Development of a new generation of GE's Jenbacher type 6 gas engines

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W. Siebenpfeiffer, *Heavy-Duty-, On- und Off-Highway-Motoren 2016*,
Proceedings, DOI 10.1007/978-3-658-19012-5_2

Abstract

Modern gas engines for power generation are a key part of today's world-wide decentralized energy supply and they are expected to play an even more significant role in future. GE's engine versions operate at high power densities, high efficiencies and low emission levels – and always with a high degree of availability.

GE's Jenbacher Type 6 gas engines cover the 1.5 to 4.5 MW power range and are efficient, flexible and reliable with high power density. Since 1989 more than 4200 gensets have been delivered to customers all over the world. More than 40 different versions are available to provide an optimal solution for every application.

To further strengthen the Type 6 platform position, GE's Jenbacher gas engine product line has been continuously working on product improvements. The recent development efforts result in the introduction of a new engine generation, both for single-stage turbocharging and two-stage turbocharging variants. Improving various engine components like cylinder head, valve train, cam shaft, power unit and combustion chamber enables noticeable improvements in performance, reliability and product flexibility. A dedicated version management results in tailor-made engine versions for various market segments. As an example, the new version J624 K09 provides an electrical efficiency of 47.0 % at 24.5 bar BMEP. In summary, a very comprehensive Type 6 gas engine product portfolio can be offered for various applications around the world.

Introduction

Throughout the last decades, the world energy demand has always been growing. Driven by the population and GDP growth in non-OECD countries, the worldwide demand increased almost steadily even in the years following the economic crisis since 2008. Today, we are facing a world of uncertainty full of challenges due to slow growth in more developed countries, the dramatic oil price drop and its impact on companies and nations as well as political instability across the world. Still current available reports project an increase in world energy demand by around 25 % until 2040 compared to 2014, once again mainly driven by non-OECD countries. Policies to address greenhouse gas emissions and a renewables scenario in many OECD countries will also drive the global need for high efficient distributed power generation and CHP plants, [1].

Gas engines for distributed power generation provide electrical and thermal energy in a flexible, efficient and reliable manner when it is needed and where it is needed. Being able to provide power on demand with short lead times means that they complement solar and wind energy plants very well, compensating their fluctuating energy supply. The ability to operate with various different types of fuel gas and low pollutant emissions are further positive features that are in line with increasing energy costs and future emission legislations. Considering population growth in developing countries and long term availability of natural gas as well, gas engines are expected to play an increasingly important role within the trend of decentralized energy supply worldwide.

From a customer point of view, considering current trends and legislations, the requirements for gas engine gen-sets involve low investment costs, low operation costs, high availability, operation flexibility concerning gas composition and ambient conditions, short lead time from stopped engine to full electrical power to the grid and compliance to grid-code requirements (voltage drop) and future emission limits etc. From an engine manufacturer point of view, this results in the following thermodynamic development targets: high specific power output, high electrical and thermal efficiencies, sufficient distance to knock and misfire borders, low MN requirement, minimum power de-rating due to ambient conditions (altitude, temperature and humidity), improved transient behavior and low pollutant emissions etc.

In 2010, GE introduced the J624 H, the world's first gas engine with two-stage turbocharging in the 3 – 5 MW segment. With a BMEP of 24 bar at 1500 rpm and an electrical efficiency of 46.3 % it provides some of the highest values in its segment. Improving the very high mean effective pressure and engine efficiency values even further is a special challenge that requires detailed investigations by means of 1D/3D simulation and SCE/MCE testing. This paper describes the development of a new generation of GE's Type 6 gas engines offering several benefits for the customer and tailor-made engine versions for various segments.

GE's Jenbacher Type 6 Gas Engine

The Jenbacher Type 6 gas engine has been part of the product program since 1989. In 1997, the J620 was introduced as the world's smallest 20-cylinder gas engine in the 3 MW power range and in 2007, the J624 followed as the world's first 24-cylinder 4 MW engine. In 2010, GE introduced the J624 H version, the world's first gas engine with two-stage turbocharging. **Table 1** shows the engine technology concept.

Table 1: Jenbacher Type 6 gas engine technology concept (Product Program 2016)

Engine version	J624 H	J620, J616 and J612 F
Engine process	4-stroke spark ignition gas engine with lean A/F mixture	
Mixture preparation	Gas-mixer upstream of turbocharger	
Turbocharging	2-stage (4 TC) with two 2-stage mixture coolers	1-stage (2 TC) with 2-stage mixture cooler
Gas exchange	Single cylinder heads with 4 valves per cylinder	
	Advanced early miller timing	Moderate early miller timing
Ignition	High energy ignition system, spark plug in prechamber	
Combustion concept	Scavenged prechamber	
Power control	Compressor by-pass and throttle valve	

The J624 H engine has been presented several times [2 to 6]. The combination of two-stage turbocharging (with mixture coolers downstream of low pressure and high pressure compressors), advanced miller cam timing and rapid lean-burn prechamber combustion concept results in high power density and high electrical and thermal efficiencies. Together with high energy ignition and advanced power control, these technology features also enable engine operation at very high altitudes, humid and hot ambient conditions as well as low NO_X emission levels without de-rating.

Figure 1 shows the gen-set consisting of generator, base engine and turbocharging/ auxiliary unit. **Table 2** shows the main data of the Jenbacher Type 6 gas engine family.

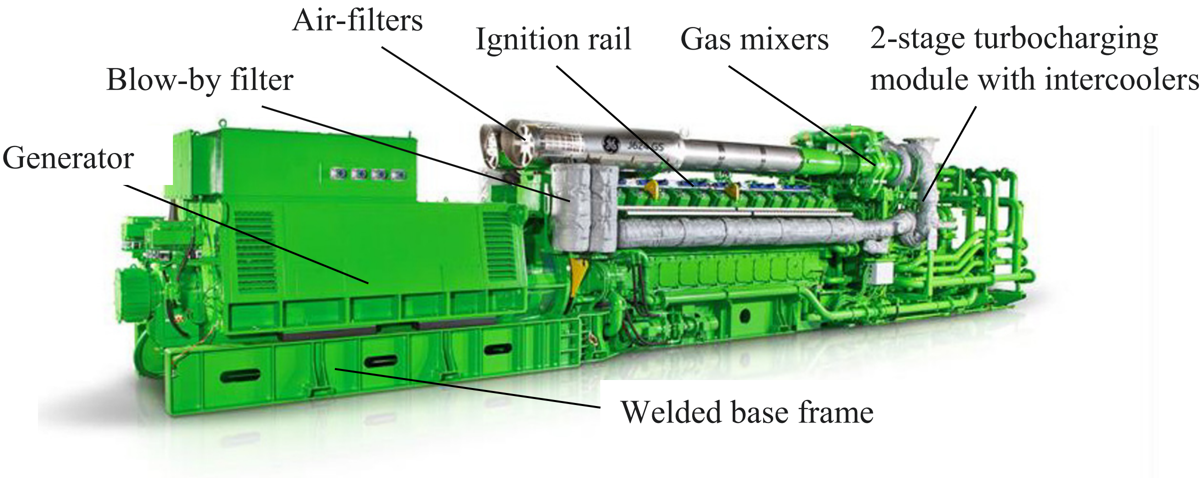

Figure 1: Jenbacher J624 H gas engine gen-set with two-stage turbocharging module

Table 2: Jenbacher Type 6 gas engine data, natural gas versions (Product Program 2016)

Engine version	J624 H	J620, J616 and J612 F
Bore [mm]	190	
Stroke [mm]	220	
Displacement [dm^3]	6.24	
Cylinders	24	20, 16 and 12
BMEP [bar]	24	22
Rated speed [1/min]	1500 (50 Hz), 1500 with gearbox (60 Hz)	
Engine power [kW_{el}]	4400	3350, 2680 and 2010
Electrical efficiency[1] [%]	46.3 @ MN >83	45.6 @ MN >84

1 NOx = 500 mg/Nm^3 @ 5 % O_2 in exhaust gas, 50 Hz operation

In addition to the natural gas versions, there are several further engine versions that are specified to run with bio gas, landfill gas, sewage gas and coal mine gas as well as with flare gas or steel gases like coke gas, blast furnace gas and furnace off gases etc. These engine versions utilize adapted mixture preparation and combustion concepts.

GE's Jenbacher Type 6 gas engine is a success story with

- more than 25 years of proven service,
- more than 4200 engines across the globe,
- an average availability of 98 %,
- serving the 1.5 to 4.5 MW power range (50 & 60 Hz, grid-parallel & island mode),
- achieving more than 90 % total combined heat and power efficiency,
- offering low emissions levels.

Figure 2 shows that several improvements during the past years have been carried out resulting in a power density of 24 bar BMEP and an electrical efficiency of 46.3 % (Product Program 2016).

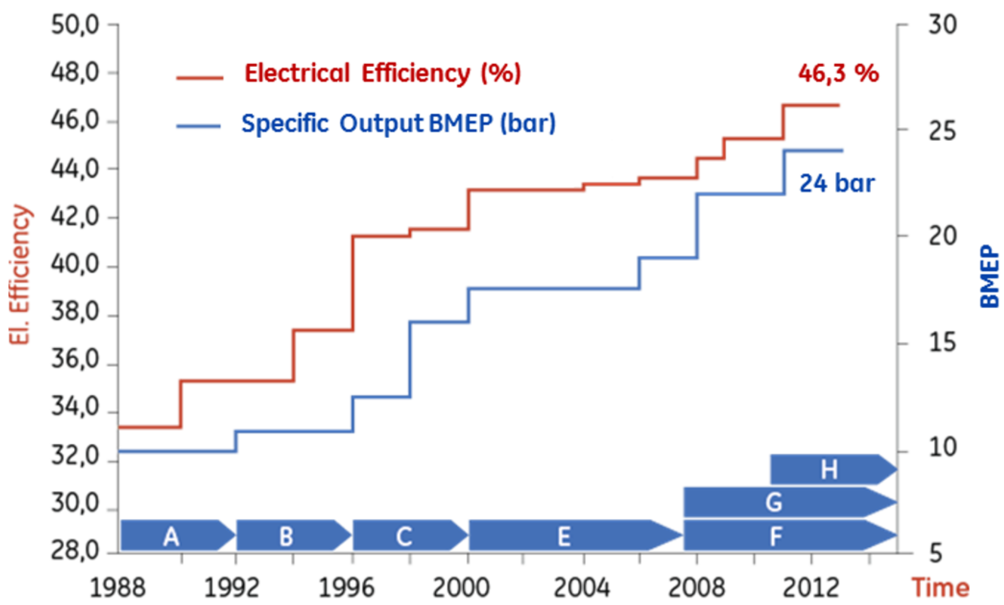

Figure 2: GE Jenbacher Type 6 gas engine development steps and versions until 2016

Development Methodology

The following section describes the methodology applied for the definition of new cam lobe profiles as well as for their performance and mechanical validation.

Simulation

Performance and mechanical 1D simulation models of the Type 6 engine have been used to define the new valve lift profiles. The performance model solves the gas exchange and the compression/expansion of the gases into the combustion chamber for a given set of valve lift curves. It also considers turbocharger behaviour, knocking tendency and HC emissions etc. The pressure traces at the intake and exhaust ports and in the combustion chamber are fed into the mechanical model that solves the dynamic response of the valve train supplying the camshaft excitation. The valve train simulation model contains the desired kinematic valve lift curve, the definition of the valve train kinematics and the resulting cam lobe profile. The mechanical model provides (amongst other things) the force, contact pressure and dynamics of all valve train components. The performance and the dynamic simulation results are interdependent and connected to each other by the pressure traces and the valve lift profiles. For this reason, an iterative process is needed using the performance and mechanical models that can be represented with the flowchart reported in **Figure 3**.

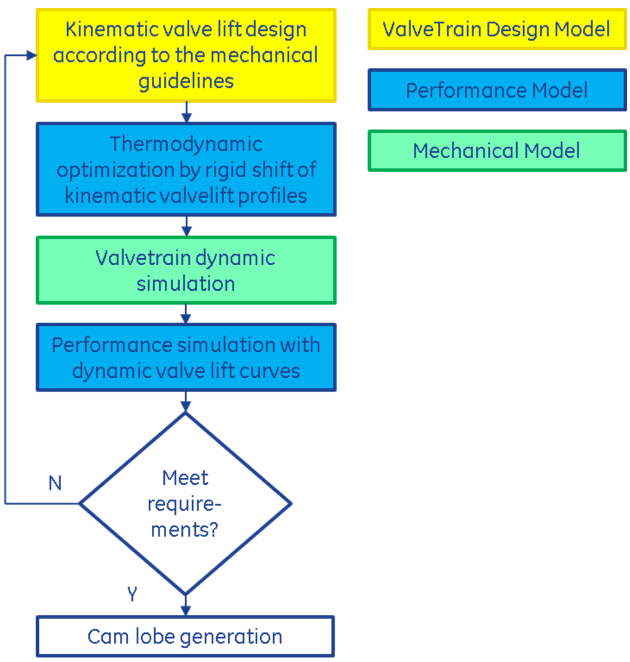

Figure 3: Valve lift curve optimization process

Testing

Validation of valve train system dynamics, system performance, durability and reliability is the primary goal of multi cylinder testing.

The main objective of valve train testing is to measure forces predominant within the valve train as well as articulation and the dynamics of its components at different operating conditions. Results are used to:

1. Cross check system performance against design target
2. Assess actual valve train dynamics against design requirements
3. Validate the mechanical valve train model

The valve train system assessment consists of:

1. Valve lift measurement by optical sensor
2. Force measurement (rocker arm – valves) by full bridge strain gauges
3. Camshaft torsional vibration measurement (ensuring consistency of valve train dynamics across different cylinder head positions)

The system was checked across the entire valve lash range expected during the engine service interval and at different engine speed and load conditions to ensure the proven level of robustness. **Figure 4** shows a cylinder head assembly equipped for valve train measurement.

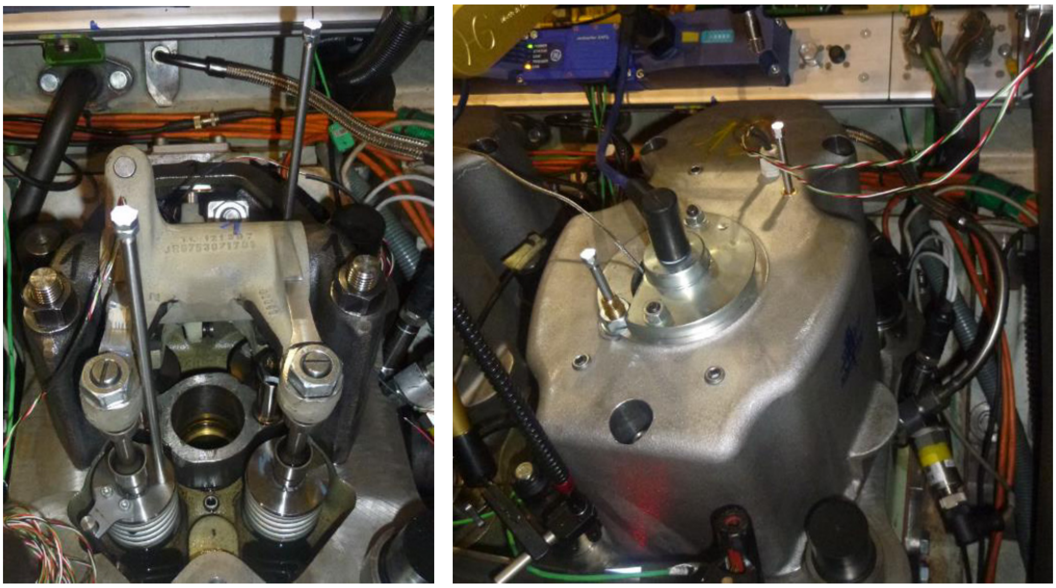

Figure 4: Valve train measurement set-up

Development Priorities

The following section describes the enabling technologies for the new Type 6 engine generation and the applied development priorities.

Cylinder Head

To enable the next level of power density, efficiency, reliability and potential for up to 40kOh component life, a new cylinder head has been developed. This development aimed to achieve, [4]:

1. Uniform temperature profile across the cylinder head flame face
2. Improved cooling effectiveness in critical areas to limit material fatigue and system distortion
3. Improved oil supply circuit and valve train lubrication
4. Improved gas exchange effectiveness

The new cylinder head design includes optimized cooling strategy (e.g. direct cooled exhaust valve seat ring), new cast material, new water jacket geometry for optimized flow distribution and cooling performance, new valve seat ring and prechamber sleeve material/geometry, optimized prechamber tip design and clamping system.

Figure 5 shows the explosion of the new GE Type 6 assembly design.

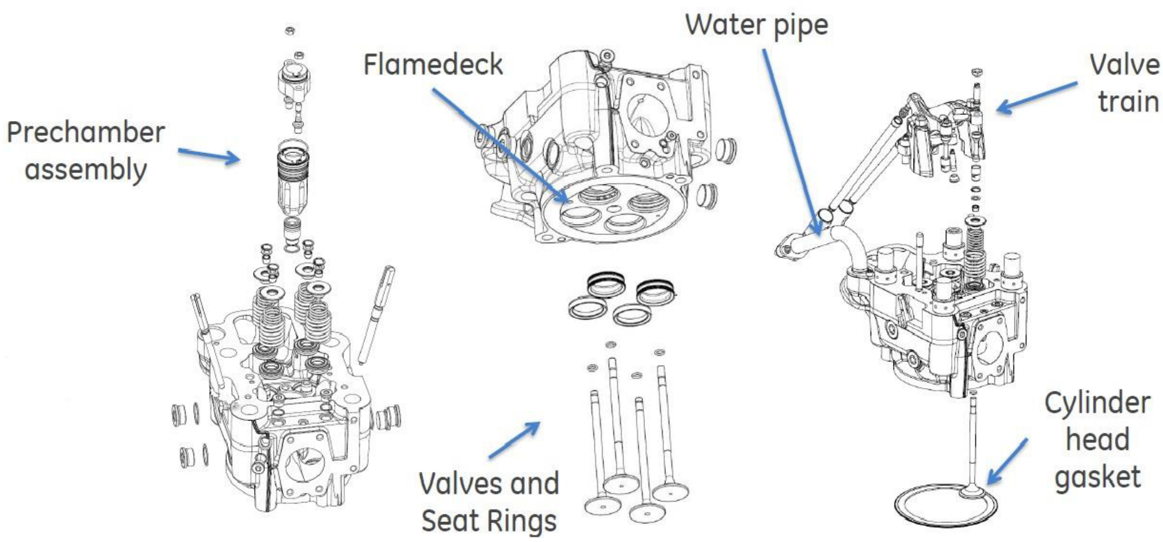

Figure 5: New Type 6 cylinder head design explosion

Valve Train

The optimization of the valve lift curves results in a load increase at the valve train articulation. This is mainly due to the earlier exhaust valve opening against higher combustion chamber pressure, higher acceleration of the intake side and higher spring forces. **Figure 6** shows the comparison between the baseline (dash) and optimized (solid) acceleration curves derived from kinematic valve lift of the 1-stage turbocharged engine versions.

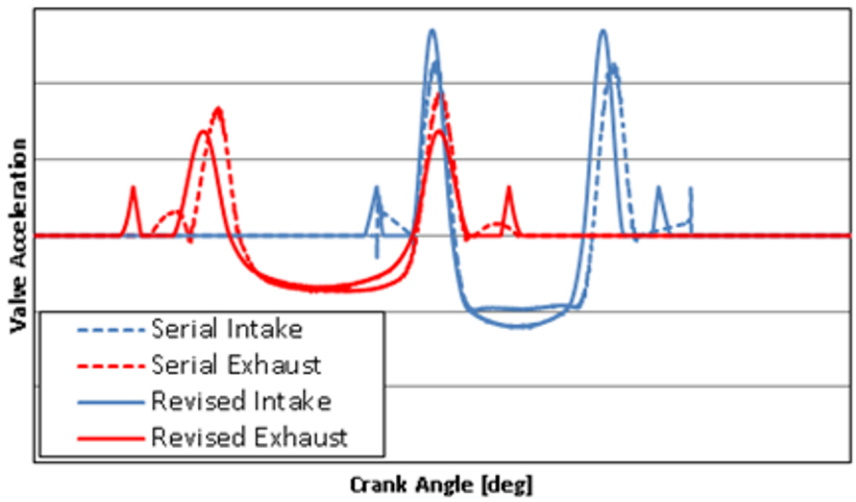

Figure 6: Kinematic intake (blue) and exhaust (red) valve acceleration

The contact pressure and the load of all individual valve train components have been simulated by the 1D mechanical model. The stress distribution resulting from the FE model of the critical valve train components has been used to identify necessary design optimization. Following this study, the roller follower has been modified to increase the contact area with the lobe and to contain the maximum Hertz pressure within an acceptable level. The pushrods have been modified for the new roller follower geometry.

Additionally, the anticipation of the intake valve closure and the demanded valve acceleration required an increase of the valve spring force in order to:

- Guarantee intake valve closure against boost pressure
- Avoid valve train contact loss against increased inertia force

Figure 7 shows the modified valve train components (marked in red).

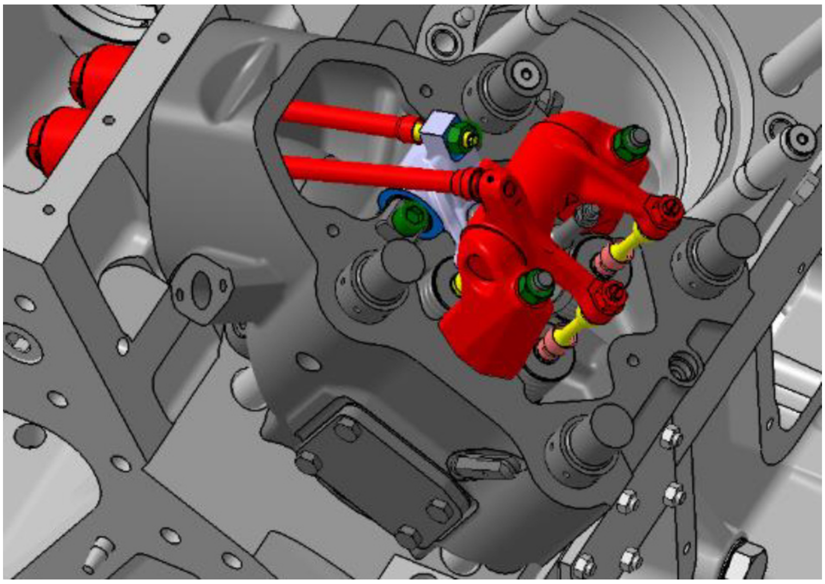

Figure 7: Modified valve train components

Power Unit

The latest generations of Type 6 engines are based on a mature steel piston design that has been developed over the last few years. A roof-shaped piston crown available in 4 different compression ratios with optimized crevice volumes – especially in the area of top land – supports the design intent of creating a power unit for up to 40 kOh exchange interval with absolutely no expense in engine efficiency compared to previous steel piston generations. In fact, the final design state was proven to be in the range of comparably lowest THC losses within GE engines combined with very high confidence in reliability figures as stated above. Since its release, the fleet leader with the latest piston design reached ~ 17 kOh at an installed base of > 800 engines.

Furthermore, the power unit design intent was to support a potential next step power density level and therefore was designed for a peak firing pressure of around 250 bar aligned with the cylinder head component design.

This could be facilitated by the introduction of a scraper ring liner in combination with advanced ring package, ring dynamics and inter-ring volumes with mature oil control and transport. The trade-off between acceptable bypass mass flows (blow by) across the ring package, component temperature at critical positions like the area of the top ring and groove and correspondingly oil transport throughout theses hot and therefore critical zones was modeled and optimized.

The main achievements can be summarized as follows.

- Guaranteed reduction of oil consumption from < 0.3 g/kWh to < 0.2 g/kWh

- Potential for lowering the minimum allowed engine load from 50 % to 30 % of nominal power in customer-specific applications
- Potential for extension of power unit exchange interval from 30 kOh up to 40 kOh

Camshaft

The core new feature of the new Type 6 engine generation and all its application-specific engine versions are the new camshafts for the single-stage and two-stage turbo-charged engines, which have improved Miller valve timings and valve lift profiles.

The new profiles improve both gas exchange (reduced pumping losses) and knock margin. The higher knock margin is mainly used to operate the engines with higher mixture temperatures in the intake receiver (cylinder inlet). This results in higher thermal efficiencies and tailor-made CHP-applications as well as higher resistance against condensation at hot and tropic ambient conditions (see chapter "Operational Flexibility").

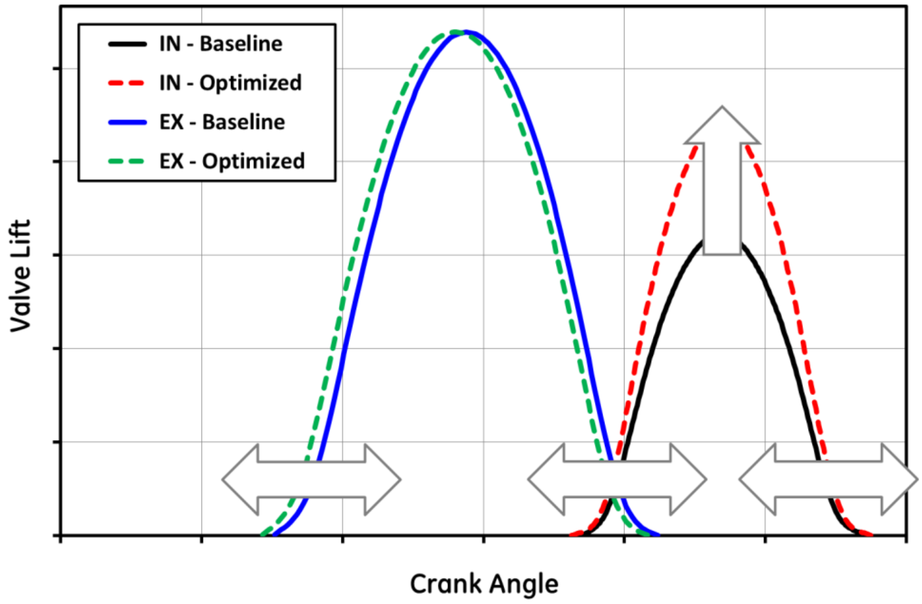

Figure 8: Valve lift profiles (sketch), optimization strategy

Figure 8 shows the available parameters for the gas exchange optimization. Exhaust opening was varied to optimize the blow-down from the cylinder. Exhaust closing and intake opening were varied to find the optimal trade-off between HC slip, residual gas content in the cylinder and cylinder-balancing. This optimization was also necessary to fulfil mechanical limits for seating velocity, respectively ramp design adapted to the boundary conditions of warm valve lash. The intake lift was raised for highest volumetric efficiency. Finally, intake closing was varied to obtain the required knocking behaviour.

Each individual opening or closing optimization has an effect on all other results. Therefore, the parameter variations were done iteratively to find the overall optimum.

Combustion Chamber

The combustion was optimized as well within the development of the latest Type 6 engine generation. Starting with a 3D CFD simulation and SCE measurement campaign, various pre-chamber variants were investigated. Some selected variants were measured later on at the multi-cylinder engine to assess their performance characteristics.

The target of the optimization was to obtain fast and highly efficient combustion, a stable and reproducible combustion (mainly in terms of COV IMEP) as well as low THC emissions. This target was applied for both 500 and 250 mg/Nm^3 NOx @ 5 % O2-dry.

A new pre-chamber design with optimized geometry has been series released meeting all requirements stated above. Furthermore, the design change is expected to have very positive impact on the exchange interval of the component. **Figure 9** shows the improved combustion course.

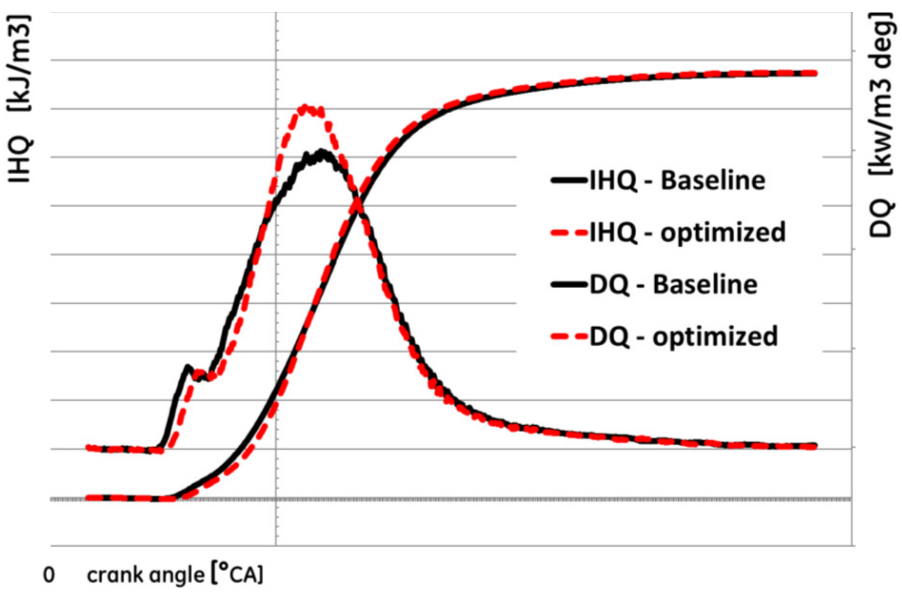

Figure 9: Integrated and differential heat release, baseline and optimized pre-chamber

Development Results and New Engine Versions

Operational Flexibility

As already mentioned in the section "Camshaft" above, the new cam profiles are not only improving the gas exchange-driven engine efficiency. The utilization of slightly advanced Miller intake valve timing also results in a higher margin to knocking border and therefore enables higher mixture temperatures at the cylinder inlet. Depending on the engine version, this could even be used to increase the compression ratio of some versions. Furthermore, tailor-made versions for CHP as well as hot and tropic ambient conditions are feasible.

CHP-applications are observed mainly in Europe or North America at standard ambient conditions and are targeting the highest possible total efficiency at 65-70°C customer return water temperature. Gen-set applications in hot and tropic ambient conditions like in South-East Asia are calling for maximum engine efficiency at a customer return water temperature that just fulfills the needed level of humidity resistance.

The great experience of GE in these applications and the continuous consideration of customer feedback enabled the development of customized products at a leading level of electrical and total engine efficiency at very high BMEP as shown in **Table 3**. The geographical bandwidth of top engine efficiency versions could be significantly extended with the new engine generation due to its enhanced humidity capability.

Power, Electrical Efficiency and Thermal efficiency

Table 3 summarizes the latest product enhancements for the new Type 6 engine generation J612, J616, J620 "J" and J624 "K" comparing 2016 data to 2017 data. In summary, the customer benefits from the following combined improvements:

- higher BMEP,
- higher electrical engine efficiency,
- higher thermal engine efficiency,
- lower methane number required,
- higher humdity allowed.

Table 3: Jenbacher Type 6 gas engine data, natural gas versions (Product Program 2017)

Engine version	J624 **K**[4]	J620, J616 and J612 **J**
BMEP [bar]	24 (2016) **24,5 (2017)**	22
Engine power [kW_{el}]	4400 (2016) **4500 (2017)**	3350, 2680 and 2010
Electrical efficiency[1] at Standard Ambient Conditions [%]	46.3 @ MN >83 and ICWT[3] 48°C (2016) **47.0 @ MN >80 and ICWT[3] 55°C (2017)**	45.6 @ MN >84 and ICWT[3] 40°C (2016) **46.0 @ MN >85 and ICWT[3] 45°C (2017)** **or** **45.7 @ MN >80 and ICWT[3] 45°C (2017)**
Electrical efficiency[1] at Hot & Tropic Ambient Conditions [%]	45.6 @ MN >80 and ICWT[3] 70°C (2016) **>46.0 @ MN >80 and ICWT[3] 50°C (2017)**	44.1 @ MN >80 and ICWT[3] 60°C (2016) **45.0 @ MN >75 and ICWT[3] 50°C (2017)** **or** **>44.6 @ MN >65 and ICWT[3] 50°C (2017)**
Total efficiency[2] in CHP-optimized versions [%]	91.9 (2016) **>92.5% (2017)**	89,3 (2016) **90.8 (2017)**

1 NOx = 500 mg/Nm^3 @ 5 % O_2 in exhaust gas, 50 Hz operation, Eta_Gen = 98.0%
2 Electrical and thermal efficiency, combined heat and power (CHP), 50 Hz operation
3 ICWT: required intercooler water inlet temperature of low temperature intercooler stage
4 J624K will be available as customer specific special release in PP2017

Figure 10 shows historical and latest Type 6 development steps in terms of electrical efficiency and power density (BMEP). The performance increase to 47.0 % electrical efficiency and 24.5 bar BMEP is being considered as a major step forward.

Nevertheless, it shall be highlighted that the achieved steps for alternative variants (e. g. hot and tropic ambient conditions) are even bigger – both for SSTC and TSTC applications. These steps could be realized also together with an increased power output.

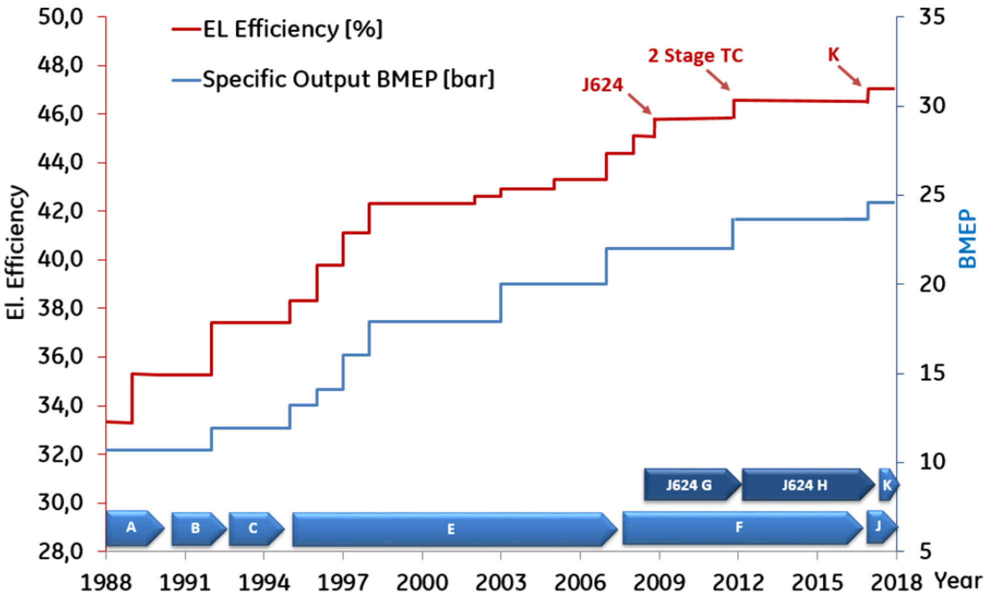

Figure 10: GE's Jenbacher Type 6 gas engine development steps and engine versions

Summary

With the latest product enhancements resulting in a new engine generation, GE's Jenbacher Type 6 gas engine family now offers a very high electrical efficiency of up to 47.0 % at 24.5 bar BMEP (4.5 MWel). Furthermore, a very high total efficiency of up to 92.5% can be provided. In addition, several new engine versions can be operated with natural gas with lower methane number and at ambient conditions with higher humidity.

These performance improvements could be achieved by the following measures: The gas exchange was enhanced by optimized intake and exhaust ports and by newly developed cam profiles. The combustion was advanced by an optimized prechamber and an improved prechamber gas system.

In addition, several mechanical improvements could be realised: Structural integrity, reliability and availability figures could be further enhanced by using new cylinder head, cam shaft, pre-chamber and power unit components. The oil consumption e. g. could be reduced from < 0.3 g/kWh to < 0.2 g/kWh.

The new Type 6 engine generation with various single-stage and two-stage turbocharged variants thus provides noticeable improvements in performance, reliability and product flexibility. Dedicated version management results in tailor-made engine versions for various segments for multiple applications around the world.

Abbreviations and Symbols

A/F	-	Air/fuel
BMEP	-	Brake mean effective pressure
CFD	-	Computational fluid dynamics
CHP	-	Combined heat and power
CO	-	Carbon monoxide
COV	-	Coefficient of variance
CR	-	Compression ratio
EIVC		Early Intake Valve Closing
EU	-	European union
GDP	-	Gross domestic product
HC	-	Hydrocarbons
ICWT		Intercooler water inlet temperature of low temperature stage
IMEP	-	Indicated mean effective pressure
IVC	-	Intake valve closing
MBF	-	Mass burn fraction
MCE	-	Multi cylinder engine
MN	-	Methane number
OECD	-	Organisation for economic co-operation and development
PC	-	Prechamber
SCE	-	Single cylinder engine
TC	-	Turbocharger
V	-	Volume
WG	-	Waste-Gate
ε	-	Compression ratio

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Springer

http://www.springer.com/978-3-658-19011-8

Heavy-Duty-, On- und Off-Highway-Motoren 2016
Global Engineering - 11. Internationale
MTZ-Fachtagung
Siebenpfeiffer, W. (Hrsg.)
2017, XI, 313 S. 256 Abb., Softcover
ISBN: 978-3-658-19011-8