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High efficient natural gas engine concepts for long haul transportation

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Abstract

Different natural gas engine technologies can be applied for commercial vehicles and those investigated in the HDGAS project are:

- Positive ignition natural gas engine with direct injection
- Dual fuel natural gas engine (premixed gas and pilot diesel injection)
- High pressure gas injection with pilot diesel injection

This paper will describe the challenges and solutions of the different engine concepts in combination with LNG tank systems in respect of

- Greenhouse gas reduction potential including measures to improve gas engine efficiency
- Emission compliance to EU VI

Keywords: LNG; direct injection; high pressure; dual fuel; natural gas;

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1. Introduction

Due to the chemical composition of natural gas the CO2 emissions can be reduced by up to 25% compared to diesel powered vehicles. However, this fact is only valid if the engine efficiency is the same as for diesel engines. Furthermore, it is important to consider all greenhouse gas relevant components.
Natural gas consists mainly of methane (depending to the source) and methane slip from the vehicles needs to be considered in the CO2 equivalent calculation, since the greenhouse effect is 25 times higher than for CO2.
Different natural gas engine technologies can be applied for commercial vehicles and those investigated in the HDGAS project are:

- Positive ignition natural gas engine with direct injection (both stoichiometric and lean)
- Dual fuel natural gas engine (premixed gas and pilot diesel injection)
- High pressure gas injection with pilot diesel injection

The high energy density of diesel allows long distance driving before refueling. Today, most natural gas vehicles are equipped with CNG tank systems which is a reasonable solution for short to medium distance driving. For long haul transportation other solutions are needed. LNG systems come into the picture which offer a significant improved driving range.
This paper will describe the challenges and solutions of the different engine concepts in combination with LNG tank systems in respect of

- Greenhouse gas reduction potential including measures to improve gas engine efficiency
- Emission compliance to EU VI

The project´s duration is 3 years and at the point of time of submission of this paper, 6 months are left to the end. For this reason the integration of the systems into the demonstrator vehicles have not been done yet and can therefore not being described. Also the engine testing and calibration is not finalized yet, meaning that only limited statements can be made in terms of emission compliance.

The paper has been set up according to the structure in the project:

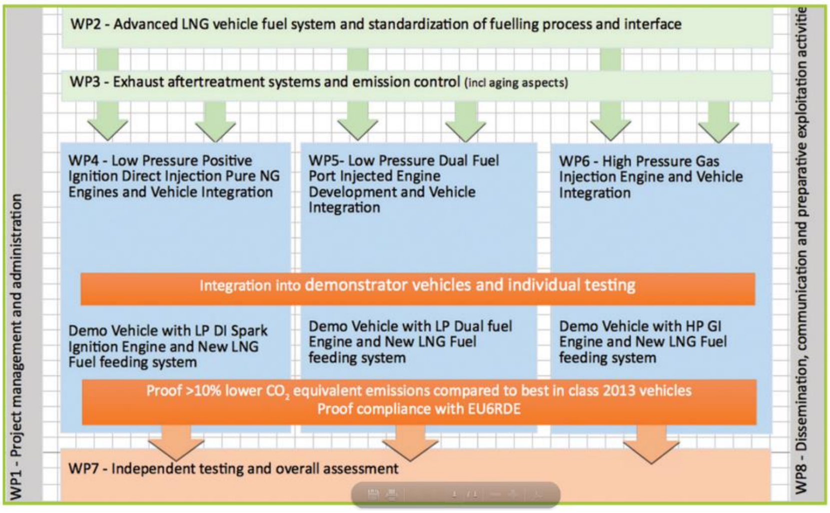

Figure 1: HDGAS project structure

Work package 2 (WP2): Advanced LNG vehicle fuel system and standardization of fueling process and interface
Work package 3 (WP3): Exhaust aftertreatment systems and emission control (incl. ageing aspects)
Work package 4 (WP4): Low pressure positive ignition pure NG engines and vehicle integration
Work package 5 (WP5): Low pressure dual fuel port injected engine development and vehicle integration
Work package 6 (WP6): High pressure gas injection engine and vehicle integration

Most significant results from the development of the different engine concepts will be presented as available to date. This includes results from the LNG fuel system development as simulations from the tanking process, the design of a standardized receptacle, the design, layout and testing of the new LNG tank and its fuel pumps with different pressure levels.
Results from the engine development will include simulations, and the outcome from single cylinder testing will be shown where hardware for the multi cylinder testing will be selected. Results from multi cylinder testing are partly available depending on the status in the respective work package / engine concept.

2. Work package 2, Advanced LNG vehicle fuel system and standardization of fuelling process and interface

2.1 Objectives

Main objectives of WP2 are:

1. To specify technical requirements and international/European standards of LNG fueling interfaces and fueling process for heavy duty vehicles (trucks and buses) and to develop selected LNG fueling components and interfaces;

- Develop a technical standard to specify a common fueling process for LNG filling stations to provide the basis for a fueling infrastructure where every vehicle can be fueled at every station;
- Develop technical standards to specify a future fueling interface taking care of user requirements such as comfort, fueling time and safety.

2. To develop an advanced LNG fuel tank system which is in line with relevant technical specifications and standards for fueling interfaces and filling processes, comprising:

- Development of several compact LNG tank systems with a capacity between 300 and 700 liters composed of a double walled aluminum or stainless-steel cylinder with improved vacuum insulation, an in situ cryogenic LNG pump, appendages/connections/interfaces and proof compliance with ECE R110 regulations and tests;
- Development of three cryogenic LNG pumps for in-situ tank usage. One cryogenic pump will be developed for generating low pressure (10-20 bar) Natural Gas (NG) for the engines with low pressure gas injection systems, the second pump will be developed for medium pressure injections of approx. 50 bar and the third cryogenic pump will be developed for generating high pressure (≈ 300 bar) Natural Gas (NG) for the engine with the high pressure gas Injection concept;
- Performing of tests according to ECE R110 regulations and for on road testing in the demonstration vehicles;
- Assessment of the performance of the developed LNG tank systems as part of the demonstration vehicles.

2.2 Results

2.2.1 WP 2.1

One very important outcome of the WP 2.1 activities is the definition of a new design for a LNG refueling connector consisting of a fueling nozzle and a fueling receptacle. In respect to the current ISO connector the new development regulates the objectives to minimize the spillage volume and to enable a diesel-like handling. In collaboration with different fueling connector suppliers a new receptacle design has been coordinated and determined. Technical drawings as well as 3D models have been elaborated within the working group. In second half of 2016 one supplier provided the first hardware (receptacle and nozzle) to Daimler. A second supplier will deliver a receptacle and nozzle in end of 2017. All in all there are currently three suppliers for receptacles and two suppliers for nozzles available. First successful tests of the fueling connector of MannTek have been received at refueling tests of the low pressure tank system, which SAG developed for the dual fuel engine of MAN.
Moreover a new ISO proposal for the fueling interface has been written and presented at the ISO group at the end of 2016. According to the usual ISO timeline the preparatory stage has been finalized at the end of 2016, following a 48 month plan, in order to make sure that during the 12 months after the 36 month HDGAS project first results of the testing with the demonstrator vehicles of the project can be used for the new ISO.

Simulation models of UASE (1D and 3D simulation of the refueling process) have been built up and deliver reasonable results for the standardization of the refueling process. The 1D simulation has been done at different initial conditions so far in order to learn about the behavior of the liquid and gaseous phase within the tank. A pump effect has been added to the model to calculate the mass flow rate. Further improvements of the 1D model like the development of a two-system-model consisting of a gaseous phase (CNG) and a liquid phase (LNG), which will show the evaporation and condensation effects are ongoing.
The 3D filling simulation using homogeneous and inhomogeneous approaches has been realized.

- Homogeneous approach -> only for cases without flash evaporation
- Inhomogeneous approach -> universally applicable

Additional source/sink terms in mass and energy conservation are required in order to account for vapor collapse (VOF approach not feasible) and have been incorporated in the modelling framework.
First insights into the simulation results show e.g. that the heat transfer at the interface between the gaseous and the liquid phase is smaller than expected. On the other hand there is a higher heat transfer between the droplets

and the vapor during the refueling process. The vapor collapse, which occurs within the tank during the refueling, is caused by the heat transfer between the droplets and the vapor.
The validation of the models will now be done by the help of data sets of real refueling tests (coordinated and conducted by Daimler and MAN) and will improve the models until the end of the project.

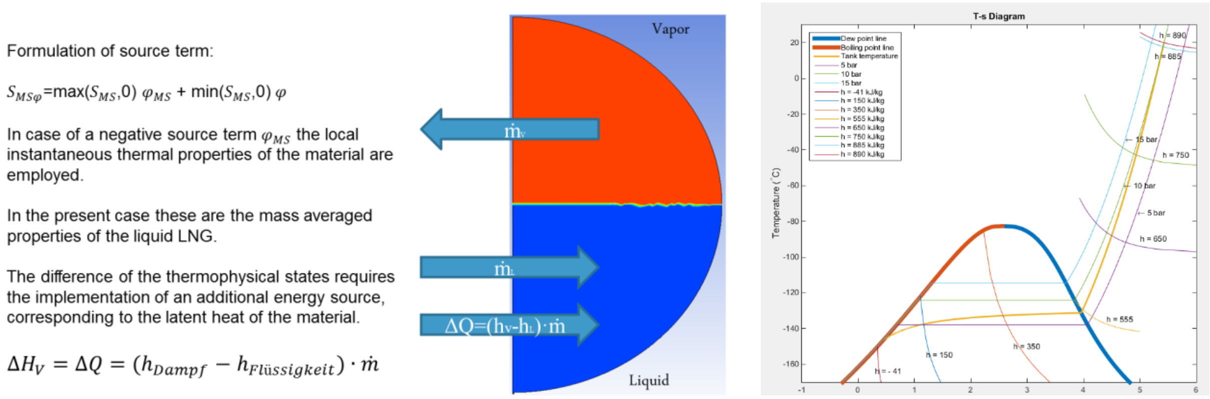

Figure 2: Formulation of source terms for 3D simulation (left); Exemplary T-S-diagram of a refuelling of 1D simulation (right)

2.2.2 WP 2.2

The low pressure tank system incl. the low pressure pump has been developed by SAG (in collaboration with MAN and Daimler) for the dual fuel engine of MAN. The LNG pump has got an electric drive and a cryogenic position measurement sensor of the pump piston in order to optimize the piston control. Possible fuel supply mass flows are between 8 bar and 12 bar. First prototypes of the tank vessel have been built in end of 2016 and successfully tested with the plumbing in March 2017 (ECE testing). The tank system with the low pressure pump has been delivered according to the WP 2 time schedule in June 2017 to MAN.
Iveco develops a vehicle with a SI engine and needs a medium pressure tank system with approx. 50 bar supply mass flow to feed this engine. Therefore, SAG develops this tank system with a hydraulic driven LNG pump next to the low pressure tank system. The plumbing of the medium pressure system has been changed in comparison with the low pressure system and is currently tested on a pump test rig. This tank system with the medium pressure pump will be delivered to Iveco for the SI engine in end of September 2017. Both tank systems of SAG are equipped with the new LNG receptacle of WP 2.1 and therefore enable a refueling with the new fueling connector with all advantages.
For the HPGI Truck of Volvo, Westport will deliver a tank system with a fuel supply mass flow of approx. 300 bar. The high pressure pump is driven hydraulically and is improved in respect to lifetime and efficiency. Moreover this tank system has got a reduced boil-off and need to vent back to station, thanks to the ability to reduce the tank pressure during operation. This high pressure pump will be delivered to Volvo by end of October 2017.
The simulation tasks of ViF and TU Graz in respect to the optimization of the spray bar position and angle within the tank as well as the development of a simulation model of the vaporizer are finalized. The results have been used by SAG for the positioning of the spray bar within the tank as well as for the dimensioning of the vaporizer and thus had a very positive influence on the development of the tank systems.

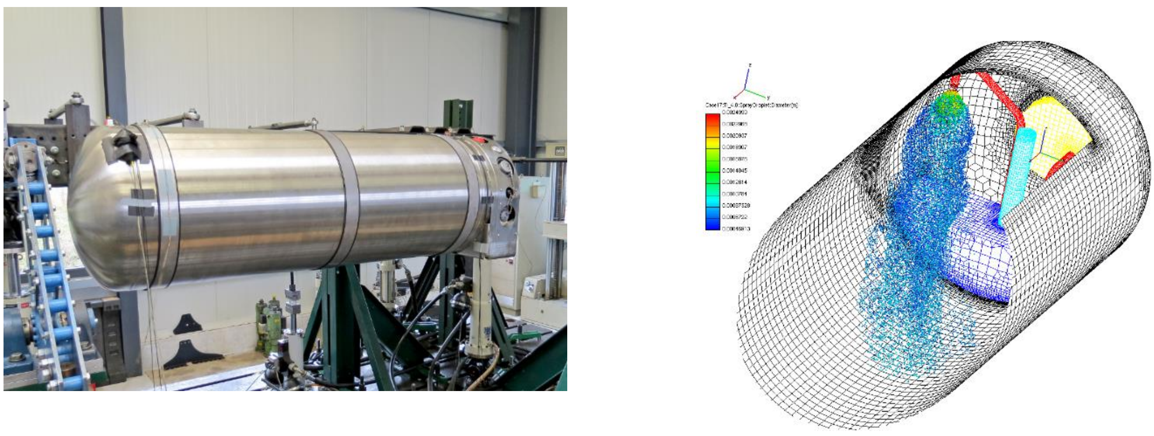

Figure 3: Left: Tank system of SAG; Right: Cross section of SAG tank system with optimized spray bar

3 Work package 3, Exhaust aftertreatment systems and emission control (incl. ageing aspects)

3.1 Objective

Stoichiometric operating natural gas applications have significantly higher exhaust gas temperatures compared to lean operating natural gas engines. The excess oxygen in the combustion chamber under lean operation leads to lower exhaust gas temperatures. This raises a significant challenge in methane control, coupled with a high light off temperature for methane oxidation (>400°C) requires optimised engine and aftertreatment solutions for lean burn natural gas applications. Another issue in the long-term use of natural gas as a fuel in lean-burn engines is the sulfur poisoning of after treatment system. Euro VI and the future emission regulations demands long durability of the catalyst. Hence minimizing deactivation, of either thermally or via poisons, will maintain methane control efficiency of the catalyst system which becomes challenging at low temperatures.

The objectives are to develop, specify, design and deliver three emissions control systems to meet Euro VI legislation for three different engines, taking into account ageing implications of the applications. The three engines are stoichiometric DI natural gas, lean burn DI natural gas and low pressure dual fuel NG/Diesel. The calibration of the lean burn DI natural gas engine is an objective of Work Package 3, the other two engines will be calibrated in WP4 and WP5.

3.2 Results

In order to comply with current emission legislation, (e.g. Euro VI), the development of more advanced exhaust aftertreatment technologies plays a key role. In order to purify the exhaust gases emitted by lean-burn natural gas vehicles and meet the current emission limitations, the typical aftertreatment system has to comprise two main sections: the first one is dedicated to the oxidation of unburned methane over a dedicated catalyst (MOC-Methane Oxidation Catalyst); the second one is devoted to the abatement of NO_x emission, via SCR (Selective Catalytic Reduction). Understanding the synergies and interactions of these catalyst systems is key to deliver highly efficient and durable aftertreatment systems. These challenges led to fundamental catalyst studies being undertaken by academic partners where the challenge of methane control and its impact SCR technology, for NOx control, was investigated for a lean burn natural gas application.
European natural gas contains relatively low levels of sulphur (<6ppm), however, even at these low levels deactivation of the methane catalyst can take place under lean operating conditions which operates at relatively low temperatures. Hence, methane control studies focussed on the impact of sulphur poisoning on the conversion efficiency of a high load PGM (Platinum Group Metals) MOC. Sulphation of the catalyst significantly impacted the light off characteristic and hence the overall conversion efficiency. This led to the development of a desulphation strategy which periodically removed sulphur from the MOC [1]. The desulphation strategy comprised of feeding the catalyst with a rich feed gas at high temperature conditions. This desulphation process was developed on a synthetic as reactor but it was ensured that the conditions used can be reproduced on an engine and the strategy can be directly transferable to an engine control strategy. Figure 4 shows the impact of the desulphation strategy on the methane conversion efficiency before, during and after the desulphation events. It was observed that after the desulphation event, the methane conversion efficiency significantly increased compared to before the event. This led to a significant improvement in the methane control. Figure 4 also shows the release of SO2 from the methane catalyst, with the SO_2 peaking at approximately 150ppm. The desulphation strategy will come with a fuel penalty, as the engine is being operated in a rich mode. However, the calibration process on the engine will be developed to minimise the frequency and duration of the desulphation events, to minimise the impact of fuel penalty.
NOx control for lean burn natural gas applications will require urea based SCR as used with diesel applications. Fundamental studies were focused on selection of the appropriate catalyst material for efficient NOx control and the impact of methane slip on the SCR system. Selection of the appropriate SCR catalyst was key, as the exhaust temperatures for a lean burn natural gas application were significantly higher than diesels but lower than stoichiometric applications. A range of catalysts were assessed for NOx control and N_2O formation [2]. N_2O is not currently regulated in Europe but is a significant greenhouse gas contributor with a CO_2 equivalent of almost 300 and hence must be minimized. Therefore, the selection of the SCR catalyst took into account the N_2O emission formed. Figure 5, shows the NOx conversion efficiency and N_2O formation for a range of SCR catalysts with zero and 10 000 ppm methane in the feed gas. It was noted that the impact of methane on the NOx conversion efficiency was negligible, hence natural gas combustion does not impact SCR NOx control, which is a positive outcome of the research. The combined Fe-SCR+Cu-SCR catalyst, which comprised of a first brick containing iron zeolite followed by a second brick of copper zeolite, gave the appropriate efficiency temperature

window required for the natural gas application and it gave low N_2O emissions and was chosen as the catalyst system to take forward to the engine testing phase.

Figure 6 shows the schematic of the aftertreatment system that will be taken forward to the engine calibration phase of the dedicated lean burn natural gas application. It consists of a novel methane control catalyst system which has been designed to minimize the impact of sulphur ageing, followed by a Fe/Cu hybrid SCR system for efficient NOx control with low N_2O formation potential.

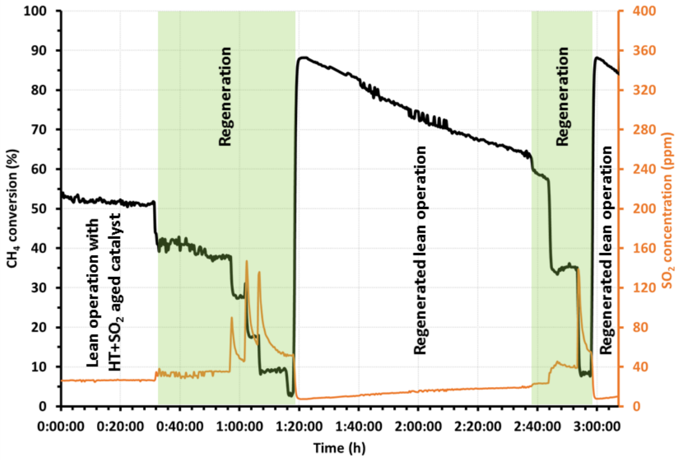

Figure 4: Impact of Desulphation events on the methane conversion efficiency

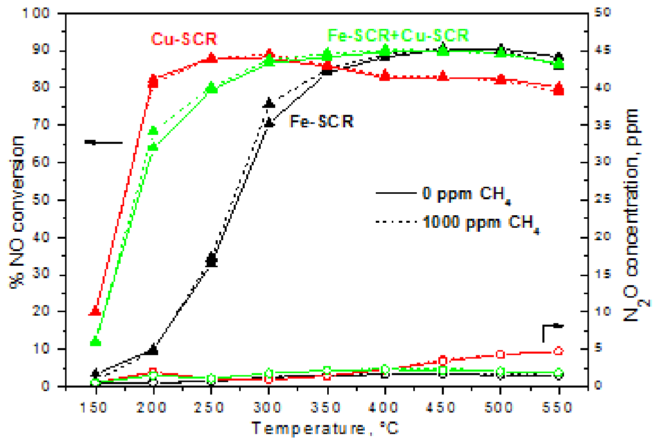

Figure 5: SCR catalyst Selection for Lean Burn Natural Gas Application

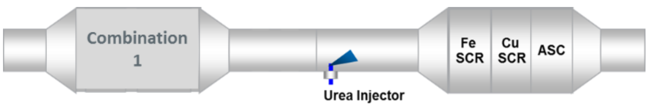

Figure 6: Schematic of aftertreatment system that will be calibration on the dedicated lean burn natural gas application

4 Work package 4, Low pressure positive ignition pure NG engines and vehicle integration

4.1 Objectives

WP4, led by FPT Industrial, is devoted to the development of an innovative positive ignition engine exclusively fuelled by natural gas, and the integration of the engine in a long haul truck, along with the new LNG tank developed in WP2 and the innovative ATS (aftertreatment system) developed in WP3. Tests aimed at demonstrating the capability to comply with Euro VI legislation and the improved fuel efficiency will be performed at test bench, using WHTC and ACEA cycles, and on the demonstrator vehicle, under real-world conditions.

The engine will be tested in two different configurations, stoichiometric and lean burn, in order to evaluate potentials in fuel consumption reduction of both. The two engines will employ different ATS but only the stoichiometric engine will be installed in the demonstrator vehicle.

The target of -10% in GHG emissions and +10% in performance (torque/power) with respect to 2013 state-of-the-art engines will be reached applying several new solutions to the HDGAS engine, such as an innovative combustion system, with specific design of the intake ports and the combustion chamber. A new fuel system is also applied to the engine, which makes it possible to employ different injection strategies which will improve air/fuel mixing and, thus, combustion efficiency, reducing pollutant emissions at the same time. The use of cooled EGR will also help to improve fuel efficiency, especially at part load operation, as thoroughly explained in the following section.

Use of high EGR ratio or very lean mixtures, while improving efficiency, will result in conditions with difficult ignitability but this problem will be overcome using a high energy ignition system. With the Corona ignition system, the air/fuel mixture is ignited in a larger volume compared to a standard spark plug ignition system, so burn delay and burn duration can be significantly reduced, leading to a swifter combustion and improved late burn behaviour, thus reducing the risk of knocking.
Various partners, from both the academic and the industrial sides, contribute to this work package. The development process started from the design phase, which was reached with the aid of the most advanced simulation tools, both 1D and 3D. The following step was the procurement and assembly of prototype engines, followed by their installation at test bench and on the demonstrator vehicle. The final step will be the demonstration of the accomplishment of the project's targets, in terms of performance, fuel consumption and pollutant emissions level.

4.2 Results

The 1D engine simulations were performed at the beginning of the project to define the thermodynamic layout of the HDGAS engine. This included the layout of the valve timing and the evaluation of different concepts for the gas exchange like early and late Miller timing of the camshaft profile. The turbocharger matching and the definition of the EGR circuit layout were performed and the potential of advanced camshaft management was investigated [1].
The effects of the various combination of components (camshaft profile, turbocharger, EGR circuit layout) on engine efficiency were calculated, helping to pinpoint the best configuration, which was employed to design the engine. Various operation modes (EGR rate, camshaft management) were also simulated, outlining the best operating strategies, to be verified during engine testing. In particular, 1D calculations confirmed the beneficial effect of EGR at part load operating point, where its presence helps reduce pumping losses and wall-heat transfer to the cylinder head, thus raising engine's efficiency.

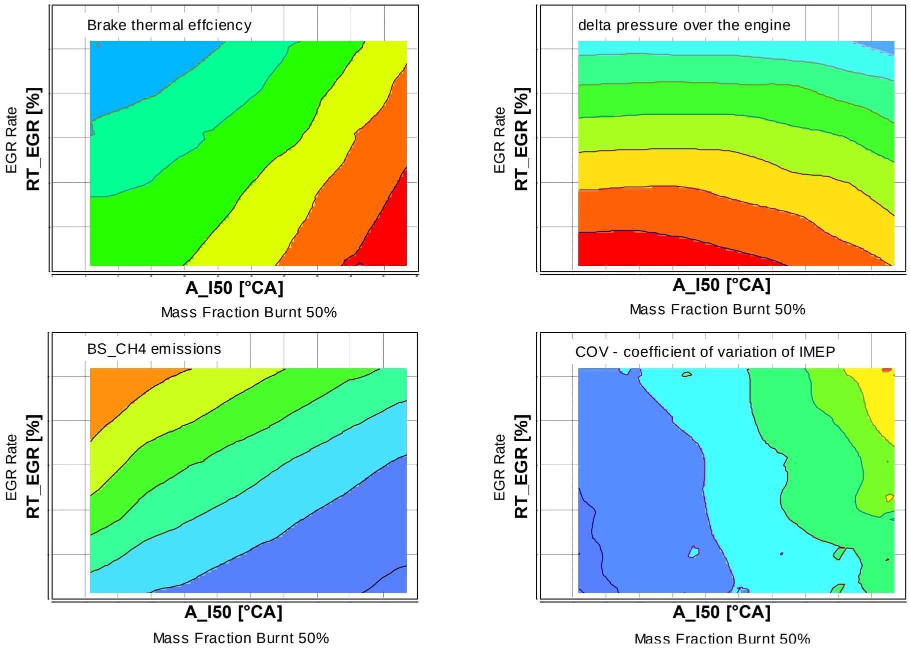

Figure 7: Influence of EGR on different parameters in part load from single cylinder testing

3D CFD simulations were employed during the design phase of some key engine components, such as the intake port and the piston shape. Various configurations were proposed at the beginning of the project, and CFD simulations gave detailed insight into air motion inside the combustion chamber, allowing to determine the pros and cons of each configuration so that the best compromise between the discharge coefficient (related to the

quantity of air entering the cylinder) and the tumble ratio (which indicates the characteristics of the flow motion inside the cylinder) was chosen.
Following the design phase, a single-cylinder testing engine was built in order to evaluate the performance of different camshaft profiles, injector configurations, cooled EGR and the combustion chamber itself. The results confirmed the indications of 1D simulations; in particular, the beneficial effect of EGR on engine efficiency at part load operation was clearly outlined. The results of testing on SCE will be also exploited during the testing phase on multi-cylinder engine, narrowing the number of engine configurations and operation modes.
In the meanwhile, prototype engines were built and installed at test bench. The procurement stage was made more difficult by the fact that some key components, such as the cylinder head, feature some characteristics which are present for the first time on a heavy duty engine and which stretched the suppliers’ capabilities to new limits.
Testing on prototypes has begun and it will continue until the end of the project in order to reach the targets for WP4 and in order to explore the potentialities of an extremely innovative engine and ATS.

5 Work package 5

5.1 Objectives

The main objectives of this Work Package are the development and demonstration of a Heavy Duty Low Pressure Dual fuel engine and its integration into a LNG Demonstration truck. The concept is characterized by:
- Exhaust emissions meeting Euro VI considering real LNG quality
- Targeted 15% substitution increase compared to 2013 dual fuel HD engines
- ⩾10% greenhouse gas reduction compared to state of the art 2013 diesels
- Diesel-like performance and drivability
- Vehicle operation in pure diesel mode
- Driving range of the truck >800 km

The basic approach for the development of a novel high power dual fuel engine concept includes the following innovative technical solutions:
- Low Pressure Port Fuel Gas Injection System
- Novel combustion system approach, based on a closed-loop integrated injection management
- Common-Rail Diesel injection system (only Unit Pump Injectors were available at Euro V)
- Cooled high pressure EGR
- Two stage turbocharging (Euro V with one stage TC)
- Unique Control Unit (not available at Euro V), featuring a closed loop variable lambda control
- New powertrain management strategies in combination of new aftertreatment materials
- Integration of fuel quality sensor

5.2 Results

The baseline testing was performed successfully; demonstrating the MAN D2676 (diesel version) engine used in the activity fulfils both performance and emissions according to Euro VI. Therefore, it is representative as sample and accepted for the next development activities. The baseline tests performed successfully
To support the dual fuel engine development, one and three dimensional simulation methods were applied. Also gas exchange simulations were carried out to optimize engine performance in terms of air charging, EGR strategy and aftertreatment. 1D and 3D simulation model has been developed.
To manage both the Diesel and the Gas application the IDIADA ECU M670 has been fully integrated into the engine in order to control the involved systems (engine, gas, aftertreatment). Comprehensive calibrations and adjustments have been carried out in stationary and transient mode.
The developed solution is under development in order to demonstrate under R49.06 emission cycles that the engine will be able to meet EURO VI for all pollutants.
In the diagram below the evolution of the development concerning emission reduction is shown.

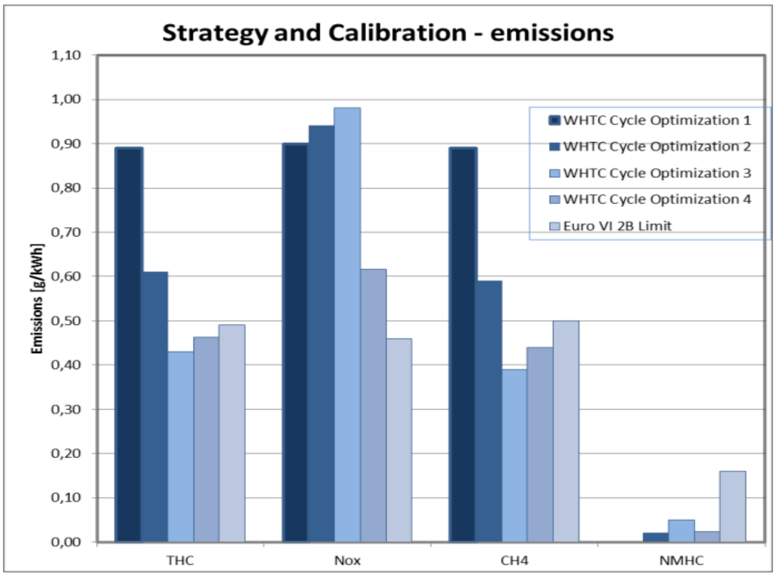

Figure 8: Evolution of the emissions during development

Following reductions have been achieved during the development

- Hydrocarbons have been reduced by more than 60% --
- NOx has been reduced around 40%
- CO has been reduced by more than 60%

This means that regarding hydrocarbon emissions, the development met Euro VI and IDIADA works on a new catalyst strategy in order to reduce NOx emissions and on the optimization of the WHTC cycle for reducing CO emissions. Also, in a parallel way, the increase of substitution ratio is in development - with the objective of reaching a substitution of more than 70% of diesel by natural gas on WHTC warm cycle. At this moment, more than 80% can be achieved on typical long-haul operation with more stable speeds and loads. The increase of the substitution rate is needed in order to reach the project target of CO2 reduction compared to diesel baseline engine.

The activities in the following months will be focused to improve the calibration strategy in terms of performance and emissions. Up to now the calibration strategy has been focused on the hot WHTC, the following steps will be the improvement of the strategy for the cold WHTC and the consideration of the composite cycle with deterioration factor.

As mentioned in regulation 49, the engine would have to be operated from a temperature between 20 ºC and 30 ºC at the start of the cycle. In that cold start condition the dual-fuel mode is not activated, so in order to operate the engine complying with the targets the following aspects will have to be improved or implemented:

- Calibration of the diesel-and dual fuel modes in terms of performance and emissions
- Aftertreatment warm-up strategy in diesel-mode (critical for the correct function of MOC and SCR)
- Development of the dual-fuel cold start strategy

All theoretical investigations related to the vehicle construction have been concluded. The design of the tank brackets has been finished, new and modified parts have been identified in the package investigation and all interfaces (electrical, mechanical, CAN) have been defined.

6 Work package 6, High pressure gas injection engine and vehicle integration

6.1 Objectives

The main objective of this Work Package is to develop and demonstrate a new Heavy Duty Natural Gas engine based on a High Pressure Direct Gas Injection (HPGI) combustion concept and validate engine performance on a long haul LNG truck. Specific objectives of this engine development and vehicle integration activity are the following:

- Exhaust emissions meeting EU VI
- > 20 % reduction of greenhouse gas emissions compared to a heavy duty diesel vehicle
- Same engine power, torque and drivability as diesel engine
- > 90% diesel substitution rate in real driving cycle
- > 800 km of driving range with the integrated LNG tank system

The technical approach for the development of this novel High Pressure Direct Gas Injection engine concept includes the following innovative solutions:

- A novel combustion technology, based on a unique high pressure gas injection system
- An optimized combustion system by means of CFD simulation and single-cylinder engine tests
- A LNG tank system including a cryogenic high pressure LNG pump for injection pressures up to 300 bar
- The final objective is to implement the new engine, tank and fuel system in a demonstrator vehicle and to assess and demonstrate emissions and efficiency for real driving conditions.

6.2 Results

HPGI (high pressure gas injection) is based on high pressure injection of methane gas directly into the cylinder at the end of the compression stroke. Ignition is obtained by injection small amounts of diesel fuel just prior to the gas injection. Due to a mixing controlled combustion, engine-out HC emissions are low. Despite the low level of soot emission tendency of natural gas, small amounts of particulate matter are formed during combustion due to the non-premixed operation of the engine.
CFD simulations were performed to pre-select injector nozzle configurations. Parameters that were investigated include number of holes, spray angle and flow rate of both diesel and gas holes. Four different nozzle configurations were chosen for further investigation in the single cylinder engine.

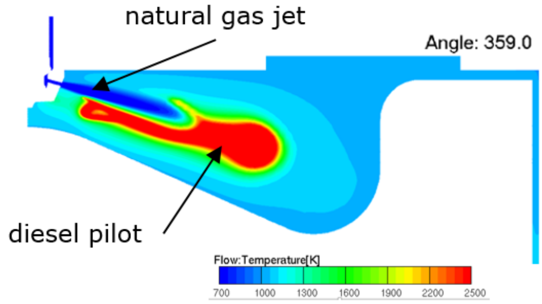

Figure 9: HPGI principle – hot gas from diesel pilot injection at the nozzle bottom ignites the methane gas jet above – as illustrated with temperature distribution calculated by CFD.

The results reported here originate from early tests of the concept using a single-cylinder engine with bore x stroke =131 x 158 mm, compression ratio = 16.8:1 and swept volume = 2.1 L. Engine operating conditions were limited to three stationary point, see Figure 10.
The injection pressure was varied from 200 to 500 bar for both fuels. A constant amount of diesel fuel of 6.5mg/str was found to provide stable engine conditions comparable to diesel engines as well as engine out methane emissions well below EUVI levels. This amount of diesel results in a GER (gas energy ratio) of 97.5% for full load operation and 90% GER in the load point with lowest tested engine speed and power (equivalent to WHSC mode6). With the chosen pilot quantities it is very realistic that a gas energy ratio > 90% can be achieved in hot WHTC. Pilot separation variations showed that the system was very insensitive when changing the pilot diesel injection separation in all the investigated load points, therefore a fixed pilot separation was applied for all operation conditions.
Soot emissions were low, below 0.006 g/kWh, for all investigated operating conditions. Increased injection pressure led to lower THC and CO emissions whereas CH_4 emissions were insensitive. Compared to diesel, HPGI showed benefits in NO_x emissions (~ 30% less at same MFB50%), depending on the chosen injection pressure.

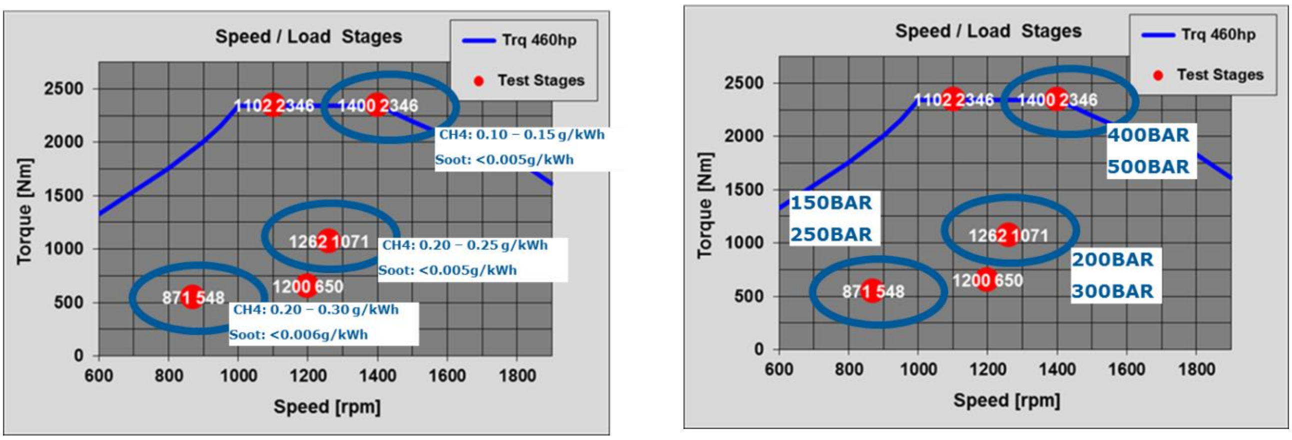

Figure 10: Engine operating conditions with fuel injection pressures (left) and engine-out emissions of methane and soot (right).

The single-cylinder tests enabled to select the optimum nozzle configuration for the multi cylinder testing. The prototype multi cylinder engine has been procured and mounted into the test cell at AVL. Multi cylinder tests are ongoing to confirm the results from the single cylinder rtesting and to ensure that the project targets can be achieved before calibration of the engine will start. In parallel the demonstrator vehicle is being prepared and equipped with the LNG fuel system for the planned demonstrator tests.

7 Summary and outlook

The project is following its time plan and all deliverables have been delivered as planned so far. Certainly the project is currently in a critical phase when all three engine concepts are being evaluated in the engine test cells, adapted and finally calibrated. Many new technologies are being implemented and major hardware and software development was necessary in order to secure proper operations of all components. The last couple of months until the end of the project (2018-04-30) will show the capability of the selected technologies and the target fulfilment of the project.

8 Acknowledgements

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