rate measurements compared to earlier readings.

Ther results from the engine runs show that increasing the ammonia energy share (AES) in engine operation reduces thermal and combustion efficiency. The coefficient of variance (COV) based on maximum in-cylinder pressure increases with higher AES, while the COV based on indicated mean effective pressure (IMEP) remains stable at a lower level compared to diesel. The shape of the heat release rate (HRR) curves for ammonia combustion remains similar for increasing AES, but higher AES results in greater heat release. An interesting pattern emerges when examining fixed AES with varying ammonia injection timing. Shifting the injection timing from -80 CAD ATDC to -40 CAD ATDC shows a transition from partially premixed combustion to fully premixed combustion. The COV based on peak pressure significantly increases during the transition between -60 and -40 CAD ATDC. At -20 CAD ATDC, a typical diesel combustion case is observed, with a diffusion flame following a brief period of premixed combustion. This suggests a clear transition occurring between -60 and -20 CAD ATDC. The earlier injections allow for premixing and heating of the mixture by the engine walls and hot air before the diesel injection, while the -40 CAD ATDC case does not have sufficient time to heat up, resulting in a colder charge at the time of diesel injection, longer ignition delay, and increased premixed combustion.

Deliverable Report 1.2 - Fuel injection strategy for optimized fuel mixture range

Deliverable report 1.2 presents the performance and emissions measurements results for different operating conditions, focusing on injection timing for ammonia and diesel, increasing engine load, and ammonia energy share (AES). The report also addresses the challenges encountered during the study, including the use of FTIR (Fourier Transform Infrared Spectroscopy) for analysis, fuel mass estimation, and achieving repeatability in the experimental setup. Furthermore, it concludes with optimal injection strategies within the tested engine operating range.

The key findings and conclusions of the study are as follows:

1. This study is the first to report engine data on ammonia-diesel combustion in HPDF mode, including emission data and detailed information about the heat release rate.

2. The thermal and combustion efficiency of AES 40% improves when delaying the injection of ammonia, reaching a plateau around -30 CAD aTDC (crank angle degrees after top dead center). For AES 50%, earlier injection timings of ammonia result in better thermal efficiency, although injection timings earlier than -30 CAD aTDC were not measured.

3. Injecting ammonia slightly before diesel injection, specifically around -15 CAD aTDC, leads to a more stable power delivery, as indicated by lower COV IMEP values for both AES 40% and AES 50%.

4. Injecting ammonia at -30 CAD aTDC and -25 CAD aTDC results in higher cycle-to-cycle variation in peak pressure, as indicated by increased COV values. Increasing the AES from 40% to 50% exacerbates this instability.

5. Ammonia injection timing significantly affects the start of combustion (CA10). Early injection of ammonia delays ignition, while delaying the injection further leads to a peak CA10 value at -25 CAD aTDC for AES 40%. Injecting ammonia after the start of diesel injection delays CA10 compared to diesel alone.

6. Injection timings of -60 CAD aTDC and -40 CAD aTDC result in a premixed combustion phase followed by a diffusion-based flame, indicating sufficient time for ammonia mixing and vaporization before diesel injection.

7. Delaying the injection of ammonia reduces unburned ammonia concentration in the exhaust, with minimum concentrations observed at -15 CAD aTDC for AES 40% and -20 CAD aTDC for AES 50%. Later injection timings result in a significant increase in ammonia concentration, particularly for AES 50%.

8. Peak NOx levels occur at different ammonia injection timings for AES 40% and AES 50%, with delays of -20 CAD aTDC and -25 CAD aTDC, respectively. Delaying the ammonia injection reduces NOx concentration, and AES 50% exhibits a lower peak NOx level than AES 40%.

9. N2O concentration shows a minimum at -17.5 CAD aTDC for AES 40% and -20 CAD aTDC for AES 50%, with a non-monotonic trend after those points, possibly indicating geometrically driven quenching effects.

10. CO and total hydrocarbon (THC) concentrations in the exhaust indicate incomplete hydrocarbon combustion. CO levels remain relatively stable for AES 40%, while AES 50% shows consistently higher CO levels across all measured injection timings. THC concentration exhibits stability for early ammonia injection timings in AES 40%, with a peak at -25 CAD aTDC for AES 50%, similar to the levels observed in AES 40% at -15 CAD aTDC and later injection timings.

11. Delaying the ammonia/diesel injection timing to -10/-10 CAD aTDC for 40 % AES and to -20/-15 CAD aTDC for 50 % AES, positively affects engine performance and emissions.

These findings provide valuable insights into the combustion characteristics and emissions of ammonia-diesel dual-fuel engines, laying the foundation for future research and optimization of ammonia injection strategies in HPDF mode.