

Preliminary Design of a Two-Stroke Uniflow Diesel Engine for Passenger Car

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ABSTRACT

The target of substantial CO₂ reductions in the spirit of the Kyoto Protocol as well as higher engine efficiency requirements has increased research efforts into hybridization of passenger cars. In the frame of this hybridization, there is a real need to develop small Internal Combustion Engines (ICE) with high power density. The two-stroke cycle can be a solution to reach these goals, allowing reductions of engine displacement, size and weight while maintaining good NVH, power and consumption levels. Reducing the number of cylinders, could also help reduce engine cost.

Taking advantage of a strong interaction between the design office, 0D system simulations and 3D CFD computations, a specific methodology was set up in order to define a first optimized version of a two-stroke uniflow Diesel engine. The main geometrical specifications (displacement, architecture) were chosen at the beginning of the study based on a bibliographic pre-study and the power target in terms. Using 3D CFD, the expansion / scavenging / compression phases were computed in order to evaluate the scavenging characteristic and the in-cylinder aerodynamics level which mainly depend on the combustion chamber geometry and on the intake and the exhaust manifolds and strategies. The scavenging characteristic was then used in 0D computations in order to evaluate each engine configuration in terms of power and consumption on the entire engine map. Indications were then deduced in order to guide the design office for the engine optimization.

One configuration was chosen to be built and tested on the test-bench. In the present paper the specific methodology is described and several indications are given for the preliminary design of such a two-stroke Diesel engine.

CITATION: Laget, O., Ternel, C., Thiriot, J., Charmasson, S. et al., "Preliminary Design of a Two-Stroke Uniflow Diesel Engine for Passenger Car," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-1719.

INTRODUCTION

The two-stroke gasoline engine is known to be cheap, compact, light, robust and friendly to use. That is why it is mainly found (fuelled with gasoline) on light mobile application such as the small powered vehicles (scooters, jet ski, outboard, snowmobile...) or mobile tools (chain saw, generator...).

The two-stroke Diesel engine appears to have a high potential in specific sectors such as that of huge power (marine propulsion or electric power plant) where some Diesel two-stroke engines called "slow engines" supply more than 100,000 HP with at least 50% of efficiency [1]. Such

engines count from five up to fourteen inline cylinders where the piston bore can reach 1 meter and its stroke 2.5 meters; the shaft revolution speed being of around 100 RPM. Their main qualities are the reliability (some electric generators have worked during more than 50 years) and low fuel consumption. However, their height (about 17 meters) and their mass (more than 1000 tons) limit their use.

Some aircraft engines also use the Diesel two-stroke cycle, a rather old technology [1] used by *Clerget* engines in the 1930's. Nowadays, another example is the *Wilksch* engine, a three-cylinder supercharged by a compressor, supplying 120 HP, and addressed to light airplanes (such as microlight...).

However, today two-stroke engines (gasoline or Diesel) cannot be found in the automotive industry even if during the 80's and the 90's there was a real interest from car manufacturers for the two-stroke gasoline engine, with many studies and patents published on this subject [3, 4, 5, 6, 7, 8, 9]. Indeed, despite the numerous advantages offered by the two-stroke engines, the tightening of pollutant emission standards and the good level of consumption reached by four-stroke Diesel engines finally drove the carmakers away. Nowadays, given the trend to reduce the costs coupled with the price increase of Diesel post-processing devices, the question of the use of two-stroke engine for automotive application can now be reopened. Considering hybrid application, or small vehicle using small (low power) combustion engine, the benefit in terms of cost becomes more advantageous compared to a Euro 6 compatible four-stroke engine.

The present study aims to examine the feasibility of a two-stroke Diesel engine designed for a hybrid automotive application, complying with the current pollutant emission and drivability standards.

CONTEXT AND OBJECTIVES

In this context of necessary reductions of greenhouse gas and pollutant emissions, the use of small urban and extra-urban vehicles is going to increase in a significant way. The use or the maintaining of Diesel engine (characterized by its high efficiency) on such vehicles represents one of the major keys allowing reaching those objectives. On the other hand, the cost of the post-processing devices (particle filter + nitrogen oxide reduction system) needed to comply with Euro 6+ standards, becomes so big that the Diesel engine applications on small vehicles may be compromised.

The use of a two-stroke Diesel engine may allow to reduce the engine outlet NOx emissions and to use only light and therefore a less expensive de-NOx system. Moreover, the double combustion frequency allows to push further the downsizing approach rendering the decrease in number of cylinders acceptable (from a NVH point of view) with a favorable impact on the mass, the bulk and the cost of the powertrain. A consequence of those advantages is that this low power but more compact and lighter engine can be used as a basis of an economic hybrid Diesel powertrain.

The two-stroke engine presents several advantages:

The extension of the operating range of Homogeneous Charge Compression Ignition (HCCI) combustion and the use of Residual Burnt Gases (RBG) to reduce the HC and CO emissions associated to such a combustion mode, naturally generating low NOx emissions.

- The doubled combustion frequency is favorable when reducing the cylinder number needed to maintain a high unitary displacement in order to favor the combustion efficiency;
- The aim is to study the application of a two-stroke Diesel engine of reduced size to urban or extra-urban vehicles with

hybrid electric power train or to smaller vehicles using only the combustion engine on an extended operating range.

The goal is to define the "strict minimum" technology for the target proposed with an objective of breakthrough in terms of NOx emissions, a saving of fuel consumption (~10%) and a decrease of cost compared to a four-stroke engine with similar performance levels. Consequently, a part of the objective is to define the engine architecture and geometry fitted to the targeted application in order to build an experimental single cylinder which will be used as a development and characterization tool. This preliminary study was realized using system simulation (0D, AMESim) and 3D CFD (IFP-C3D) tools following a specific methodology proposed and developed by IFPEN. Several technological challenges to be dealt with were identified:

- Air loop control;
- Burnt gas use;
- Internal aerodynamics;
- Control of the transitions between combustion modes.

The bibliography was also used to choose and to define the architecture of the engine

LITERATURE REVIEW

The two-stroke Diesel engine has been used for a longtime, mainly for large marine applications (including ships and tankers with Sulzer/MAN engines [1]) and for some aeronautic or ground applications (Junkers *Jumo 205* engines or *Detroit Diesel* engines [1]). The aim of this part was to establish the widest overview of existing two-stroke Diesel engine technologies in order to help identify and define the most interesting architecture for the targeted small automotive hybrid application with low power and complying with the current pollutant emission standards. Thus, the bibliographic research showed that in-line, V or opposed pistons two-stroke Diesel engine exists supplied either with a simple pump crankcase or more often, a supercharger (alone or coupled with a turbocharger). Likewise, several scavenging systems are available: loop scavenging with piston-controlled inlet and exhaust ports (*Schnürle* type [2]), loop scavenging using valves to control both intake and exhaust phases (*S-2* Toyota engine [3]), and uniflow scavenging. The latter, with 10 to 12 intake ports distributed all around the cylinder and 2 to 4 exhaust valves, is the most used scavenging mode. Indeed, as we shall see, it allows a better control of the scavenging and of the trapped burnt gas ratio. It is also well adapted to Diesel combustion due to its ability to generate a swirl motion [1], which is classical aerodynamics for direct injection Diesel engines. It is noteworthy that the two-stroke Diesel combustion system has followed the same improvement as the four-stroke Diesel engines (especially common rail and high pressure direct injection).

A revival of interest for two-stroke Diesel engines can be observed during the last decade, mainly from Daihatsu [4],

AVL [5], Daimler-Benz [6], Yamaha [7] and some universities [8][9]. These different studies were focused on small displacement engines with a reduced cylinder number (2 or 3) designed to be integrated in small automotive vehicles (combustion engine only or hybrid powertrain). For this kind of application, the two-stroke Diesel technology is indeed interesting because it maintains an acceptable engine acyclic level while benefiting from the good efficiency of the Diesel combustion. During the design phase, particular attention must be paid to the lubrication of the connecting rod small end the piston/liner set and to the thermal resistance of the piston.

This bibliography helps in making the first choices for the definition of the engine architecture:

- The uniflow technology with intake ports and exhaust valves was taken as the basis for the present study;
- Direct high pressure common rail Diesel injection taking advantage of latest four-stroke Diesel engine improvements.

0D SIMULATION OF TWO-STROKE SINGLE-CYLINDER ENGINE

Presentation of the 0D Simulation

Combustion model

The use of simulation tools appears at different steps of the engine development: from the understanding of the physical behaviour to the preliminary design of the engine. For these different stages, the balance between accuracy/predictivity and CPU cost of the models is not the same. In order to simplify and provide all the tools necessary to help engine control development and pre-calibration processes, IFP Energies nouvelles is developing an engine library called IFP-Engine in the AMESim platform edited by LMS IMAGINE.Lab. This library contains phenomenological models for a precise description of the physical phenomena and real-time models for engine control pre-calibration.

Two-stroke scavenging model

In this study, a combustion model based on the Barba approach [10] is chosen to compute the combustion heat release rate. This model has been especially improved for the two-stroke engine application. Indeed, the scavenging flow modeling has to be provided. The notion of “perfect displacement” and “perfect mixing” scavenging processes is well-known in two-stroke engines. They represent the fundamental conception of scavenging. These simple scavenging theories postulate the ideal cases of scavenging for a cylinder with a fresh air charge.

In the perfect displacement process, all fresh charge entering the cylinder is retained and “perfectly displaces” the exhaust gas. This air enters the perfect scavenge volume. Concerning the perfect mixing scavenging, the entering air has no perfect displacement characteristic, but once in the combustion chamber, it is “perfectly” mixed with the exhaust

gas [11]. The resulting exhaust gas is composed of the mixed cylinder charge. These two scavenging processes are represented in Figure 1. The Delivery Ratio (DR) defines the mass of air supplied during the scavenging period as a function of a reference mass, which is the mass required to fill the swept volume under atmospheric conditions. The scavenging efficiency (SE) is defined as the mass of delivered air which has been trapped, by comparison with the total mass of charge which is retained at exhaust closure.

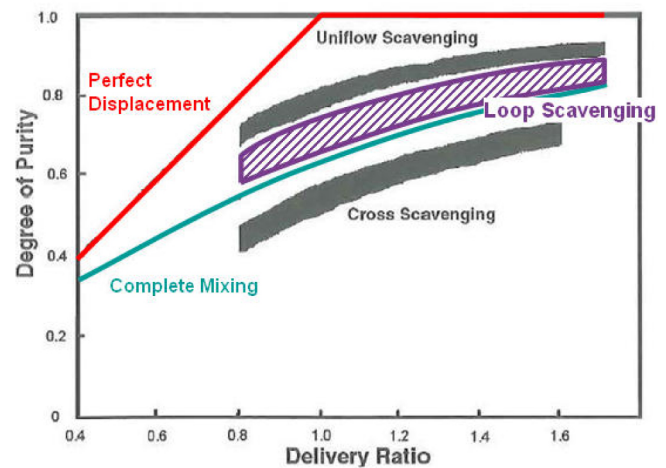


Figure 1. Scavenging efficiency of the two ideal scavenging processes [12]

It is obvious that the real situation is very different from both of these ideal cases. Compared to the cross or loop scavenging, the uniflow scavenging is well-known as being the best way to obtain an efficient two-stroke engine. Indeed, its scavenging efficiency is very close to the perfect displacement case. The route of the fresh air flow inside the cylinder, from bottom to top, allows to displace the exhaust gas efficiently and to limit fresh air shortcuts.

In order to simulate the engine behavior with its two-stroke specificities (air mass flow, trapping ratio, in-cylinder fuel/air equivalence ratio, etc.), it is necessary to predict the scavenging process and as a consequence, the exhaust gas composition. So the 0D simulation needs to use a specific scavenging profile, which has to be representative of our future single-cylinder configuration. This scavenging time evolution is provided by 3D calculations and this aspect is discussed later in this paper. It represents the time evolution of the in-cylinder residual gas rate and the exhaust residual gas rate. An example is represented in Figure 2. The scavenging profile is supposed not to be affected by the IMEP level or the air mass flow. Nevertheless, it is strongly dependant of the inlet port geometry, the exhaust valve lift or the engine characteristics (bore/stroke etc.). That is why, for each case, 3D calculations are performed, in order to generate this scavenging profile that will be used by 0D simulations.

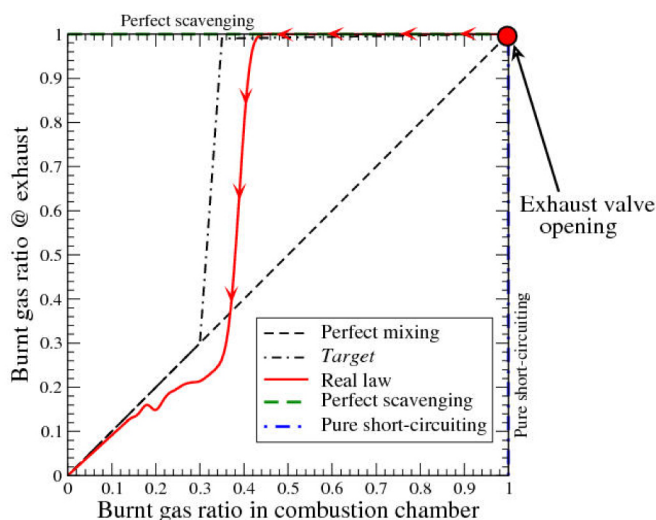


Figure 2. Scavenging profile for a real case, and for the perfect mixing, the perfect scavenging and the pure short circuiting processes. The scavenging phenomena begins at the exhaust valve opening.

Validation and fitting of the 0D Diesel combustion and two-stroke scavenging models are carried out on a single cylinder architecture (as presented in Figure 3).

With the input parameters (inlet and exhaust pressures, exhaust valve lift, inlet ports geometries ...) and thanks to the scavenging characteristic, the simulation can calculate all the two-stroke specificities, and of course the standard engine values. This work is a required step to correctly design the engine, and to study the best inlet and exhaust permeabilities for a two-stroke uniflow application. Indeed, the bibliography [5] shows that the design of the inlet ports and the exhaust permeability can strongly affect the scavenging efficiency, and consequently the air mass flow and the combustion.

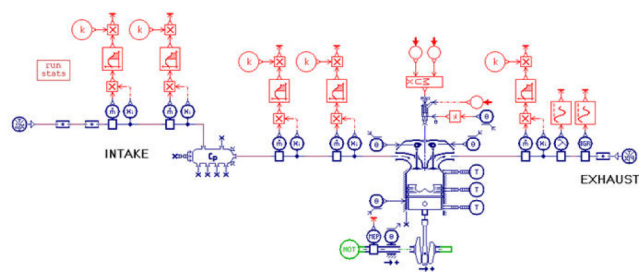


Figure 3. AMESim sketch of a single cylinder simulator, enabling to simulate the two-stroke process

Engine characteristics

At the beginning of the study, few engine characteristics were fixed. These engine characteristics are summarized on Table 1. It is important to note that four exhaust valves are used, in order to maximize the permeability. Moreover, a VVA system allows to have a good control/accuracy on the scavenging process, by changing lift, and/or its duration.

Table 1. Single cylinder characteristics

Displaced volume	400 cc
Stroke	88 mm
Bore	76 mm
Connecting Rod	180 mm
Compression ratio (geometric)	20:1
Inlet	12 ports
Exhaust	4 valves, VVA system
Architecture	Two-Stroke Uniflow
Maximal Power	20 kW @3500 rpm

The initial inlet ports are 7.18mm high, and the exhaust valves maximum lift is 6mm (Figure 4). These values will change during the simulation. However the exhaust valve lift cannot be too high, because of the short two-stroke lift duration.

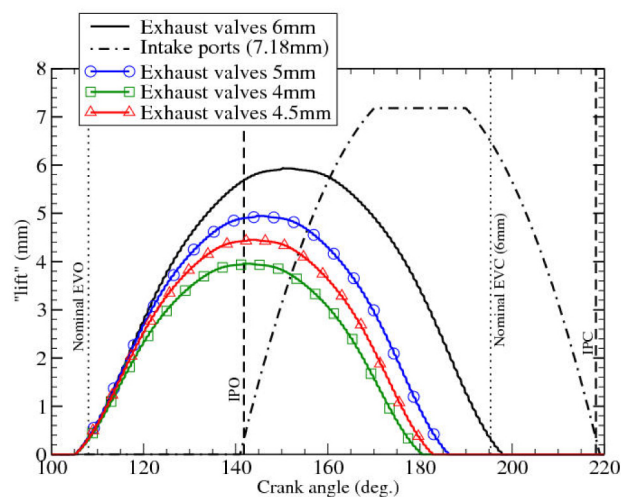


Figure 4. Initial inlet port geometry and exhaust valve lifts

Methodology with 3D calculations and CAD

An important part of this work is to understand the influence of inlet port geometry, exhaust valve lift phasing, and engine parameters on the scavenging efficiency. Only the 3D calculations can precisely predict the air mass flow inside the cylinder, to calculate the scavenging efficiency. The 3D results can be synthesized in a scavenging profile, presented above, which is then implemented inside the 0D simulation. This way, it is possible to understand the effects of engine parameters (pressure, injection, engine speed) on the combustion. At the same time, to start and then improve the 3D calculations, an engine CAD is needed. This work allows to design several inlet ports, in order to test all of them with 3D. So the methodology of this work can be summarized according to Figure 5.

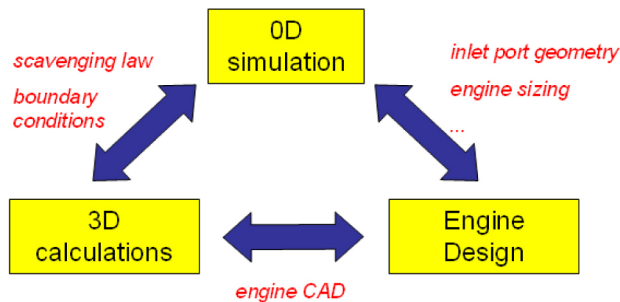


Figure 5. Work methodology

All the simulations presented in this paper are done for the maximum power point. Indeed 20 kW are expected at 3500rpm. So the best scavenging efficiency has to be obtained for this point, but a good trapping ratio is also expected to minimise air mass flow. Too much air mass flow imposes to strongly increase the intake pressure and thereby complicating the future multi cylinder air loop. Consequently, the best balance between IGR rate and trapping ratio is searched.

The settings of the tested point are 3500rpm and 9 bar of BMEP. FMEP is estimated at 0,9 bar, and the power needed to achieve the intake pressure value with a mechanical compressor is also calculated (compressor efficiency of 65%) so that the cost of the fresh air supply is taken into account. With this approach, it is possible to study the balance between a good scavenging (to decrease the IGR rate) and a reasonable delivery ratio (to decrease the cost of the air mass delivery).

Results

Exhaust permeability variation

The first simulations deal with variations of the exhaust valve profile, that is to say its phasing, duration and maximum lift. The intake and exhaust pressure are constants (2 bar and 1 bar, respectively). The inlet ports are 7.18mm high (c.f. Figure 4).

The effect of the maximum exhaust valve lift can be observed on the trapping ratio (Figure 6). As expected, the height of the exhaust valve lift strongly changes the trapping ratio. With a large exhaust lift (6mm), the permeability is higher, and it increases the delivery ratio. But as the scavenging profile shows in Figure 2, when approximately 60% of burnt gases are scavenged, the process becomes very close to perfect mixing. This means that the short circuiting of fresh air increases very quickly, and the trapping ratio decreases.

Figure 6 clearly shows the effect of the exhaust valve lift phasing. By moving the EVO, it is possible to change the blowdown, which is the time between the opening of exhaust valves and inlet ports. The blowdown has to be long enough, to allow the exhaust phase to begin, and to greatly decrease the in-cylinder pressure before the intake phase. When the

EVO is delayed, the intake and exhaust lifts overlap. This increases the delivery ratio because the engine permeability is enhanced. As previously, when engine permeability is too high, the trapping ratio decreases because of short circuiting.

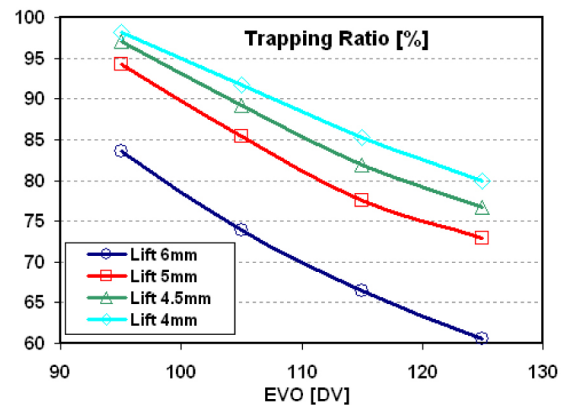


Figure 6. Effect of the maximum valve lift on trapping ratio in function of the Exhaust Valve Opening (EVO)

The IGR rate starts to decrease when EVO increases (Figure 7). But if the blowdown phase is too short, a large amount of burned gas inside the cylinder will backflow through the intake plenum when the inlet ports open. And even with high delivery ratio and permeability, the IGR rate does not continue to decrease because the fresh air is mixed with burn gas into the intake plenum.

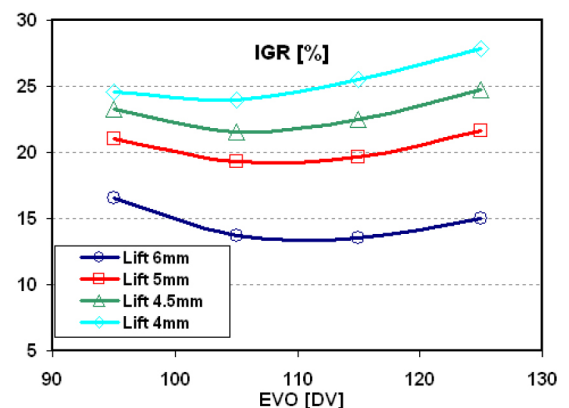


Figure 7. Effect of the maximum valve lift on IGR rate in function of the Exhaust Valve Opening (EVO)

As explained previously, a mechanical compressor is simulated in this project. Of course, it is also possible to add a turbo compressor in the exhaust line, but this paper deals with the first results, with only one mechanical compressor in the intake pipe. Figure 8 shows that the use of this compressor has a main drawback: all the power needed for the air compression is directly taken on the engine power. So it is common to talk about “compressor penalty”, which is the

amount of torque taken from the crankshaft. The 6mm lift curve has the highest penalty, because of high delivery ratio.

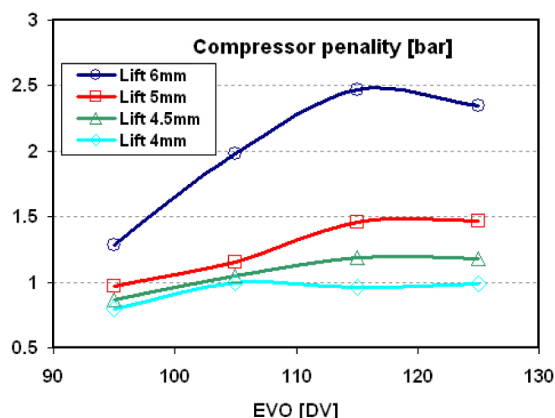


Figure 8. Effect of the maximum valve lift on intake air compressor power penalty

Intake and exhaust pressure variation

For this part, exhaust valve and inlet port profiles are fixed as in the example given in Figure 2. The intake pressure effect is observed with these simulations. As showed on Figure 9, ISFC is improved when the intake pressure increases. This is mainly due to the decrease of the in-cylinder fuel/air equivalence ratio. When EVO is delayed, the same conclusion can be observed: the delivery ratio is higher, IGR rate is reduced, and consequently Fuel/Air equivalence ratio and ISFC are enhanced.

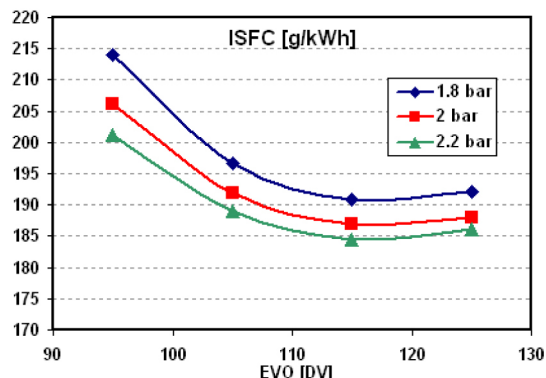


Figure 9. Effect of air intake pressure on ISFC

In Figure 9 the case with 2.2 bar of air pressure reaches the best ISFC nevertheless, when the mechanical compressor power is taken into account, the results seem clearly different (Figure 10). It is a balance between ISFC and compressor penalty. Finally, in this case, an air pressure of 1.8 bar gives the best results. But another parameters have to be checked, such as in-cylinder Fuel/Air equivalence ratio (FAER). Indeed, a too high value can generate smoke and HC or CO emissions.

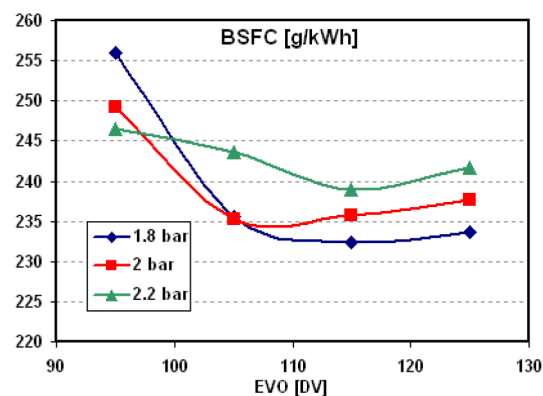


Figure 10. Effect of air intake pressure on BSFC

With the simulations, it is also possible to plot maps, as illustrated in Figure 11 that represent the in-cylinder fuel/air equivalence ratio as a function of intake and exhaust pressures. Indeed, as the in-cylinder Fuel/Air Equivalence ratio (FAER) has an impact on soot and NOx formation, knowing the required power output - thereby the injected quantity - one can use these maps to determine the appropriate intake and exhaust pressures so as to control the in-cylinder FAER (for example to reach a FAER between 0.6 and 0.7 one could use an intake pressure of 2.6 bar and exhaust pressure of 1.4 bar).

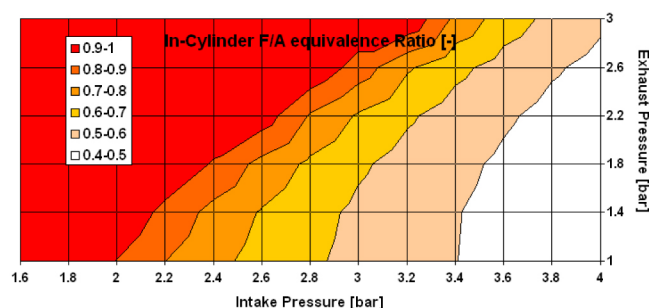


Figure 11. In-cylinder Fuel/Air equivalence ratio in function of pressures

Discussions

The 0D simulations are very useful to explore an engine configuration by changing input parameters. In this work, the objective is to design the best two-stroke engine architecture in order to test it in a test bench in the future. A lot of inlet ports geometries and exhaust valve profiles were tested by means of 3D and 0D calculations. For the maximum power point, the aim is to get an efficient scavenging (i.e. low IGR rate) without too much air mass flow. Figure 12 presents part of the variations done in this work. BSFC is plotted as a function of the IGR rate, for all the cases. It is interesting to note that BSFC is minimum when IGR rate is around 15% as with too high scavenging efficiencies, the air mass flow and the intake pressure levels need high mechanical compressor power. When IGR rate is high, the in-cylinder Fuel/Air