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SWUMBLE 3-Cylinder High Efficiency Gasoline Engine for Future Electrified Powertrains

SWUMBLE 3-Zylinder hocheffizienter Benzinmotor für zukünftige elektrifizierte Antriebe

Abstract

Stringent worldwide CO_2 targets are leading the automotive industry towards carbon neutrality. Although the deployment of electric vehicles is part of the solution, a large part of the manufactured vehicles in 2030 will still feature advanced hybrid architectures and will continue to be equipped with internal combustion engines. In this context, improvements in engine efficiency are still very important to reduce the CO_2 emission of the vehicle. In parallel, it has become mandatory to reduce pollutant emissions in all driving situations to make the use of combustion engines acceptable in as many areas as possible.

In this context, IFPEN has developed a high efficiency and low pollutant emissions solution. It has coupled a high compression ratio with high Miller rate and EGR dilution to operate the engine under stoichiometric conditions. Despite these difficult conditions for flammability, a fast combustion is achieved thanks to an innovative and complex in-cylinder fluid motion called Swumble. Unlike current SI engines that generally only use tumble fluid motion, this innovation combines tumble, cross-tumble and swirl motion. This combustion system enables high brake thermal efficiency and reduced particulate emissions simultaneously.

In this paper article, the development of a 3-cylinder 1.2L engine in the 90kW/L class is described. It utilizes the innovative combustion system mentioned above including a dedicated airpath/EGR system and its associated control algorithms. Firstly, the combustion system is presented. Secondly, the thermodynamic layout and the design of the airpath including the turbocharger and EGR system are presented. Finally, the major control strategies of the complete system are described.

The engine shows a maximal thermal efficiency of 41% under warm steady states conditions, which is a world benchmark for a small gasoline engine.

Kurzfassung

Strenge weltweite CO2-Ziele führen die Automobilindustrie in Richtung CO2-Neutralität. Obwohl der Einsatz von Elektrofahrzeugen Teil der Lösung ist, wird ein großer Teil der im Jahr 2030 hergestellten Fahrzeuge über fortschrittliche Hybridarchitekturen verfügen und weiterhin mit Verbrennungsmotoren ausgestattet sein. In diesem Zusammenhang sind Verbesserungen des Motorwirkungsgrades nach wie vor sehr wichtig, um den CO2-Ausstoß des Fahrzeugs zu verringern. Parallel dazu ist es obligatorisch geworden, die Schadstoffemissionen in allen Fahrsituationen zu reduzieren, um den Einsatz von Verbrennungsmotoren in möglichst vielen Bereichen akzeptabel zu machen.

In diesem Zusammenhang hat IFPEN einen Motor mit hohem Wirkungsgrad und geringen Schadstoffemissionen entwickelt. Sein hohes Verdichtungsverhältnis mit einer hohen Miller-Rate sind gekoppelt mit einer AGR-Verdünnung, um den Motor unter stöchiometrischen Bedingungen zu betreiben. Trotz dieser schwierigen entflammbarkeits Bedingungen wird dank einer innovativen komplexen Ladungsbewegung im Zylinder namens Swumble eine schnelle Verbrennung erreicht. Im Gegensatz zu aktuellen SI-Motoren, die im Allgemeinen nur Tumble-Ladungsbewegungen verwenden, kombiniert

diese Innovation Tumble-, Cross-Tumble- und Swirlbewegungen. Dieses Verbrennungssystem ermöglicht gleichzeitig einen hohen effektiven thermischen Wirkungsgrad und reduzierte Partikelemissionen.

In diesem Artikel wird die Entwicklung eines 3-Zylinder-1,2-Liter-Motors beschrieben. Es nutzt das oben erwähnte innovative Verbrennungssystem, einschließlich eines speziellen Ladeluftweg- / AGR-Systems und der zugehörigen Steuerungsalgorithmen. Zunächst wird das Verbrennungssystem vorgestellt. Im Anschluss werden das thermodynamische Layout und die Gestaltung des Luftwegs einschließlich Turbolader und AGR-System vorgestellt. Abschließend werden die wichtigsten Steuerungsstrategien des Gesamtsystems beschrieben.

Der Motor weist unter warmen stationären Bedingungen einen maximalen thermischen Wirkungsgrad von 41% auf, was einen weltweiten Maßstab für einen kleinen Benzinmotor darstellt.

Introduction

The reduction of greenhouse gases and air pollutant emissions is one of the main objectives of the transportation sector today. This is driven by the fast evolution of the different environmental regulations all over the world. In order to accomplish this ambitious objective, it is necessary to reduce the fuel consumption via the development of new technologies in the automotive industry. Vehicle electrification is one of the most effective methods to contribute to this reduction. Such technology will be increasing in the future and will especially be implemented in powertrains hybridization. As such, around 70% of the vehicles in 2030 will still be equipped with an internal combustion engine in Europe [1]. Among the powertrain technologies, gasoline engines will be the most common engine technology. Despite electrification, R&D efforts still need to be focused on improving the engine efficiency in order to improve the vehicle CO_2 emissions. As discussed by Gautrot et al. [2], the improvement of engine brake efficiency yields significant reductions on the hybrid vehicle CO2 emissions.

In the race for better efficiency, the first measure for improvement is to increase the compression ratio of the engine. Nevertheless, this generates a well know problem in Spark-Ignition (SI) engines which is the auto-ignition of pockets of air-fuel mixture, commonly known as engine knock. This is one of the main obstacles preventing today’s engines from attaining higher load operations and subsequently higher thermal efficiencies.

Different methods exist to avoid the “knock” phenomena. One method is to reduce the intake valve lift duration, enabling Miller cycle operation and thus lowering of the effective compression ratio. However, this comes with a high loss of aerodynamics inside the combustion chamber and turbulence reduction close to the top dead center (TDC), which results in higher combustion durations and poor performance [3]. Another method to reduce knocking is to re-introduce burned gases inside the combustion chamber via Exhaust Gas Recirculation (EGR). The difference in air intake gases composition leads to a higher specific heat capacity of the gases inside the combustion chamber which reduces the temperature of the fresh gases during the combustion process and reduces auto-ignition [4]. However, EGR increases the combustion duration which results in combustion instabilities and thus unacceptable engine performances.

In order to make the most of the combined technologies (high compression ratio, Miller cycle and EGR), IFPEN has developed a concept named Swumble^{TM}. It consists of an innovative approach exclusively based on the design of the intake engine ducts and combustion chamber [5], making this technology adaptable to multiple engine families. The contribution of the paper is to present experimental results of a prototype multi-cylinder turbocharged engine equipped with this new technology. A maximum power output of 90 kW/L (full lambda 1) is achieved with a brake efficiency higher than 40% on a significant area of the engine map. Investigations carried out in catalyst heating mode show that this concept allows stable combustion for extremely late phasing, helping to rapidly reach the catalyst light-off temperature. Moreover, it produces a low level of raw emissions, especially particulate matter.

The paper is organized as follows. First, the benefits of the Swumble^{TM} combustion system is explained and illustrated with 3D calculation results. In the following section, the characteristics of the multi-cylinder engine equipped with a new generation of Swumble^{TM}

concept is presented, and the air system technologies are detailed. In the following section, experimental results showing engine performance in terms of efficiency, full load and pollutant emissions under cold operation are presented. CO_2 benefit drawn by this technology is highlighted through vehicle simulation results. Finally, positioning of the presented engine regarding to state of the art engines is given and future work is discussed.

Swumble^{TM} combustion system concept

As discussed previously, promising combustion technologies that have the potential to increase fuel efficiency are limited by the degradation of the combustion. In order to obtain a more turbulent performance close to TDC, it is possible to increase the level of tumble, by designing high tumble ducts or by using flaps in the intake ports for example [6][7]. The drawback of these kinds of approaches is that they tend to reduce the flow capacity, and therefore reduce the mass of fresh air admitted during the intake process. Another solution would be the utilization of an active pre-chamber [8], but it presents several difficulties for system integration, especially with direct injection engines. Furthermore, these approaches generally require expensive hardware modification.

The Swumble^{TM} concept consists in an innovative approach exclusively based on the design of ducts and combustion chamber with low flow capacity degradation [5]. It is well known that the motion inside the internal combustion engine is described with respect to the three axis of reference (X, Y, Z) as illustrated in Figure 1. The concept combines a high level of tumble associated with swirl motion.

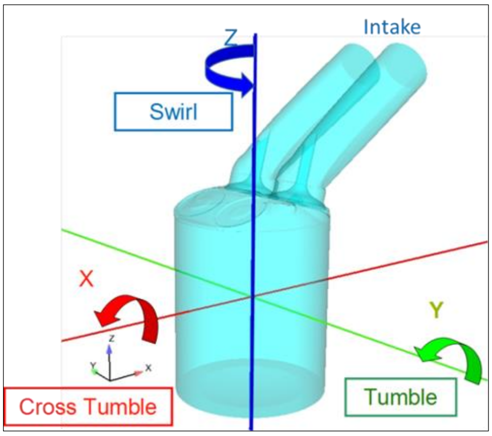


Figure 1 : Swumble^{TM} fluid motion [5] is a combination of Tumble and Swirl motions.

Figure 2 details the fluid motion during the compression stroke. The pictures show the combustion chamber and the ducts of the multi-cylinder engine that will be further discussed in the following sections. The stream lines come from computational fluid dynamics (CFD) calculations using the software Converge. In Figure 2(a), at the end of the intake phase, the vortex is well established with a variable axis that progressively straightens while the piston is going up, as seen in Figure 2(b). At the end of the compression stroke, the fluid motion ends in a tumble-like aerodynamics at Top Dead Center (TDC) as can be seen in Figure 2(c).

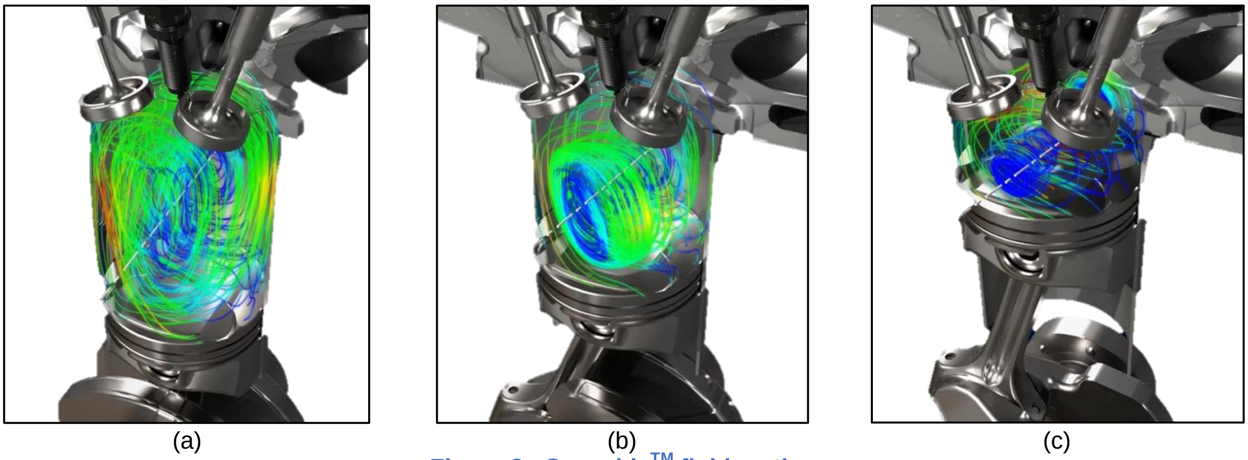

(a) (b) (c)

Figure 2 : Swumble^{TM} fluid motion.

In addition to its high capability of keeping a fast fluid motion all along the compression phase, the Swumble^{TM} concept has a very limited impact on the air flow capacity. Compared to other technologies mentioned above, its benefit relies on improving the flow capacity and turbulence trade-off.

As a high turbulence is ensured near TDC, a fast flame propagation can then be obtained, which significantly limits soot and HC formation thanks to a good mixing, and also results in a reduced propensity to knock [9]. Those characteristics are further highlighted in the experimental results section.

Multi-cylinder engine set-up

A three cylinder internal combustion engine based on a PSA EB2ADTS 96kW engine was designed and manufactured. The series-production cylinder head was removed and replaced by IFPEN cylinder head featuring Swumble^{TM}. The cylinder head is equipped with intake and exhaust Variable Valve Timing systems (VVT), an intake valve lift duration of 140°CA for Miller cycle and a 350bar injection system to optimize air-fuel mixing and reduce particulate emissions.

Engine displacement [l]	1.2
Vol. compression ratio [-]	13.65 : 1
Bore x Stroke [mm]	75 x 90.5
Number of intake /exhaust valves	2 / 2
Valve lift CA duration, at 1mm [°]	Intake 140 Exhaust 210
Injection system	DI central
Injector	Bosch HDEV6 6 holes
Injection pressure [bar]	350

Table 1 : Multi-cylinder engine main features.

Air system architecture

EGR system capability is desired in order to make the most of this high compression ratio engine. In order to fully benefit from the high compression ratio of the engine, an EGR system is desired to reduce the engine knock limitations. In addition, due to strong constraints on the air loop (high boost intake pressure, reduced exhaust enthalpy), the flexibility and efficiency of a variable geometry turbocharger is ideal. Consequently, all the air loop of the series-production engine has been removed and replaced by cutting edge air system technologies.

Figure 3 illustrates the prototype engine. The intake air filter has been preserved from the original engine. High efficiency VNT turbocharger is mounted instead of the fixed geometry turbocharger. The air charge air cooler has been removed to implement a compact and fully integrated Water Charge Air Cooler (WCAC). For the EGR circuit, the intake of the exhaust gas recirculation system is located downstream the three-way catalytic converter. A high efficiency and high flow capacity EGR cooler is used to cool the exhaust recirculation gases. In order to control the EGR flow rate, an EGR valve is located downstream the EGR cooler. The EGR circuit is finally connected upstream the compressor, where air and EGR gases are mixed. In case the required amount of EGR rate is not achieved by completely opening the EGR valve, an additional intake valve is placed upstream the compressor inlet, in order to increase the depression upstream of the compressor and hence increase the delta P and flow of recirculated exhaust gases into the intake system. Further details about the EGR system and the turbocharger are provided in the following sections.

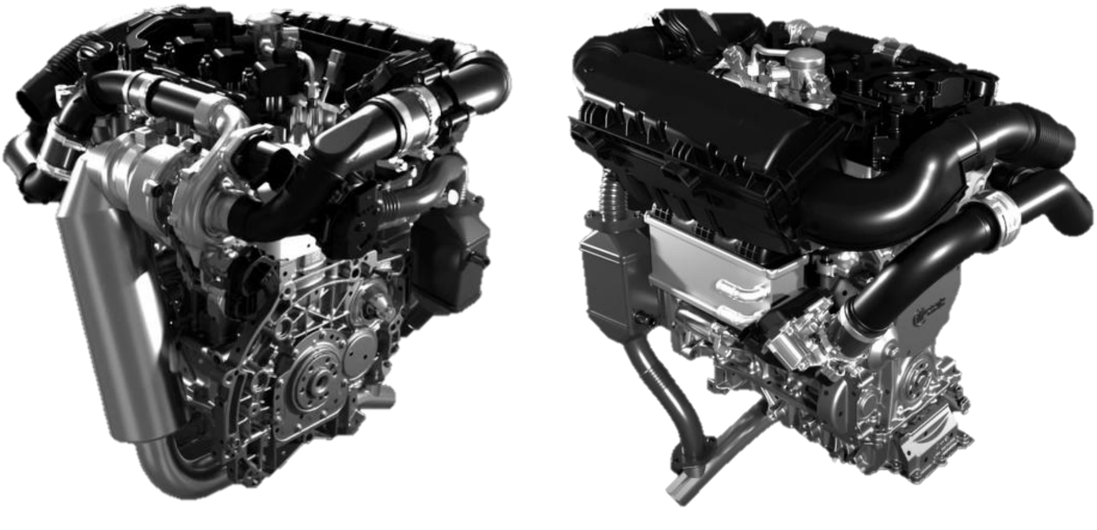


Figure 3 : Air system architecture of the prototype engine.

Air / EGR system description

EGR Cooler

Cooled EGR is widely used in turbocharged ICE (Diesel and SI), as its introduction into the combustion chambers enables a controlled reduction of reactivity of the mixture produced by the reduction in oxygen concentration as well as the combustion temperature.

As for two of the main factors affecting functionality of the EGR cooler, thermal efficiency and gas permeability, an advanced design proposal intended for this engine has been developed. The technical challenge is to effectively balance the maximal exhaust gas outlet temperature with the minimal gas pressure drop intended for higher engine loads.
The EGR cooler design includes some novel features such as, the use of high conductivity materials such as aluminium, the introduction of inner fin turbulator on both circuits plus an optimized cross section / length ratio. It allows the decrease of the pressure loss by more than 50% and a weight reduction of more than 35% compared to conventional iso-efficient EGR cooler designs in stainless steel.

EGR actuator

Low Pressure EGR is known to bring fuel consumption benefits on gasoline engines. These benefits are most of the time found with high EGR rate (25% or more) where the engine can be close to combustion stability limits. Accuracy of EGR rate control is key to get the best from the LP EGR system.
The Low pressure EGR valve is sized and designed to allow repeatable flow over time and high flow repeatability from part to part.
The intake valve is used to increase the differential pressure across the EGR system giving 2 advantages. Firstly, it allows higher EGR rate in areas of the engine map to be achieved where the differential pressure would normally be insufficient, and secondly it also allows EGR rate estimation to be estimated accurately with a DP sensor.

WCAC

Due to the usage of LP EGR as described previously, it becomes mandatory to be able to manage the intake temperature in order to avoid condensation phenomena. This is possible thanks to an indirect charge air cooling system using a smart low temperature coolant loop including a low temperature radiator and a water charge air cooler. The charge air temperature will be driven by the coolant temperature which could be simply regulated by a thermostat tune around the dew point temperature.
Moreover, a compact high efficiency WCAC is used on this engine. In such a configuration, the WCAC ensures the function of the intake manifold and is able to cool down the charge air gas directly close to the intake runners. The internal design of the WCAC allows to improve the coolant differential pressure and heat power trade off by the usage of an inner fin turbulator coupled with a fully structural concept able to optimize the external packaging and the air spray on the heat exchanger.
In the end, this charge air layout allows to decrease the charged air differential pressure by more than 50% compared to usual Air CAC technologies and this benefit is fully useful due to the mass flow increase induced by the LP EGR rate up to 25%.

Turbocharger description

The Swumble^{TM} combustion concept enables high-torque & power density and utilizes high EGR rate in part load. Thus, the boost target of the multi-cylinder engine is driven by two main points:

1. The rated power and low-end torque operating points
    - which set the compression ratio and the flow boundaries ;
2. The EGR rate at partial load
    - which demands high turbocharger efficiency to minimize pumping losses.

Since the maximum exhaust temperatures reached by the Swumble^{TM} combustion concept, at this power density are below 980°C, a VNT^{TM} turbine could be considered. This technology, pictured in Figure 4, initially designed for diesel engines, gives flexibility to change the turbine permeability and flow while maintaining a high level of efficiency.

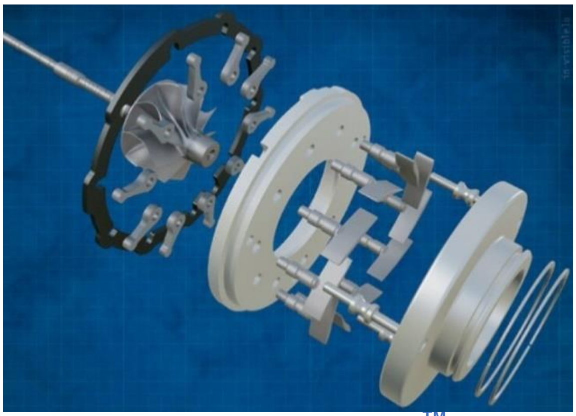


Figure 4 : Design of the Garrett VNT^{TM} cartridge.

The turbine stage materials were chosen for a continuous working temperature of up to 980°C. Considering the boost needs described before, a 2nd generation gasoline VNT turbine was selected. Gen2 gasoline VNT turbine has higher efficiency at low flow, while increasing efficiency by more than 15% at high flow versus GEN1 turbine stage (see Figure 5). Turbine stages similar to this, designed to fit the Miller cycle gasoline engine needs, are planned to go in production soon.

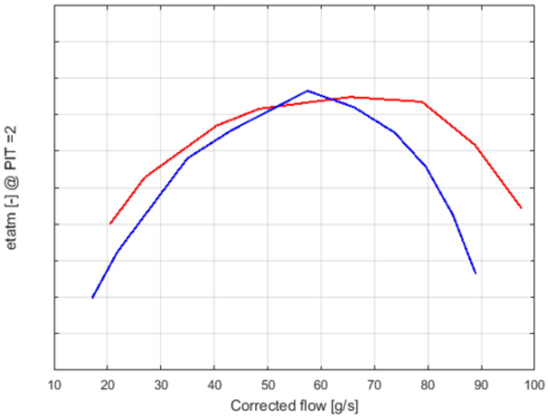


Figure 5 : Turbine efficiency at PiT = 2, blue: gen1 turbine, red : gen2 turbine.

The excellent engine efficiency is translated into a reduced air demand, that helps to select a relatively small turbocharger, with contained rotating inertia. Main parameters of the turbocharger are described in the table below.

Compressor	Compressor wheel diameter	41mm
	Compression ratio	Higher than 3
Turbine	Turbine wheel diameter	37.6mm
	Vanes number	8
	Expansion ratio	Lower than 2

Table 2 : Main characteristics of Swumble^{TM} turbocharger.

Test-bench setup

Figure 6 shows a picture of the engine test cell. Several pressure and temperature sensors are placed all along the intake and exhaust pipes of the engine. Each cylinder is equipped with Kistler 6041B pressure cylinder sensors. Fuel consumption measurement is provided by a Coriolis fuel mass flow meter AVL KMA 4000. Exhaust particle are monitored with an AVL Smoke Meter and with a Horiba MEXA-2000 SPCS particle counting system set to count all the particles down to 10nm mobility diameter.
The engine control is managed by a fully open ECU McLaren TAG400i.

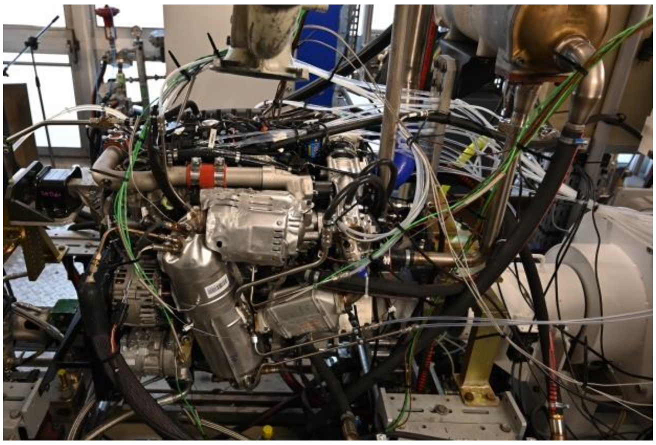


Figure 6 : Prototype engine in the test cell.

Engine tests operating conditions

All the tests are performed using a standard E10 RON 95 gasoline fuel. The ambient air is regulated around 50% of relative humidity and 20°C at sea level pressure. The oil and water coolant temperatures are fixed at 90°C. In order to be representative of real-life vehicle operating conditions, WCAC coolant temperature is regulated at 25°C. The intake manifold temperature is thus a consequence of the WCAC efficiency.

In this phase of the study, the Gasoline Particulate Filter (GPF) have been removed. The turbine downstream pressure was then calibrated in such a way to be representative of a full after-treatment system (three way catalytic converter + gasoline particulate filter) by means of a backpressure valve.

Even though a higher fuel injection pressure rail and a new double overhead camshafts driving system (opening valves via rocker arms instead of directly) are leveraged, the friction mean effective pressures for different engine operating points remain similar to that of the base engine.

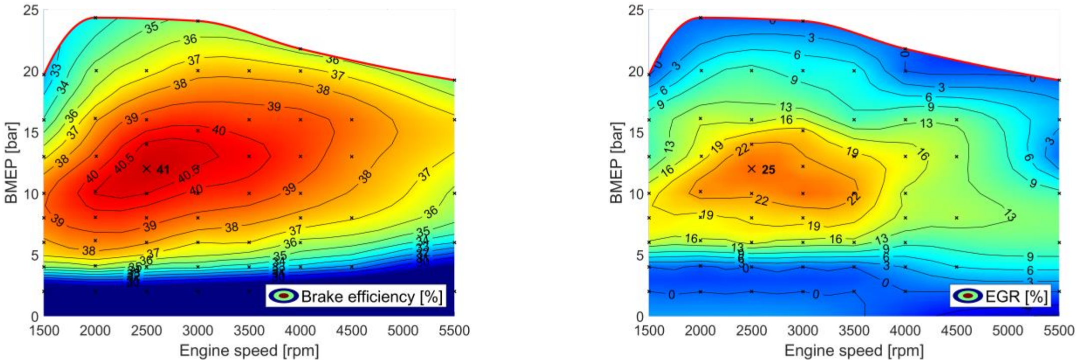
Experimental results

Engine map results

Figure 7 and Figure 8 present the results obtained on the whole engine operating area. The dots represent the optimized operating points. An optimization using the actuators

(EGR rates, VVT position, start of injection, spark advance) was performed in order to obtain the best engine brake efficiency taking into consideration the combustion stability and imposing lambda 1 on the whole operating area.

For these first optimized operating points, the maximum brake efficiency reaches 41% as illustrated in Figure 7(a). Figure 7(b) illustrates the EGR rates utilized throughout the operating map, showing a rate of above 20% on the high efficiency area.

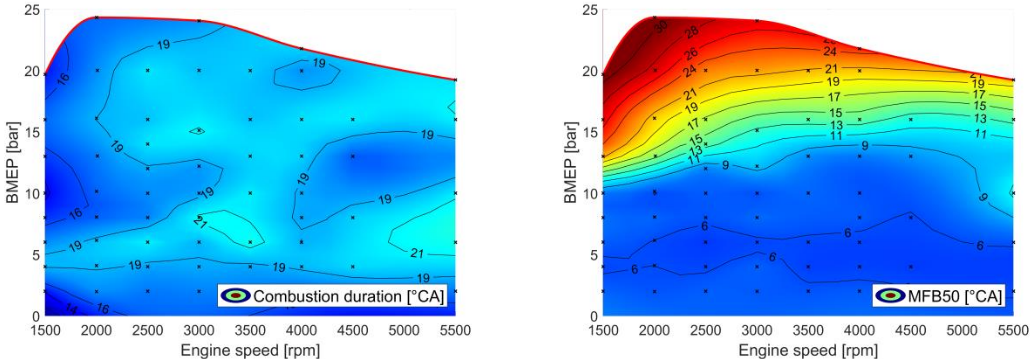


(a) (b)

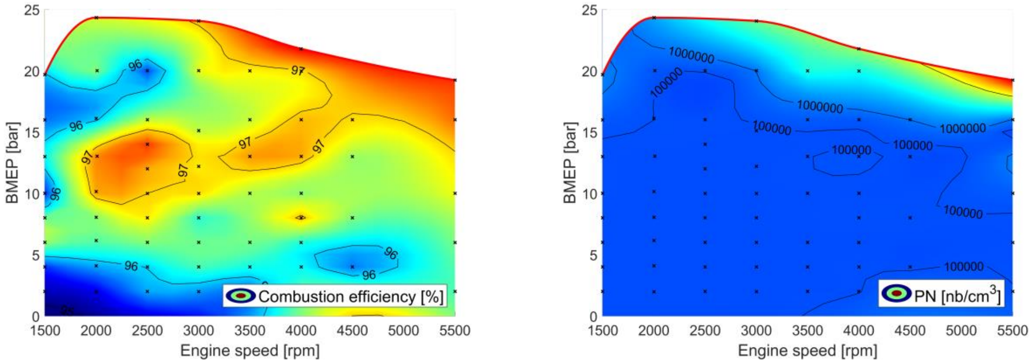
Figure 7 : Experimental results obtained at test bench on effective efficiency and EGR rates.

Despite high EGR rates, the combustion duration (difference between MFB90, angle where 90% of the Mass of Fuel has Burned, and MFB10) is short, under 21 °CA as presented in Figure 8(a). One can also highlight that the combustion is fast at high load and low engine speed despite high compression ratio and high Miller rate. Figure 8(b) illustrates MFB50, the midpoint of the combustion process; an optimal combustion phasing (CA50=~8°ATDC) is achieved until 12 bar BMEP which is very good considering the high compression ratio. At higher loads, a delayed MFB50 is preferred to avoid knocking instances.

The high level of turbulence and good mixing homogeneity is illustrated by the high level of combustion efficiency as shown in Figure 8(c) and the low level of particle number emissions, under a hundred thousand of particles per cubic centimeter, as illustrated in Figure 8(d).



(a) (b)



(c) (d)

Figure 8 : Experimental results obtained at test bench on CA50, combustion duration, combustion efficiency and particule number.

In order to stress the good behaviour of the turbocharger, Figure 9 shows that special care was taken to place the engine breathing lines close to the best efficiency line.

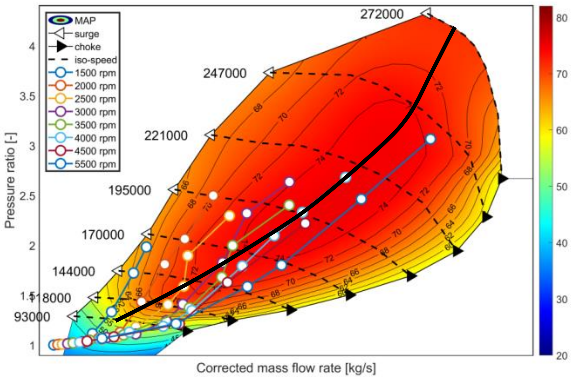
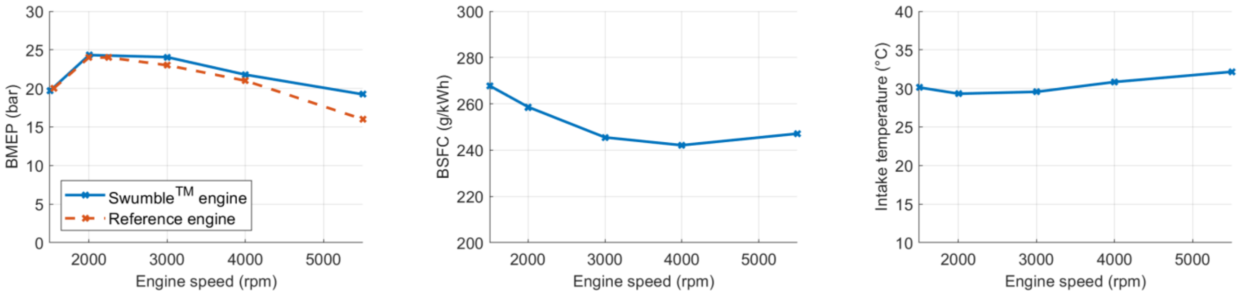


Figure 9 : Compressor map.

Full load results

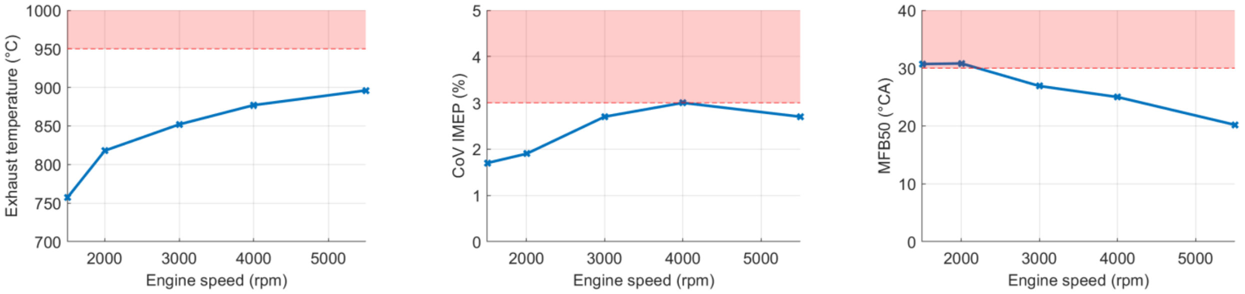
Figure 10 presents results in terms of BMEP, Brake Specific Fuel Consumption (BSFC) and intake temperature. Figure 10(a) presents a comparison between the Swumble^{TM} engine and the reference one. Even though the prototype engine uses Miller cycle (which decreases the ability of the engine to admit air) the full load is not compromised, and the maximum power output is even notably increased to reach more than 19 bar BMEP at 5500 rpm, corresponding to a specific power of 90 kW/l. In addition, the equivalence ratio is kept at stoichiometry throughout the full load curve, obtained without any EGR, allowing to keep a very interesting fuel consumption as highlighted in Figure 10(b). Finally, the intake temperature pictured in Figure 10(c) shows the good ability of the WCAC to maintain low intake temperature even at high mass flow rates.



(a) (b) (c)

Figure 10 : Full load results obtained at test bench.

The illustrations in Figure 11 display the operation limiting factors. In the three illustrations, the dotted red line represents the imposed critical threshold. Thanks to the very fast combustion of the system and an extended expansion stroke relative to the compression stroke (Miller effect), the exhaust temperature stays well below the limit imposed by the VNT turbine (950°C), as illustrated in Figure 11(a). Moreover, looking at the compressor map in Figure 9 shows that the compressor efficiency, on the rated power point, helps to keep the temperature below the exhaust temperature limit at lambda 1. The main limiting factor for high engine speeds is the combustion instability, which is evalutated by the cycle to cycle variations in IMEP (limitation imposed at 3% IMEP CoV) as shown in Figure 11(b). At low engine speeds, the limitation is due to the combustion phasing (MFB50) limited to 30°CA to prevent pre-ignition phenomenon.



(a) (b) (c)

Figure 11 :Operation limiting factors at full load.

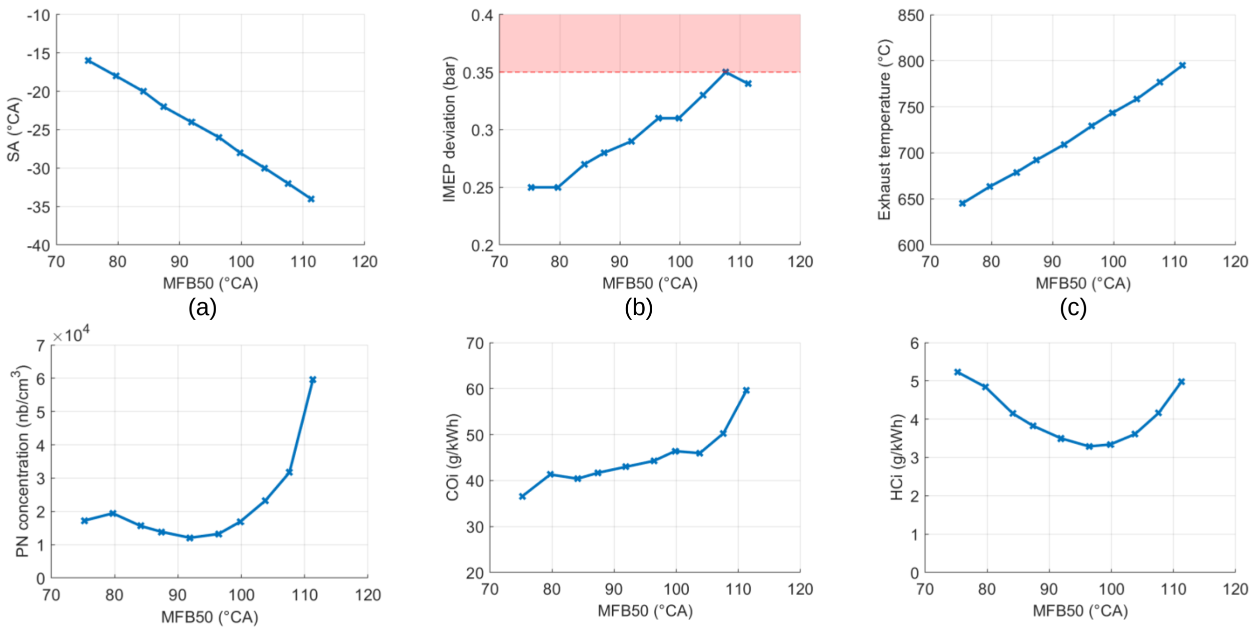
Warm up results

During a cold engine start, the emissions are relatively high since the catalysts have not reached their optimal operating temperature. To reduce the cold-start emissions, a strategy for fast engine warm-up is needed. The conventional approach is to significantly delay the spark timing. However, this leads to unstable combustion. The high turbulence motion of the Swumble^{TM} concept greatly helps to achieve a good fuel air mixture and a rapid combustion under cold conditions.

Figure 12 shows a typical idle engine operating point in catalyst heating mode: 1350 rpm and 1.7 bar IMEP, at 40°C engine water and oil coolant temperatures and 20°C intake air temperature. Usually, multiple injections strategies are applied to stabilize combustion for this type of operating points by attempting to create a local rich mixture near the spark plug but maintaining a global stoichiometric mixture [10]. With Swumble^{TM} concept, the best results in term of pollutants emissions and combustion stability is obtained using one simple injection (start of injection of 280°CA).

Figure 12 (a), Figure 12 (b) and Figure 12 (c) respectively present results of spark advance, IMEP deviation and exhaust temperature, regarding to MFB50 variation. Combustion stability is kept under the acceptable criteria of 0.35 bar IMEP deviation, despite a MFB50 of 110°CA. A temperature of 800°C is reached, which allows the delivery of a high exhaust heat flow to rapidly warm-up the catalyst.

Figure 12 (e), Figure 12 (f) and Figure 12 (g) respectively present results of particle concentration, CO and HC emissions. The low levels of emissions are obtained thanks to the high turbulence motion.



(a) (b) (c)

(d) (e) (f)

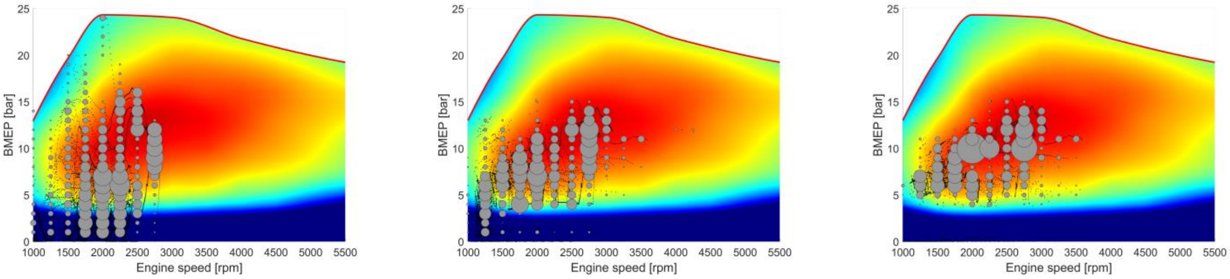
Figure 12 : Spark advance sweep on 1350rpm 1.7bar IMEP operating point (Twater = Toil = 40°C).

Vehicle consumption projection

In order to evaluate the benefit drawn by such an engine in terms of $C0_2$ reduction, some simulations have been performed thanks to the Hybrid Optimization Tool integrated in the IFP-Drive library of Simcenter Amesim [11], [12]. Two vehicles have been considered, the first one corresponds to a C-segment and the second ones to a D-segment. Three types of architectures are simulated:

- Pure thermal powertrain
- Mild parallel Hybrid Electric Vehicle (HEV): 48V, 20 kW electric motor power, 1.2 kWh battery
- Full parallel HEV: 350V, 60 kW electric motor power, 2 kWh battery

The simulation consists of evaluating the consumption over a WLTC homologation driving cycle. Figure 13 presents the operating points locations for the three architectures on the Swumble^{TM} engine map for the C-segment vehicle case. One can notice that with an increasing level of hybridization, a greater fraction of the operating points are located in the highest efficiency zone.

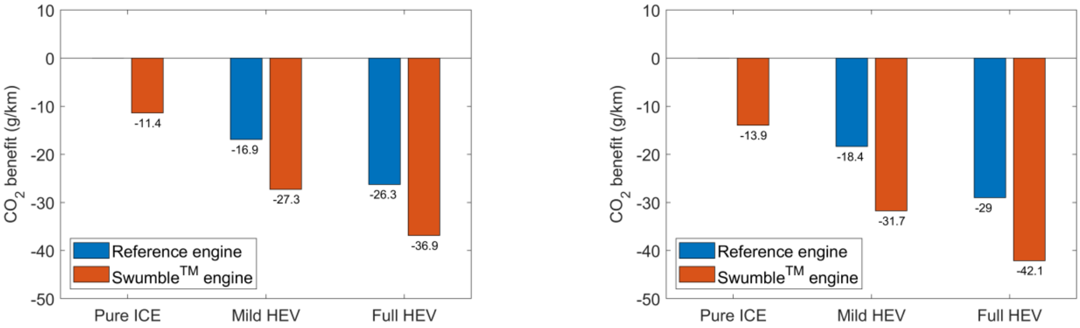


(a) Pure ICE (b) Mild HEV (c) Full HEV

Figure 13 : Operating points location of Swumble^{TM} engine on WLTC for three architectures.

Similar studies were conducted for the reference engine. Figure 14 presents the benefit in terms of CO_2 emissions for both vehicle classes, respectively C-segment in Figure 14 (a) and D-segment in Figure 14 (b), for the three powertrain architectures. Two observations can be discussed

- Electrification brings a CO_2 reduction of about 15-20% for the mild HEV case and 25-30% for the full HEV case.
- Improvement of engine efficiency map brings an additional benefit of at least 10% CO_2 reduction for all levels of hybridization.



(a) C-segment (b) D-segment

Figure 14 : CO_2 reduction on WLTC thanks to improvement of the engine efficiency map for the two vehicle segments.

Conclusions and future work

This paper displays the development of a new concept for high efficiency spark ignition engines. This concept is based on an innovative fluid motion which combines tumble and swirl, creating a Swumble^{TM} motion. No moving parts are used at the intake of the engine to create this Swumble^{TM} motion; instead, the design of the intake air duct is the driving factors for the Swumble^{TM} motion. Thanks to an increased charge motion, a large dilution is achievable which allows low engine-out pollutants and particulate emissions.

The results obtained on a prototype multi-cylinder engine show high efficiency associated with high specific power capacity. Figure 15 presents the engine performance relative to state of the art engines based on the peak effective efficiency and specific power output.

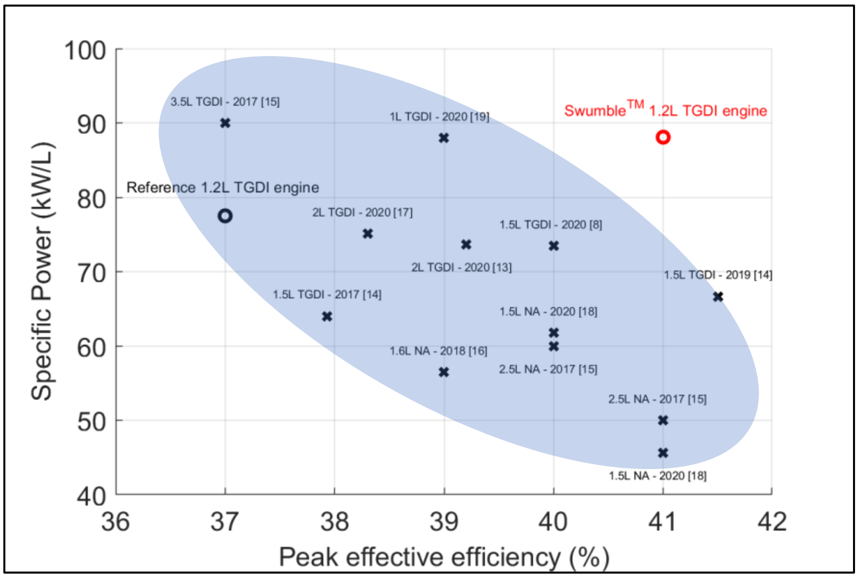


Figure 15 : Swumble^{TM} engine versus state of the art engines.

Further improvements are anticipated for the engine. A promising path consists of updating the turbocharger thanks to next turbine generation illustrated in Figure 16 (turbine efficiency improvement). Thanks to this technology, combined with the efficient combustion system, an increase of EGR rates is possible, which would allow to further optimize other levers such as the compression ratio and the Miller rate.

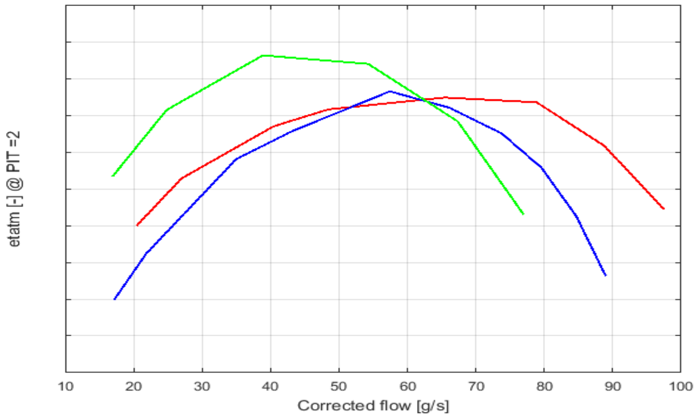


Figure 16 : Turbine efficiency at PiT=2, blue : Gen1, red : Gen2, green : next step.

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