SWUMBLE^{TM} 3-Cylinder High Efficiency Gasoline Engine for Future Electrified Powertrains

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Summary

IFPEN has developed a high efficiency and low pollutant emissions engine solution for future electrified powertrains. A high compression ratio coupled with high Miller rate and EGR dilution allows to operate the engine under stoichiometric conditions. In these extreme conditions of inflammability, a fast combustion is achieved thanks to an innovative complex in-cylinder fluid motion called Swumble^{TM}. It consists of the combination of tumble, cross-tumble and swirl motion, in contrary to current SI engines that generally only use tumble fluid motion.

In this article, the development of a prototype three cylinders engine implementing the Swumble^{TM} combustion system is presented. The engine shows more than 41% of break efficiency in a significant operating range under warm steady states conditions and maximum specific power of 90 kW/L at full lambda 1. Low level of raw emissions, especially particulate matter, are measured under cold conditions.

1 Introduction

Greenhouse gases and air pollutant emissions reduction is one of the major concerns of the transportation sector nowadays. This is driven by the fast evolution of the different environmental regulations all over the world. In order to accomplish with this ambitious objective, it is required to reduce the fuel consumption via new technologies development 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 especially through powertrains hybridization. This means that around 70% of the vehicles in 2030 [1] will still be equipped with an internal combustion engine in Europe. Among the powertrain technologies, gasoline engines will be the most spread engine technology. Despite electrification, R&D efforts still need to be focused on improving the engine efficiency, to improve the vehicle CO_2 emissions. As an illustration, Fig. 1 shows the beneficial impact that the engine brake peak efficiency has on the hybrid vehicle CO_2 emissions on a WLTP cycle.

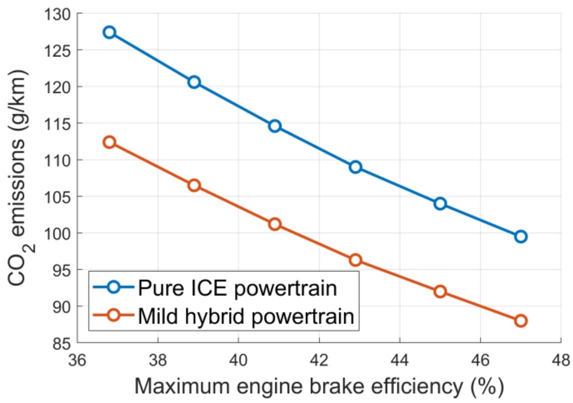


Fig. 1: Impact of engine efficiency on CO_2 emissions of thermal and mild hybrid vehicles.

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

There exists different methods to avoid knocking phenomena. One method is to reduce the intake valve lift duration, allowing to operate in Miller cycle and thus reducing the effective compression ratio. However, this comes with a high loss of aerodynamics inside the combustion chamber and subsequently a turbulence reduction close to the top dead center (TDC). This leads at the end to higher combustion durations and poor performances [2]. Another method to reduce knocking is to introduce Exhaust Gas Recirculation (EGR) inside the combustion chamber. The differences 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 [3]. However, EGR increases the combustion duration which results in combustion instabilities and thus unacceptable engine performances.

In order to take the most of the promising combined technologies (high compression ratio, Miller cycle and EGR), IFPEN has developed a concept named Swumble™. It consists in an innovative approach exclusively based on intake engine ducts and combustion chamber specific designs [4], making this technology adaptable to multiple engine families. The contribution of the paper is to present the very first results of a prototype multi-cylinder turbocharged engine equipped with this new technology. Maximum output power of 90 kW/L (full lambda 1) is achieved with a brake efficiency higher than 41% on a significant area of the engine map. Investigation carried out in catalyst heating mode shows 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.

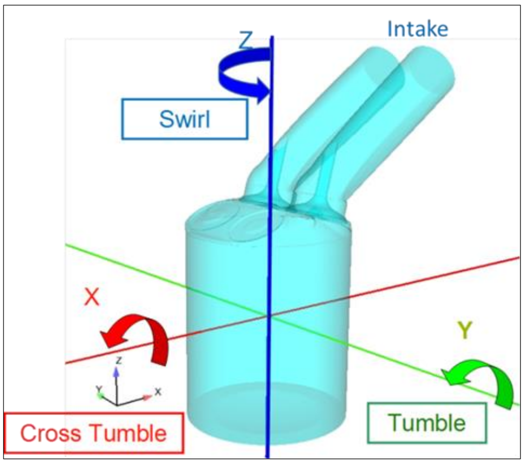
The paper is organized as follows. First, the benefits of a Swumble™ combustion system is explained and illustrated with 3D calculation results. In the following section, the characteristics of multi-cylinder engine equipped with new generation of Swumble™ concept is presented. In the fourth section, experimental results show engine performances in terms of efficiency, full load and pollutant emissions under cold operation. Finally, limitation of the air system is illustrated and some perspectives are given.

2 Swumble™ combustion system concept

High compression ratio is a well-known measure for improving theoretical thermodynamics engine efficiency, however it comes with an increase of knock sensitivity. The combination with Miller cycle strategy and air-fuel charge dilution by EGR reduces this negative aspect. However, combining these technologies comes with new challenges. By using the Miller cycle, high loss of aerodynamics and subsequent turbulence close to TDC is observed [2], which leads in the end to higher combustion duration and poor performances. In the same way, dilution with EGR also contributes to reduce flame speed leading to combustion instabilities.

For better turbulence performance close to TDC, higher Tumble levels have been targeted using different devices (flaps in the intake ports for example) [5-6]. 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 prechamber, but it presents several difficulties for system integration, especially with direct injection engines. Nonetheless, all of these approaches imply expensive hardware modification.

The Swumble™ concept consists in an innovative approach exclusively based on ducts and combustion chamber specific designs with low flow capacity degradation [4]. 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) illustrated in Fig. 2. The concept combines a high level of Tumble with Swirl motion, as shown by 3D CFD computation in the right picture. Additionally, it has been observed by Anselmi et al. [7] that adding a Swirl motion helps to reduce knocking sensitivity.



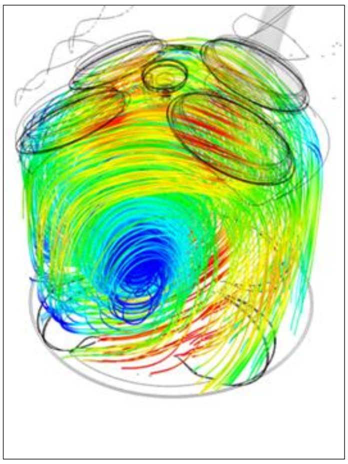


Fig. 2: Swumble^{TM} fluid motion [4] is a combination of Tumble and Swirl motions.

Fig. 3 displays a comparison of turbulent kinetic energy (TKE) for different CFD results obtained running on Miller cycle, between a tumble oriented engine and the Swumble^{TM} equipped engine. The flow admission capacity remains almost the same in both cases. Indeed, 3D calculations were performed imposing the same intake and exhaust boundary conditions for both cases on the 2500rpm/12 bar BMEP operating point, showing a similar intake air flow (only -0.7% of difference of the trapped mass for the Swumble^{TM} concept). When running the Swumble^{TM} engine, higher maximal values of TKE are obtained. In addition, a better distribution inside the chamber and high values of TKE close to the spark plug electrodes is observed. Moreover, the flame front (shown as a black solid line) has a symmetrical evolution, having already covered a larger area of the domain under the exhaust valves, when compared to the tumble reference case. The Swumble^{TM} concept allows then to improve the flow capacity and turbulence tradeoff compared to classical Tumble.

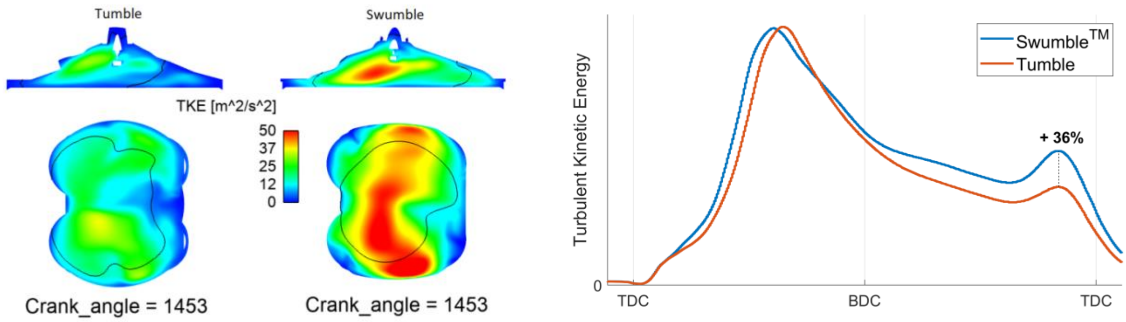


Fig. 3: Turbulent Kinetic Energy distribution obtained and flame fronts on both Tumble and Swumble engines.

3 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

Tab. 1: Multi-cylinder engine main features.

3.1 Air system architecture

As discussed previously, EGR system capability is desired in order to take the most advantage of this high compression ratio engine. In addition, considering strong constraints on the air loop (high intake pressure, low exhaust temperature), the flexibility of a variable geometry turbocharger is mandatory. Consequently, all the air loop of the series-production engine has been removed and replaced by cutting edge air system technologies.

Fig. 4 presents the prototype engine. The intake air filter has been preserved from the original engine. A *Garrett* 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), provided by *Valeo*. This last allows high efficiency, temperature control and condensation management. Concerning 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 provided by *Valeo* allows to cool down 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 reduce the compressor’s upstream pressure and increase the amount of exhaust gases introduced into the intake system.

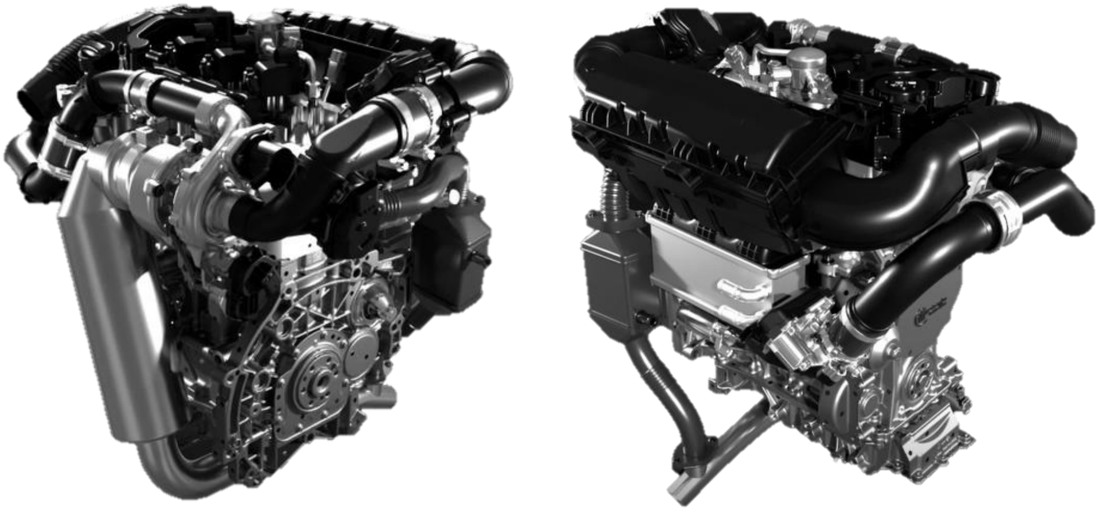


Fig. 4: Air system architecture of the prototype engine.

3.2 Test bench set-up

Fig. 5 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.

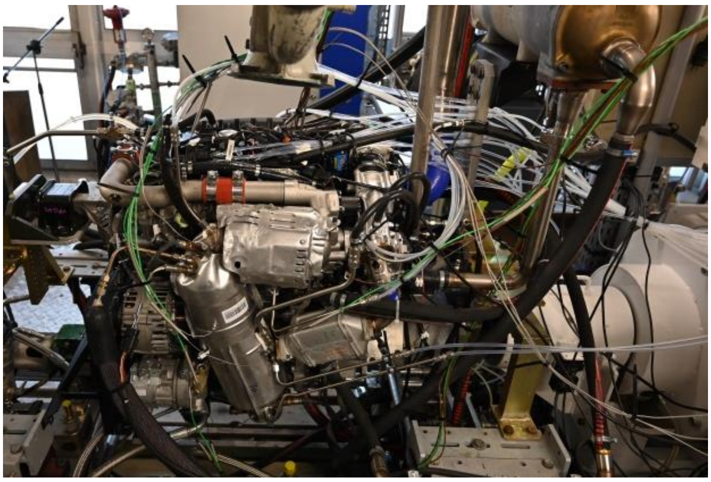


Fig. 5: Prototype engine in the test cell.

3.3 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 it is used a higher fuel injection pressure rail and a new double overhead camshafts driving system (opening valves via rocker arms and not directly), the friction mean effective pressures, for different engine operating points, remain at the same order of magnitude than the base engine (see Fig. 6).

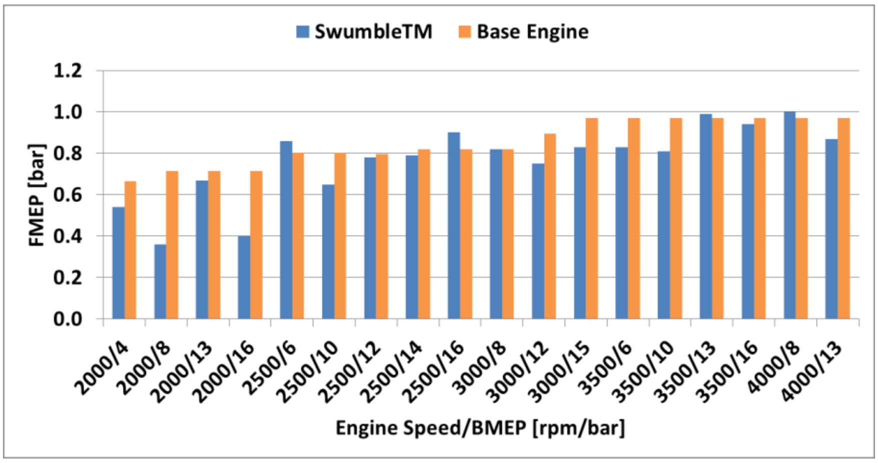


Fig. 6: Friction mean effective pressure: comparison with base engine level.

4 Experimental results

4.1 First results

Fig. 7 gives an overview of the first results obtained during the very first weeks of the engine tests. Twenty-one points at the core of the engine map as well as five points at full load were experimentally tested. An optimization using the actuators (EGR rates, VVT position, start of injection, and 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 exceeds 41%. These first results have been obtained considering non optimized FMEP (as shown above), not optimized oil and coolant temperatures, and with a standard E10 RON 95 gasoline. EGR rates is above 20% on the high efficiency area. Despite these high dilution rates, the combustion duration (MFB90-MFB10) remains small. The combustion efficiency is very high despite the high compression ratio. Finally, the particulate emissions are kept below 10^5 nb/cm^3 on a very large operating area. All these observations are indicators of high level of turbulence and good mixture preparation, testifying the relevance of the Swumble™ concept.

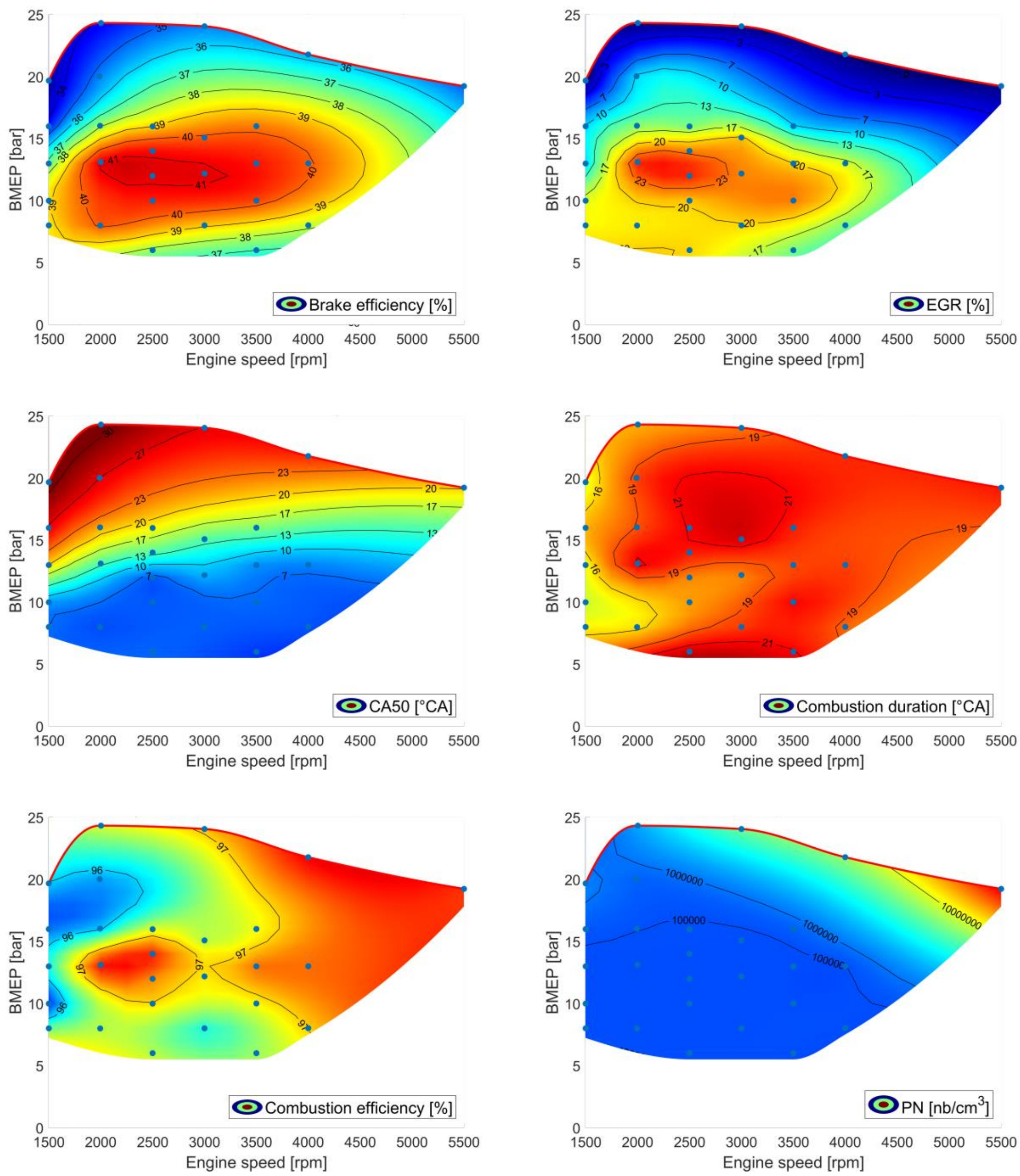


Fig. 7: Experimental results obtained at test bench.

4.2 Full load results

Fig. 8 presents a comparison of the full load between the reference engine and the prototype engine. Even though the prototype engine uses Miller cycle (which decreases the ability of the engine to inhale the air) the full load is not compromised, and the maximum output power is even notably increased (90 kW/l). In addition, the equivalence ratio is kept at the stoichiometry on the whole full load curve. The full load curve is obtained without EGR. Thanks to the very fast combustion of the system, the exhaust temperature stays far away from the limit imposed by the VNT turbine (960°C). The only limitation that appears is linked to combustion instabilities for high engine speeds (limitation to 3% CoV IMEP). At low engine speeds, the limitation is due to the MFB50 limited to 30°CA to prevent pre-ignition phenomenon.

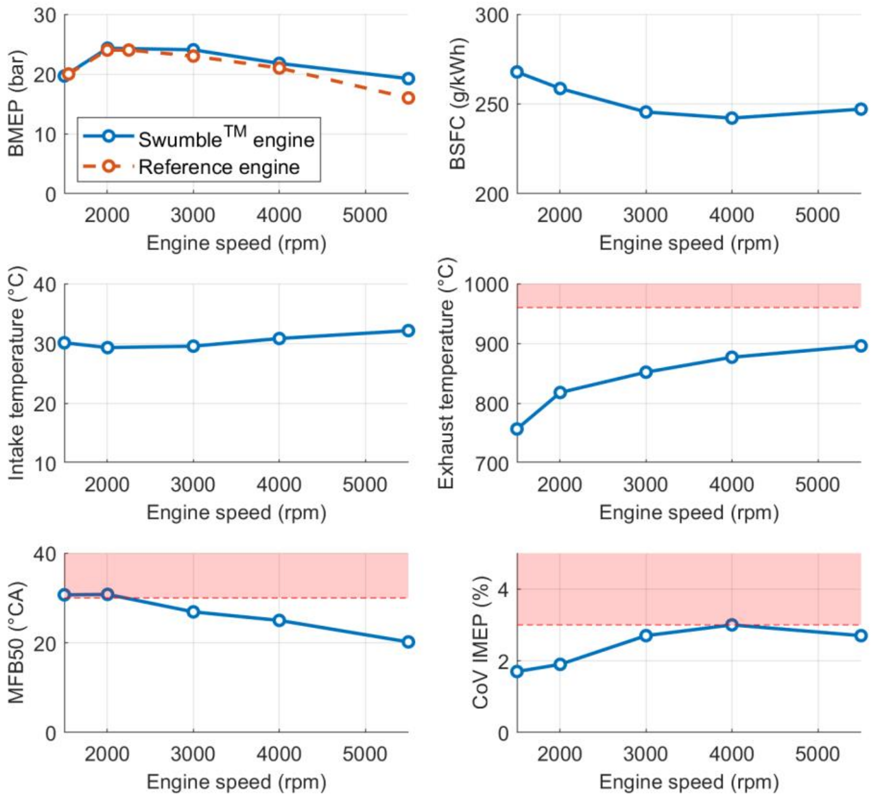


Fig. 8: Full load results obtained at test bench.

4.3 Warm up results

After a cold engine start, the emissions are relatively high since the catalysts have not reached their operating temperature. To reduce the cold-start emissions, a strategy for fast engine warm-up is needed. The main measure for improvement is to extremely delay the spark timing. However it leads to instable combustions. The Swumble™ concept with high turbulence motion greatly helps to prepare a good fuel air mixture and burn it quickly under cold conditions. Fig. 9 shows low levels of CO, HC and Particle Number (PN) emissions obtained on a typical idle engine operating point in catalyst heating mode: 1350rpm/1.7bar 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 searching to create a local rich mixture near the spark plug but staying in global at lambda 1 [8]. With Swumble^{TM} concept, best results in term of pollutants emissions and combustion stability were obtained only with one simple injection (SOI=280°CA). Combustion stability is kept under the acceptance criteria of 0.35bar IMEP deviation, despite a MFB50 of 110°CA. A temperature of 800°C is reached, which permits to deliver a high exhaust heat flow in order to rapidly warm-up the catalyst.

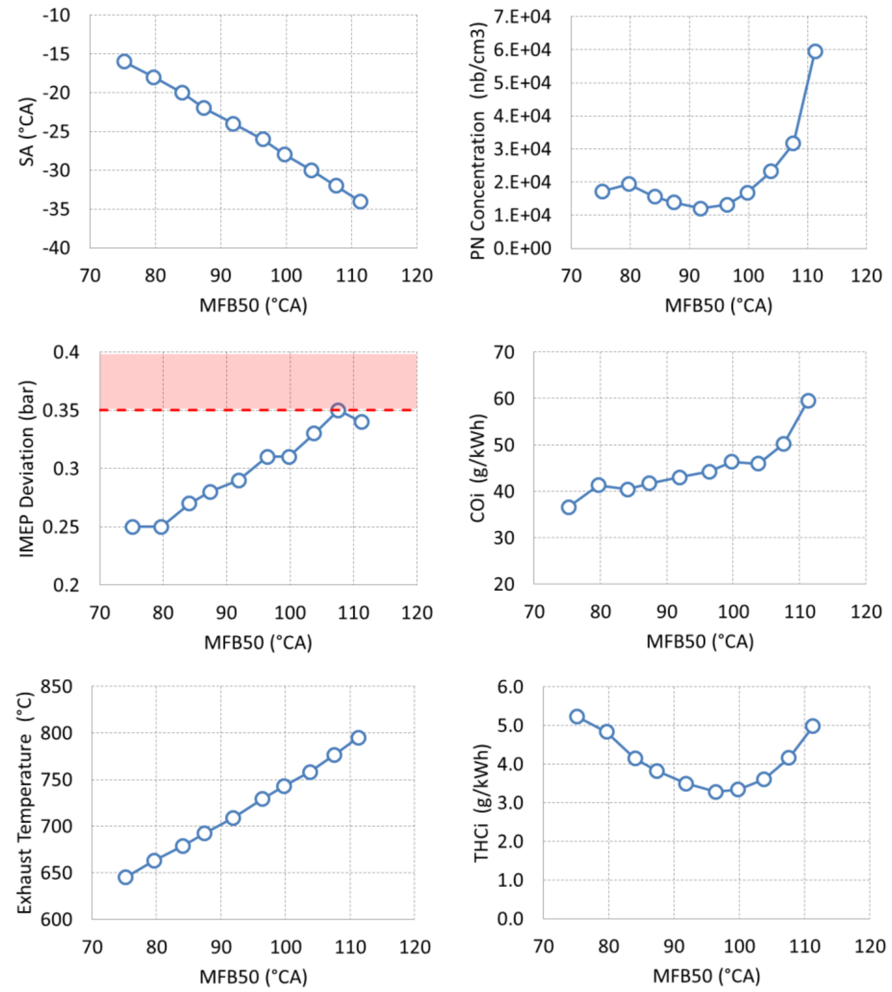


Fig. 9: Spark advance sweep on 1350rpm/1.7bar IMEP operating point (Twater=Toil=40°C).

5 Perspective of air system improvement

Fig. 10 shows measurements of an EGR sweep performed on a 3000rpm/12bar BMEP operating point. Thanks to high turbulence generated by Tumble™ concept, combustion duration and combustion instabilities remain very low (respectively < 21°CA and < 2%) up to 25% EGR rate. However, effective efficiency begins to decrease at 25% EGR rate. To obtain higher EGR rates, the turbocharger requires more energy to compress the intake mixture and therefore closes the VNT actuator. This leads to a higher upstream turbine pressure and to an increase of LP-IMEP. Air loop system efficiency becomes a key parameter to reach higher engine effective efficiencies.

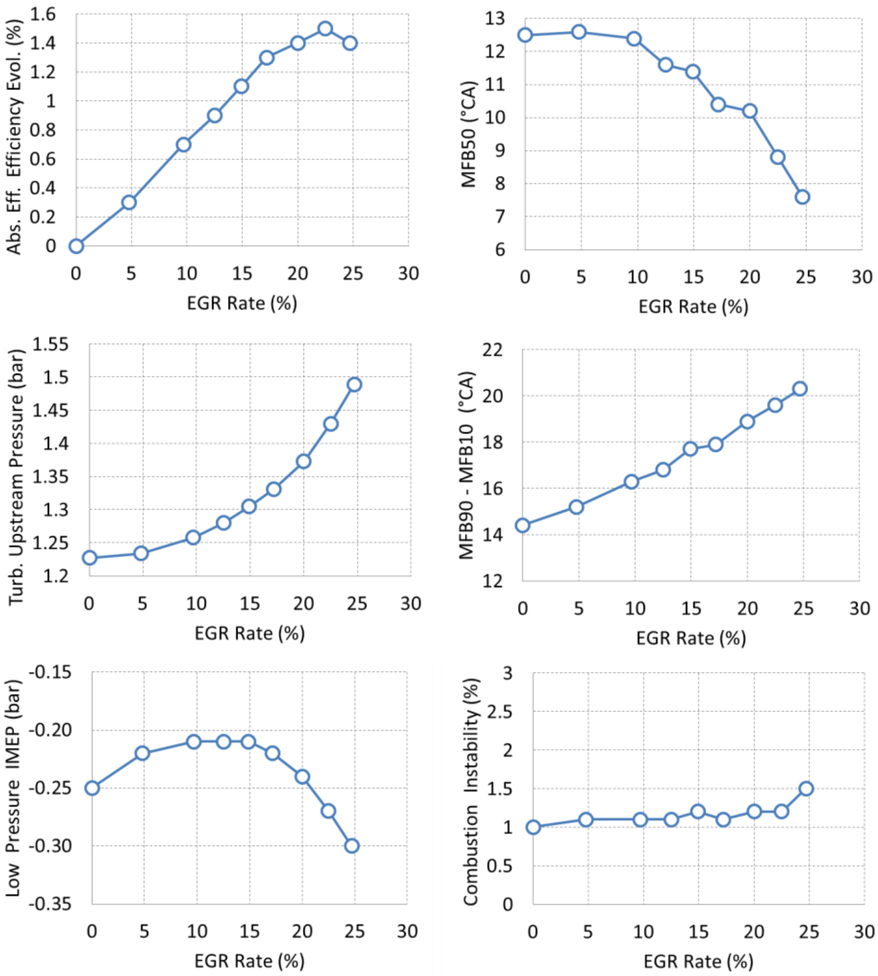


Fig. 10: EGR rate sweep on 3000rpm/12bar BMEP operating point.

Reducing upstream turbine pressure by optimizing turbocharger efficiency would be a way of improving the efficiency of the engine. Fig. 11 shows the sensibility of effective engine efficiency to a turbine upstream pressure reduction. This test is performed by decreasing turbine downstream pressure in order to simulate a more efficient turbocharger. The turbine upstream-downstream pressure ratio remains almost the same during this sweep. Around +0.2% of absolute effective efficiency is won with 40 mbar lower upstream turbine pressure. As expected, LP-IMEP decreases and a better combustion phasing is obtained due to less HP-IMEP.

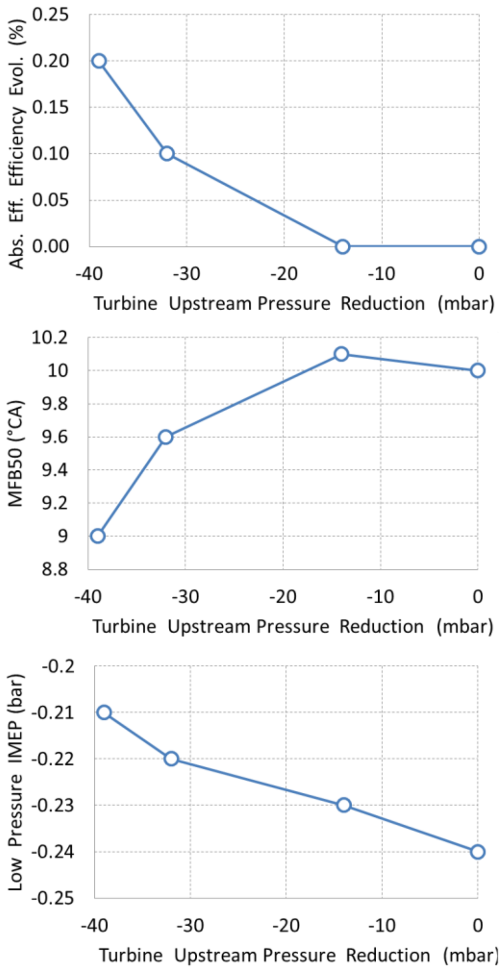


Fig. 11: Impact of turbine upstream pressure reduction on a 3000rpm/12bar BMEP operating point at the same EGR rate (20%)

6 Conclusion

This paper displays the development 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 mobile device is used at the intake of the engine to create this Swumble^{TM} motion.

The new concept shows an improved flow capacity and turbulence tradeoff. Thanks to an increased charge motion, it permits a large dilution capability associated with low engine-out pollutants and particulate emissions.

The first results obtained on a prototype multi-cylinder engine show high efficiency associated with high specific power capacity. First analysis show that the maximal efficiency is not limited by combustion but by air system limitations. That constitutes an interesting perspective to keep working towards the research of very high efficiencies.

The development is still ongoing and evaluation under transient conditions will be part of the very next steps.

7 Acknowledgement

The authors would like to acknowledge Valeo and Garrett for their collaboration on the air loop and the associated hardware provided; Didier Ambrazas, Christophe Lechard, David Bizien and Jérémy Jarry for the design, manufacturing and assembly of the engine; Adrien Nail for the fine work performed in operating the multi-cylinder engine.

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