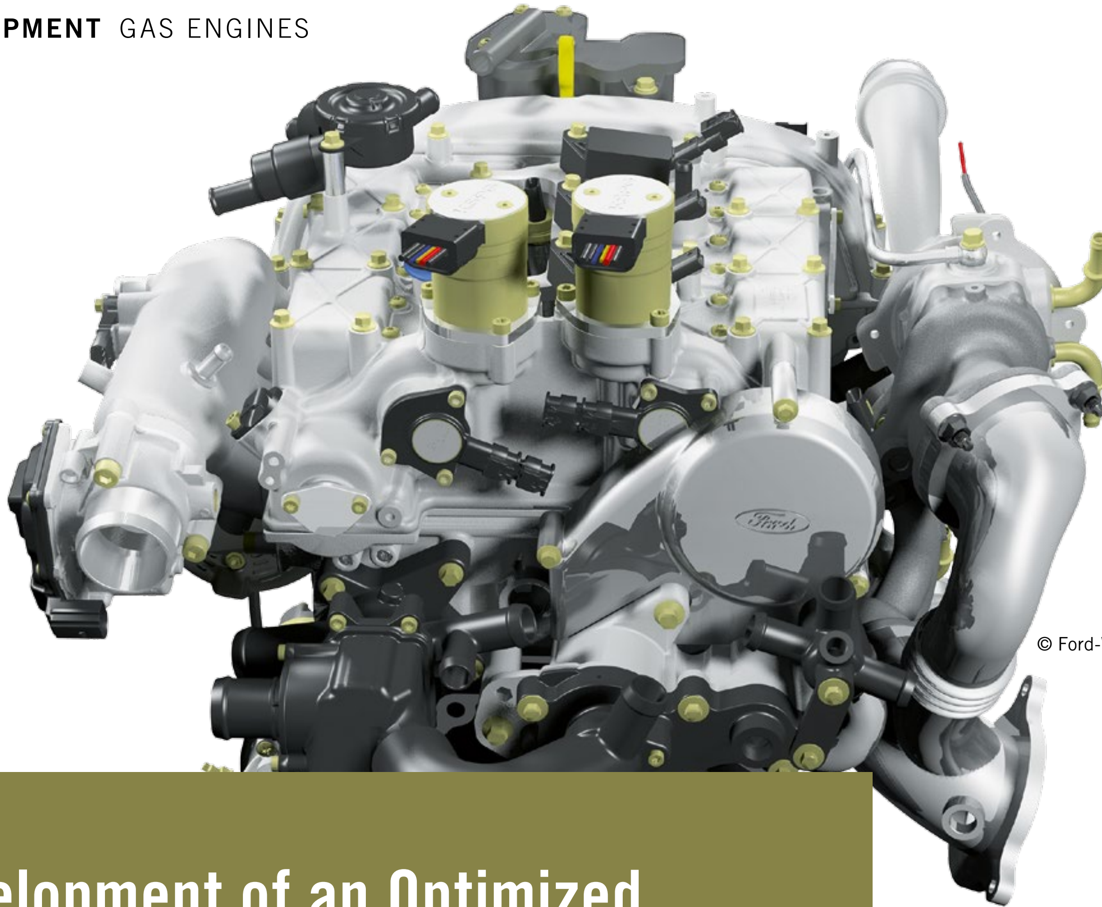

Development of an Optimized Methane Engine for Passenger Cars

Methane is an interesting alternative to conventional fuels. A Tank-to-Wheel CO_2 reduction of more than 20 % is already possible with fossil methane without any optimization of the engine. An adaption of the engine to the high knock resistance increases the efficiency and further reduces the CO_2 emissions. The unlimited miscibility of fossil methane with sustainably produced bio-/e-methane enables a future Well-to-Wheel CO_2 reduction to nearly zero.

MOTIVATION

Methane is an interesting alternative to conventional fuels, in particular for the use in especially optimized spark ignition engines. It is the main component of Natural Gas (NG), biomethane, and in particular completely sustainable e-methane. All of these fuels can be mixed in any blend ratio for use in natural gas vehicles. Because of the very

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Item	MTDI target
Fuel	Methane
Compression ratio	13 : 1
Rated power output	110 kW
Maximum torque	240 Nm at 1500 rpm
Maximum cylinder peak pressure (average/max)	p_{max} = 160/185 bar
Rated speed	6000 rpm

TABLE 1 Targets MTDI engine (© Ford-Werke GmbH)

favorable C/H ratio of methane, a CO_2 reduction of more than 20 % compared to gasoline operation is already achieved with fossil methane. Due to the high knock resistance of methane, an engine efficiency improvement can be achieved as well [2]. Furthermore, methane combusts very cleanly. In stoichiometric operation, particulate emissions are hardly measurable and NO_x vehicle emissions can be reduced to a level below imission limits by means of considerably simpler aftertreatment technology than used on diesel engines.

MTDI ECOBOOST ENGINE WITH CNG DIRECT INJECTION

So far, available natural gas vehicles are usually equipped with a derivative of existing gasoline engines. In general, for cost reasons, disadvantages with regard to lower specific power and lower break mean effective pressure compared to gasoline operation are accepted. As part of the EU-funded H2020 project GasOn, a specially designed natural gas Methane Turbo Direct Injektion (MTDI) engine was developed based on the Ford 1-l three-cylinder Ecoboost engine [1], with the key data listed in **TABLE 1**. Due to significantly higher mechanical and thermal loads, caused by the high compression ratio, the high boosting level and the early combustion phasing, the engine has been designed for a very high peak pressure capability. Methane direct injection reduces the filling losses, which are inevitable with port fuel injection. Furthermore, parallel sequential turbo boost, in conjunction with a fully variable valve train, provides the air necessary to achieve the ambitious engine attributes. The variable valve control on the inlet side, which can continuously adjust the valve lift or the valve opening duration in addition to the phase position, makes it possible to reduce gas exchange work. A similar system on the exhaust side is used for continuous control of the turbocharging system.

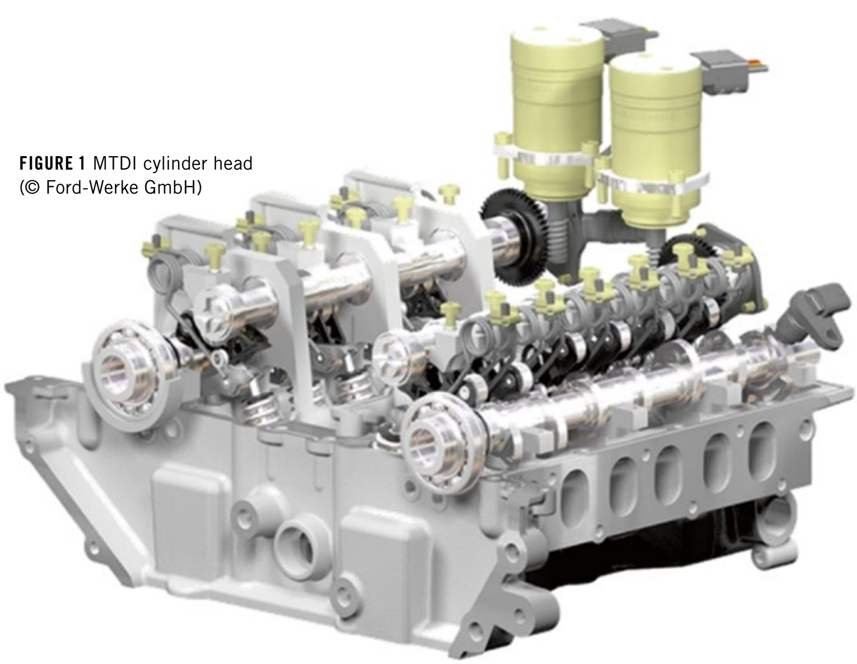

FIGURE 1 MTDI cylinder head (© Ford-Werke GmbH)

ADAPTATION OF HIGHLY LOADED ENGINE COMPONENTS

The increased mechanical and thermal loads require a revision of various components of the base engine in order to operate the MTDI engine durably. The revision of the entire cooling circuit, including cylinder head, block and additional components, such as the bearing housing of the second turbocharger or the gas control valve, has been supported by intensive CAE work. As a result, hot spots in the cylinder head and block are sufficiently cooled without significantly increasing the pressure loss of the entire cooling system. Furthermore, the engine is equipped with an electrically actuated thermostat, which allows higher block coolant temperatures at part load operation of the engine. This leads to reduced piston friction and thus to reduced fuel consumption.

The integration of the new valve train system required a re-design of the MTDI cylinder head. Bore spacing and diameter, as well as valve sizes of the production engine are maintained. The MTDI cylinder head, **FIGURE 1**, has two separate, integrated exhaust manifolds, each one connected to only one exhaust valve per cylinder and consequently serving only one of the two turbochargers. A three-piece water jacket ensures adequate cooling. The high combustion pressures require two additional cylinder head bolts per cylinder. The design of the entire exhaust system was carried out using a combination of a CFD and a topology optimization tool [6], which led to an 11 % increased maximum exhaust mass flow compared to the base variant.

The pistons are equipped with a cooling gallery and a specially developed ring carrier. The shape of the combustion chamber is designed by means of CFD calculations, optimizing the mixture formation at the high compression ratio.

The open-deck deep-skirt cylinder block has been adapted to the high performance boundary conditions by means of CAE structural analysis and thermal loading simulation. This led to a reinforcement of the bearing block and the top end of the cylinder liners. Newly adapted structural elements allow the inclusion of additional cylinder head bolts. The weight of the block remains almost identical to the standard block. Cooling slots have been introduced to the most thermally loaded bore bridges in order to get cooling water very close to the hot spots, achieving acceptable material temperatures. A separate oil gallery feeds the oil spray nozzles to cool the pistons. A solenoid valve controls the oil flow. The crankcase ventilation has been adapted to the high combustion pressures by combined oil return and venting channels with adapted cross sections, directly cast into the block. The standard cast crankshaft is replaced by a forged steel shaft.

The installation of a variable compression system has been provided for within the design of the engine. Function and working principle of this system are described in [3, 4]. The challenge was to use this system in a motor which provides only limited room for installation due to its small bore spacing and which has very high peak pressures at the same time.

Since there are significant advantages over port fuel injection, a system for natural gas direct injection has been developed for the MTDI engine, following specific installation dimensions and operating specifications. The optimization of the flow and metering characteristics of the injection system as well as the development of a control strategy were carried out with intensive CAE support.

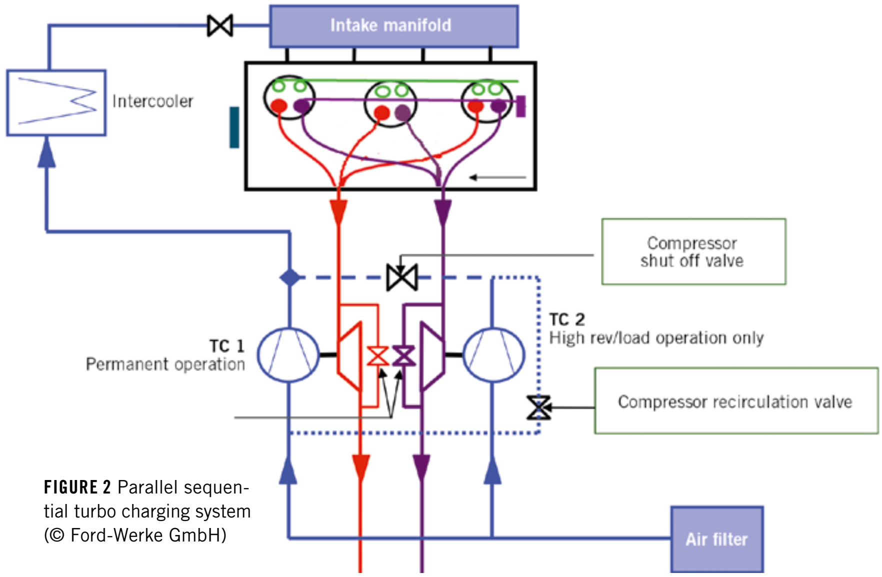

FIGURE 2 Parallel sequential turbo charging system (© Ford-Werke GmbH)

In order to avoid injector damage, a limitation of the injection window is required, which enables injector opening only within a sufficient distance to critical cylinder pressures.

The MTDI engine features a mechanically actuated Continuously Variable Valve Lift (CVVL) system that continuously adjusts valve lift and the corresponding event length. The system is applied to both the intake and exhaust side. A detailed description of the working principle and the dynamic behavior of the CVVL system are described in [5]. All valve train components for the intake and the exhaust side are integrated into the valve cover.

The ambitious specific torque and power output targets for the engine require a high boost pressure level. For this purpose, a parallel sequential turbocharger system was designed by means of 1-D CAE simulation. The system consists of two turbochargers of the same size, a compressor shut-off valve and a recirculation valve, **FIGURE 2**. The first turbocharger (TC 1) is in continuous operation, the second one (TC 2) is activated at higher speeds and loads with the help of the CVVL system. The engine operation transition from single-turbo to bi-turbo mode requires special attention. Extensive CAE investigations were carried out for this purpose. Finally, the shift range for the selected turbochargers was set to 2,700 to 2,800 rpm. With the illustrated arrangement of the components, a smooth transition can be calibrated without negatively impacting driving comfort.

FIGURE 3 shows an overall view of the all-new engine, uncompromisingly designed for high-efficiency methane operation, including the previously introduced new technologies.

Pure methane operation is very challenging for the combustion process itself. Intake ports, combustion chamber and piston geometry have been adapted adequately. The intake ports of the cylinder head feature a masking of the intake valve seats to generate sufficient charge motion during the ignition event, even for Early Intake Valve Closing (EIVC) operation conditions. Because of the high compression ratio combined with the small displacement of the engine, the design freedom for the geometry of the piston top land is very limited. Furthermore, a large adjustment range of the fully variable valve train requires suitable valve pockets. With regard to those limitations, the piston geometry

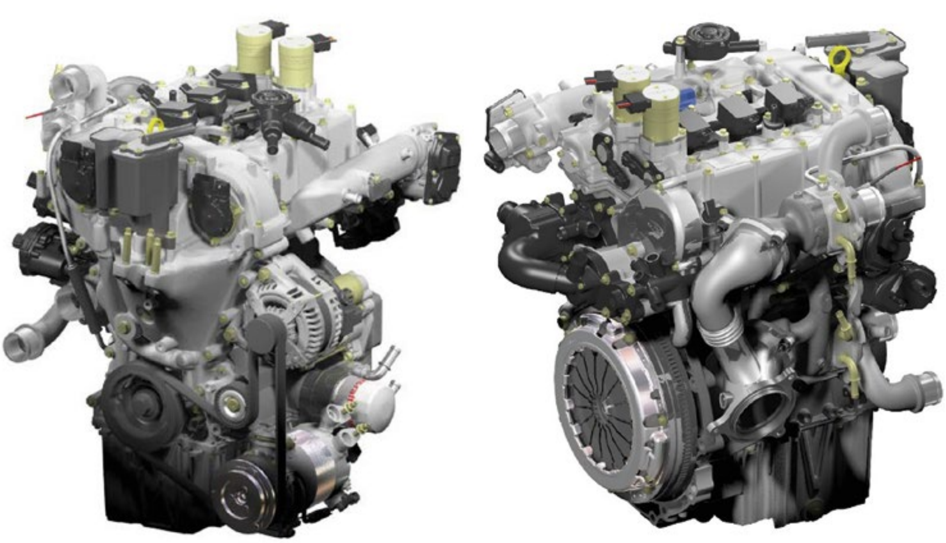

FIGURE 3 MTDI engine designed for methane operation (© Ford-Werke GmbH)

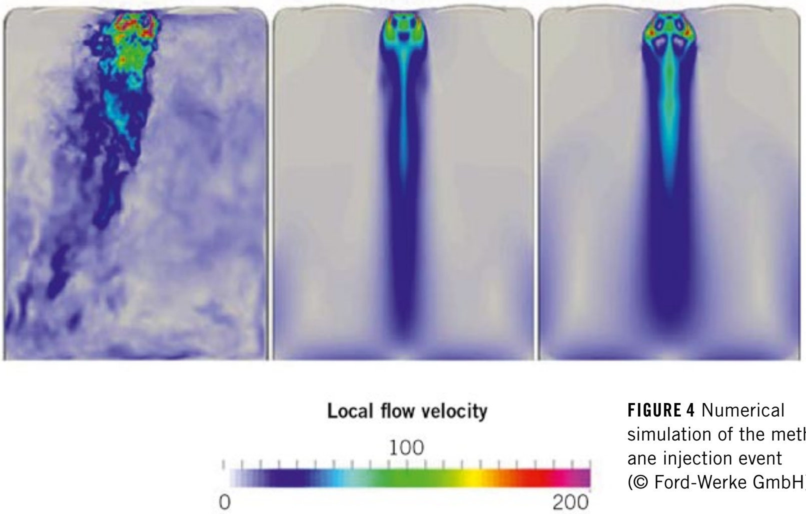

FIGURE 4 Numerical simulation of the methane injection event (© Ford-Werke GmbH)

for the combustion of methane was designed to achieve a mixture preparation as homogeneous as possible.

Because of the very complex behavior of the gas injection process, the optimization of methane direct injection requires a detailed numerical 3-D CFD simulation study. Contrary to a gasoline engine, fuel evaporation does not need to be considered in the DI-methane engine. Gas dynamics and pulses are very different. In order to get reliable simulation results of the methane direct injection, specific modeling techniques were developed and tested in a first step. As an example, **FIGURE 4** shows a comparison of detailed numerical simulations with LES and various RANS CFD models. Although RANS presents the flow field in more detail, LES shows a better correlation of the highly dynamic gas jet with measured data.

ENGINE TEST RESULTS

FIGURE 5 summarizes the full load curve and measured efficiencies in the entire engine map for single-turbo and bi-turbo operation. The engine delivers a power output of 120 kW, exceeding the performance target by 10 kW. The maximum torque of 240 Nm, equal to 30 bar Break Mean Effective Pressure (BMEP) is achieved at 1,500 rpm. In addition to the high peak efficiency of 38 %, this results in an extremely large range of efficiency across the engine map. Driving cycle simulations deliver 93 g/km CO_2 in the NEDC cycle and 120 g/km CO_2 emissions for the higher loaded WLTP cycle for a 7-seat van in the medium segment. The combination of the technologies described above enables very low CO_2 emissions, which strongly support the future emission goals.

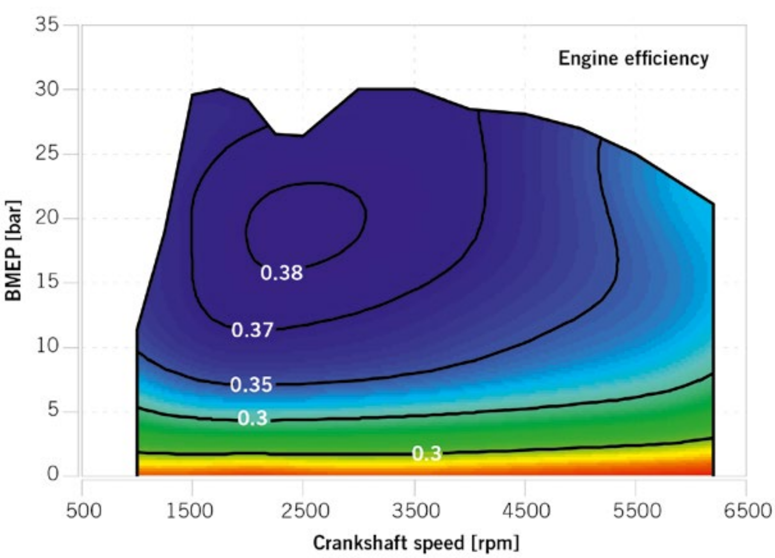

FIGURE 5 MTDI engine efficiency map and full load for single- and bi-turbo mode (© Ford-Werke GmbH)

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