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Development of a two stroke direct injection jet ignition compressed natural gas engine

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Abstract

A traditional two stroke engine with crankcase scavenging also adopting an exhaust reed valve and lamellar intake is modified to accommodate a high pressure Compressed Natural Gas (CNG) direct injector and has the traditional spark plug replaced by a jet ignition device of the same thread. The jet ignition device is a pre-chamber accommodating a Gasoline Direct Injection (GDI) injector operated with CNG and an 8 mm racing spark plug. The jet ignition pre-chamber is connected to the main chamber through calibrated orifices. The CNG is injected after the exhaust post closes. The GDI injector operated with CNG introduces a slightly rich amount of fuel in the pre-chamber. The spark plug discharge initiates the pre-chamber combustion that then propagates to the main chamber though multiple jets of high energy partially burned hot combustion products that quickly ignite the main chamber mixtures. The Computer Aided Design (CAD) model of the engine including the jet ignition device is discussed in detail. The Computer Aided Engineering (CAE) model of the engine is shown to produce efficiencies well in excess of 35% in the area of best operation. The load is controlled by fine tuning the injection and ignition events and increasing the overall air-fuel ratio. The solution offers an opportunity to produce an efficient alternative to four stroke engines with improved power density, running on alternative fuel having larger availability and better combustion properties and reduced pollution than traditional diesel and gasoline fuels.

Keywords: Environmentally friendly vehicles, Two stroke engines, Direct injection, Jet ignition, Compressed natural gas

1. Introduction

A two-stroke engine is an internal combustion engine that completes the process cycle in one revolution of the crank shaft compared to two revolutions for a four-stroke engine. Two-stroke engines are used mostly with the smallest and largest reciprocating power plants and less commonly with the medium sized.

Two-stroke engines are simple, lighter and feature a higher power-to-weight ratio and low manufacturing cost. A two stroke engine is able to generate 1.6...1.7 times greater power than a four-stroke engine of the same volume. It is also possible to have a smooth rotation with a small number of cylinders.

The downsides of two stroke engines are emissions and efficiency. A clear disadvantage of a two stroke engine is the gas exchange process, especially in the cheapest design with crank case scavenging. The intake process suffers low efficiency mostly due

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to shortness in effective strokes. Mean effective pressure and efficiency are low mostly due to the long opening of the exhaust.

Pollution has also played a dominant role recently for the reduced popularity of small two stroke engines with crankcase scavenging. This two stroke engine mixes fuel and engine oil for lubrication and this further adds to the already higher emissions than a four stroke engine. The main source of pollution from two stroke engines with crank case scavenging comes from the lubrication oil, because with this simple design they do not have a dedicated lubricating system and the oil burned in the combustion chamber causes exhaust pollution.

Small transient two-stroke engines have received much less investment during development than four stroke engines. The two stroke engine was very popular throughout the 19...20th century in small displacement applications such as chain saws, outboard motors, lawn mowers, motorcycles, snowmobiles and snow blowers. Two stroke engines are still used for small, portable, or specialized machine applications such as outboard motors, motorcycles, scooters, lawnmowers and dirt bikes, but their popularity has been largely reduced.

Recently, the addition of direct injection and some refinement of the crank case scavenging with reed valves and lamellar intake plus precise lubrication have produced more fuel efficient and less polluting builds in outboard and snowmobile applications, such as Yamaha HPDI [1] or Bombardier E-TEC [2, 3], meeting emission requirements and delivering acceptable fuel economy in the engine's most commonly used rpm range.

The most relevant areas of development of two stroke engines for transport are non-symmetrical port timing, supercharging scavenging, dry sump, direct injection, and throttle-less load control.

In the classic symmetrical port timing, opening and closing of the ports by the piston is symmetrical. The mechanism is very simple, cross-flow and loop-flow are symmetrical porting. The drawbacks are short circuiting, translating into charge loss, poor intake and exhaust efficiency, and the impossibility of super charging. The process of symmetrical port timing is as follows: exhaust port open; intake port open; intake port close; exhaust port close. The replacement of the products of combustion in the cylinder from the previous power stroke with fresh air charge to be burned in the next cycle must be completed in the very short time duration available between the end of the expansion stroke and the start of the charging process. If the scavenging is insufficient, it results in high fuel consumption, lubricating oil contamination, and large internal exhaust gas recirculation. In non-symmetrical porting timing, the opening and closing of the intake and exhaust is non-symmetrical, but the design is much more complex. The process of non-symmetrical port timing is as follows: exhaust port open; intake port open; exhaust port close; intake port close as in a four-stroke engine. The advantages for non-symmetrical port timing are: super charging can be possible, and scavenging is more efficient.

In conventional crank case scavenged two stroke engines, the air and fuel is mixed upstream of the cylinder, the intake port and exhaust ports are open at the same time, and this causes some unburned mixture to escape from the cylinder. Direct injection only receives air to the crank case, and fuel is injected directly into the cylinder, so no fuel escapes from the cylinder, thus increasing fuel economy and reducing emissions. Precise lubrication of the reciprocating and rotating components mitigates the burned oil issue.

Two direct injection systems are used in transport two stroke engines: low-pressure air assisted and high pressure direct injection. The Orbital low pressure air assisted direct injection system utilizes a single injector to inject the gasoline fuel and compressed air into the combustion chamber. The Orbital system is used in motor scooters manufactured by Aprilia, Piaggio, Peugeot and Kymco, in outboard motors manufactured by Mercury and Tohatsu, and in personal watercraft manufactured by Bombardier [2, 3]. The high pressure direct injector system is the traditional four stroke direct injection engine technology. This system is now available on marine engines and watercraft [1] and many other applications are expected shortly.

The present paper considers the opportunity to further benefit from the advantages of high pressure Direct Injection (DI) in a crank case scavenged engine with symmetric port timing changing the traditional spark ignition to Jet Ignition (JI) for throttle-less load control. The work is done considering the use of Compressed Natural Gas (CNG) rather than gasoline. The long term goal is to design a two stroke CNG engine for passenger car applications. The present paper reports on the preliminary results obtained for the DI JI combustion system.

2. Jet ignition and direct fuel injection

Jet ignition is a technology used in stationary or marine natural gas internal combustion engines application [4, 5] with pre-chamber injection of part of the fuel and ignition spark initiated or self-glow-plug assisted. Jet ignition pre-chambers have also been proposed for transport engines with in-cylinder homogeneous mixtures [6] or bulk, lean stratified [7, 8] produced by direct injection.

With jet ignition, the main chamber air-fuel mixture is ignited by multiple jets of hot reacting gases issued by the jet ignition pre-chamber holes and crossing the main chamber at very high speed. The jet ignition pre-chamber is a small volume connected to the main chamber volume through calibrated orifices and accommodating a fuel injector and a spark (or glow plug). The dedicated injector delivers a locally stoichiometric fuel to the pre-chamber volume, also receiving air from the main chamber during the compression event.

Jet ignition has been traditionally coupled to lean premixed operation, but the coupling to direct injection has opened up the opportunity to have direct injection and jet ignition producing a confined near stoichiometric air fuel mixture receiving jet ignition streams (combustion in the bulk).

In addition, by modulating the phasing of the injection and jet ignition events it is possible to modulate the amount of premixed and diffusion combustion for operation gasoline-like, diesel-like and mixed to better optimize performances over the load/speed range.

The two stroke engine in the version with crankcase scavenging and spark ignition combustion of a homogeneous mixture of gasoline, air and lubricating oil produced by a carburetor has been the preferred 2 wheel mobility solution of developing countries over the last few decades because of the power density and simplicity of operation and maintenance. Considered intrinsically inefficient and polluting, two stroke engines have in large part disappeared. However, as 2 stroke diesel and natural gas engines for power generation and marine applications are actually the most efficient fuel energy conversion devices, reaching almost 60% of top fuel energy conversion in mechanical work, the two stroke option may return to interest for the mobility industry as well, with interesting solutions adopting direct injection already available in snow mobiles and outboards and some small motorcycles.

This paper addresses two disadvantages of the two stroke engine, namely low top efficiency and very large penalties reducing the load or changing the speed by using coupled direct injection and jet ignition.

Direct injection reduces the amount of fuel that may escape the combustion chamber. Direct injection may also provide more fuel rich areas surrounded by air. Jet ignition may ignite main chamber premixed fuel and air with very high energy all across the chamber or in a selected region as well. Direct injection and jet ignition carefully coupled may permit completely throttle-less load control, with the main chamber fuel air mixture restricted to a selected area where the jet ignition would start combustion that will complete almost instantaneously. In the latest developments, jet ignition and direct injection are coupled together to modulate the amount of premixed and diffusion combustion to achieve the best trade-off of fuel conversion efficiency and pollutant formation all through the speed and load range. CNG is the fuel considered in the exercise.

The present paper reports on the design of the jet ignition device, the computations done to operate the direct injector and the jet ignition injector, and present preliminary results of simulations for the injection events and the engine operation in the case of a traditional gasoline two stroke engine of top brake efficiency in the mid 20% modified to DI JI of CNG.

3. CAD/CAE Modeling

Jet ignition plus direct injection is the enabler of a viable two stroke engine that delivers excellent fuel economy and low emissions within the constraints of today's cost, weight and size, bulk combustion and ignition, tolerant to high Exhaust Gas Recirculation (EGR) internal, always lean burn, load change throttle-less, and may permit premixed-diffusion combustion modulation.

The JI injector is a production Gasoline Direct Injection (GDI) piezo injector permitting with CNG of reduced pressure the injection of the amount of fuel needed to work locally stoichiometric in the pre-chamber. The DI injector is a prototype CNG solenoid high pressure delivering the large volumes of CNG injected at up to 300 bar, also proved effective in working with hydrogen.

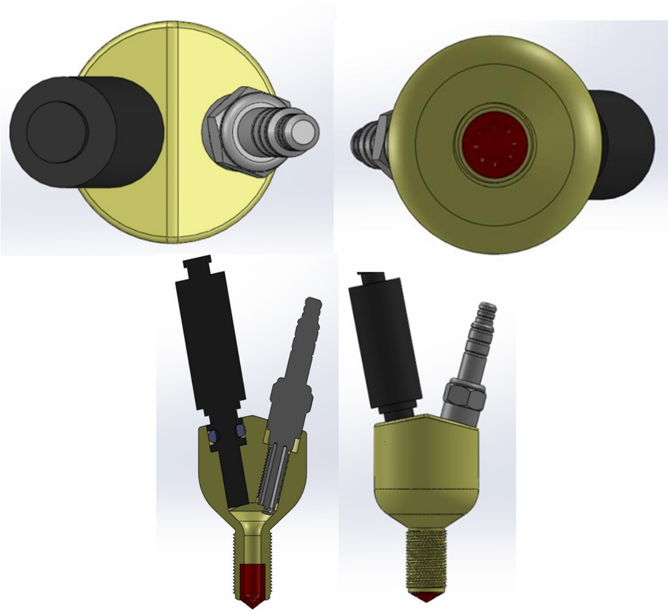

Figure 1: Jet ignition device

Fig. 1 presents a sketch of the jet ignition device. It is a small pre-chamber accommodating another direct injector and a small spark plug.

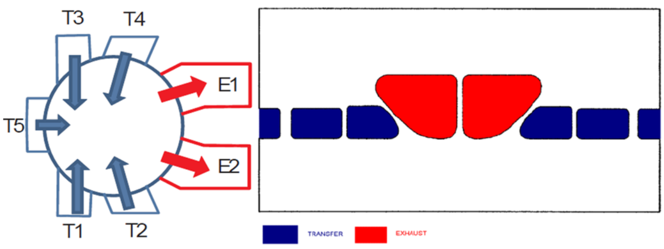

Figure 2: Loop scavenging (from [9])

The CNG DI injector permits high flow rates, fast actuation and injection shaping. The need for high power density is better satisfied in a CNG engine due to the excellent ability for turbocharging and running higher than gasoline compression ratios.

The absence of a particulate emission limit allows for operation at up to a stoichiometric air/fuel ratio to provide large mean effective pressure (BMEP). CNG DI injectors permit almost unlimited injection flexibility for multiple injections and unparalleled control of injection rate for rate-shaping.

Fig. 2 presents a sketch of the loop scavenging (from [9]). This design is typical of racing engines where the exhaust is finely tuned to produce the pattern of pressure waves that maximizes the removal of the exhaust gases. The present definition of the transfer port and exhaust port openings is not yet optimized. The reed valve on the exhaust as well as the lamellar intake is not modeled.

The performances of the injection system are analyzed first. Then, an engine performance model is built.

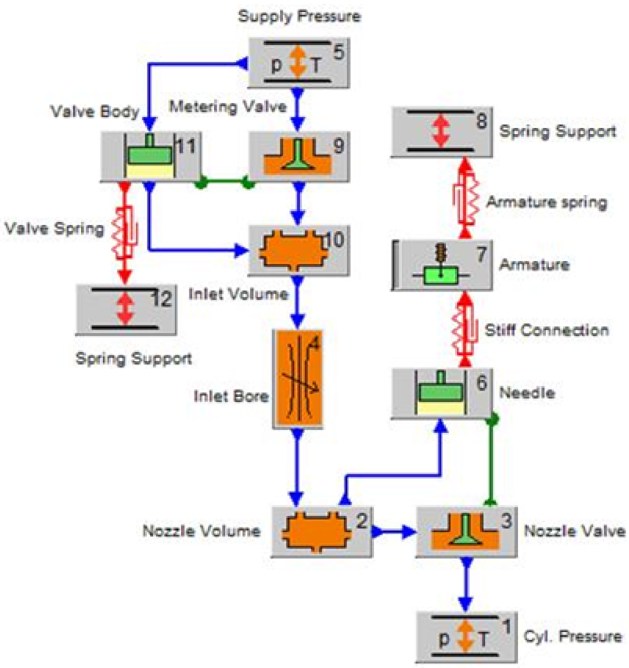

Figure 3: AVL BOOST [10] model of the CNG DI injector

Fig. 3 presents the AVL BOOST [10] model of the CNG DI injector.

Fig. 4 presents the results of a simulation with 300 bar injection pressure. The tip of the injector

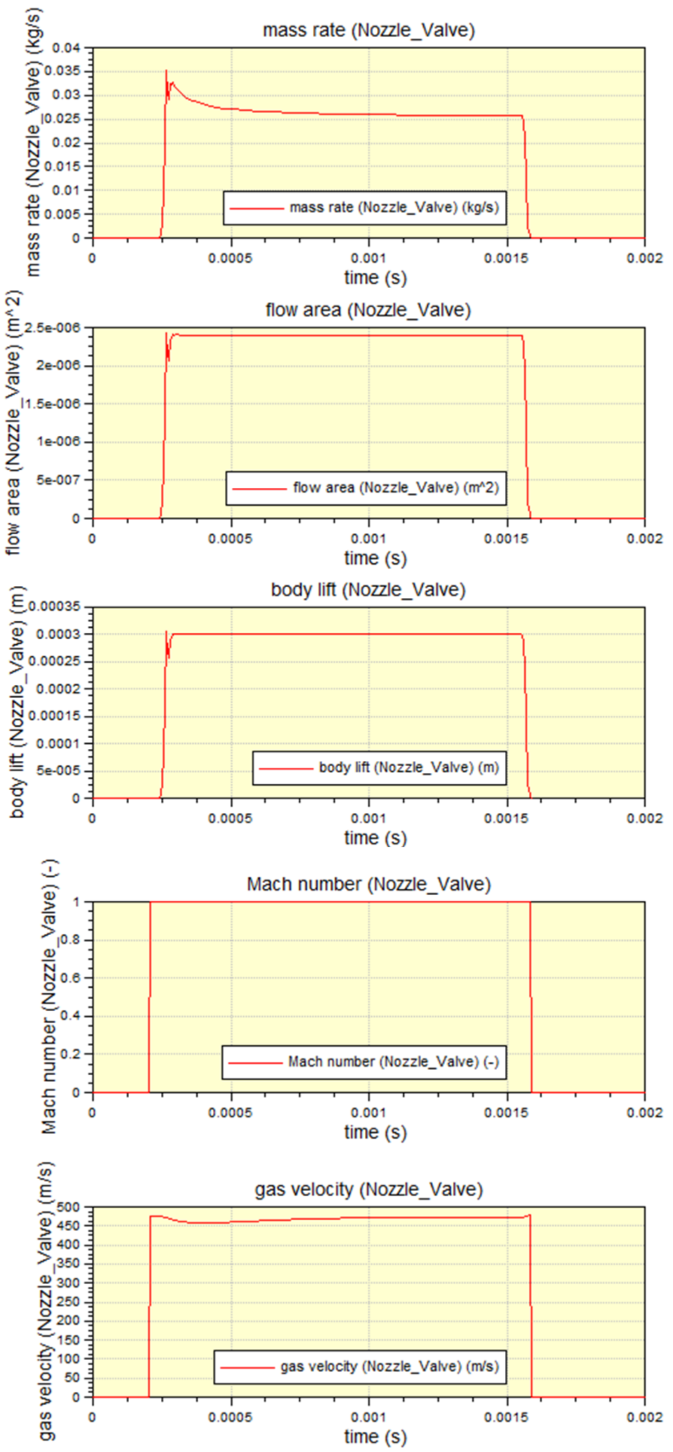

Figure 4: CNG DI injector operation at 300 bar

may be changed to fit the requirements of the specific combustion chamber in terms of jet orientation and number.

To achieve the turn-down ratios from full load to zero load changing the amount of fuel injected rail pressure and electric opening times are adjusted to the speed and load demand. Presented are the mass flow rate, the lift and flow area, the velocity and Mach number.

In the preliminary simulations, modulation of direct CNG injection and jet ignition pre-chamber operation is not considered in the rest of the paper and only the gasoline-like operation is taken into account.

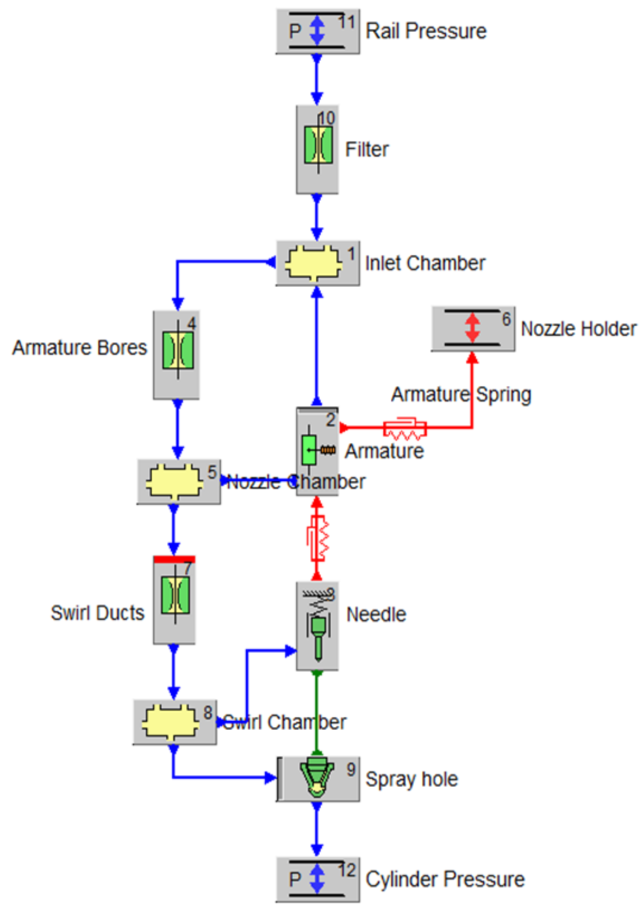

Figure 5: AVL BOOST [10] model of the GDI injector for CNG delivery to the pre-chamber

Fig. 5 presents the AVL BOOST [10] model of the GDI injector. Because of the unavailability on the market of suitable CNG injectors to deliver the very small amount of CNG needed to make the pre-chamber mixture slightly fuel rich, a GDI injector is used with CNG rather than gasoline.

Fig. 6 presents the results of operating this injector at 80 bar. These results are the flow area and the volumetric flow rate (for gasoline).

Roughly, the mass flow rate with CNG is the flow area multiplied by the speed of sound and the den-

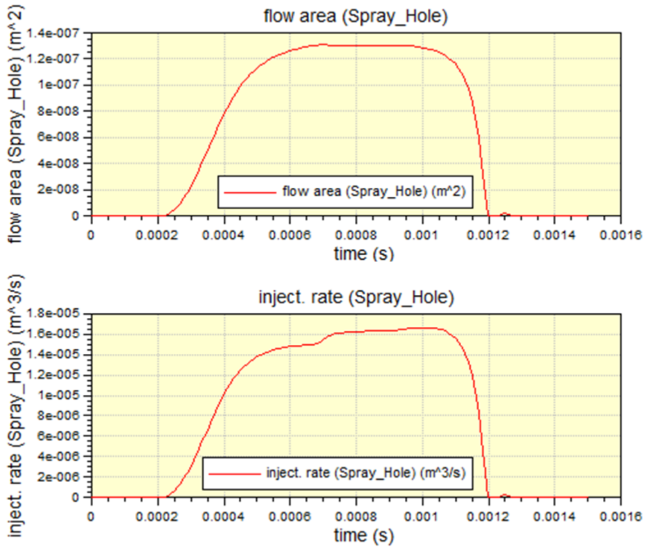

Figure 6: Gasoline DI injector operation at 80 bar

sity of methane at the injection pressure conditions, but some adjustments are needed to account for the compressibility of methane.

As the density and speed of sound of CNG are much less than for gasoline, the minimum opening times of the GDI injector are small enough to deliver the right amount of CNG in the pre-chamber. This solution has already been adopted in many prototypes of jet ignition pre-chamber for engine tests.

The engine assembly is shown in Fig. 7.

Table 1: Basic engine parameters

DISPL./CYL. [1]	0.400
NO. OF CYLINDERS	2
COMPRESSION RATIO	15.0
EFFECTIVE CR (VC-TDC)	8.28
BORE, mm	82.0
BORE/STROKE	1.08
CON. ROD LENGTH, mm	150
STROKE, mm	75.0
CLEARANCE VOL., m^3	$0.286 \cdot 10^{-4}$
#1 EPO, deg	85.0
#1 EPC, deg	275
#1 IPO, deg	115
#1 IPC, deg	244

The basic engine parameters are listed in Table 1.

Preliminary engine results are presented. Simulations are performed with Ricardo WAVE [11].

As mentioned previously, the exhaust may be fitted with a reed valve changing the exhaust area as a function of speed and load, and a lamellar intake may help to prevent back flows to the throttle. Neither of these features are modeled in the present simulations.

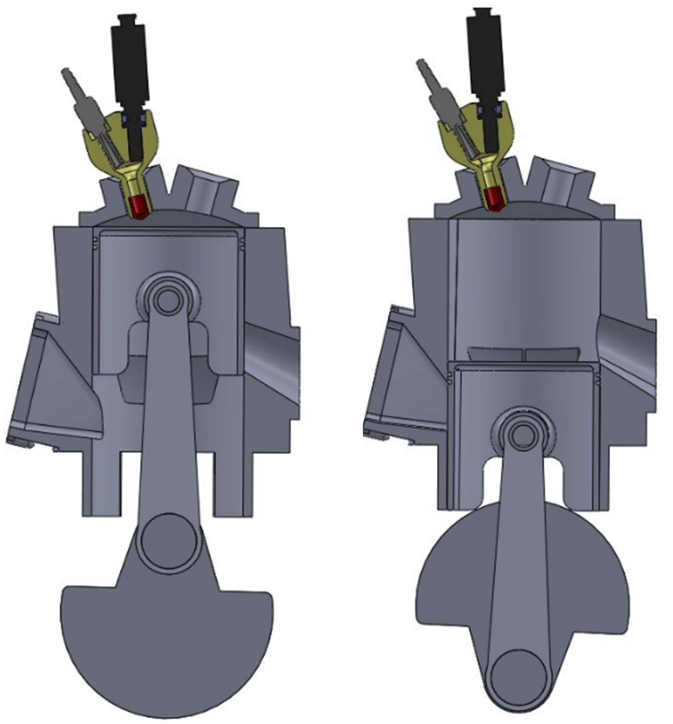

Figure 7: Sketch of the engine with piston at TDC and BDC positions

The throttle is also not modeled, as the load is controlled through the quantity of fuel injected.

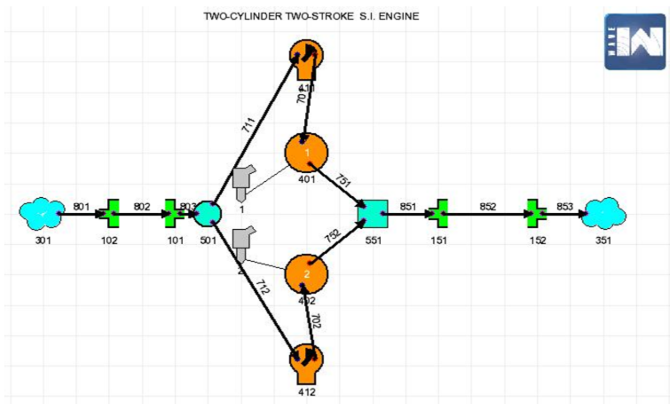

Figure 8: Ricardo WAVE [10] 2 stroke 2 cylinder CNG engine model

Fig. 8 presents the model layout, while Figs 9 and 10 present the brake efficiency and the operating lambda vs. the brake mean effective pressure at various engine speeds.

The baseline gasoline engine model was delivering top efficiencies in the mid 20% sharply decreasing

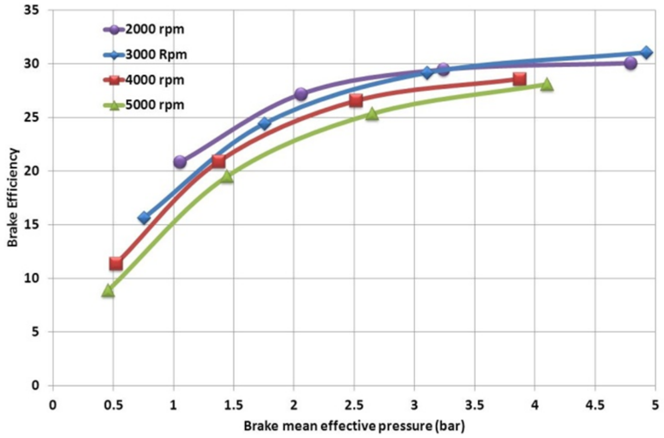

Figure 9: Computed brake efficiency vs. brake mean effective pressure at various engine speeds

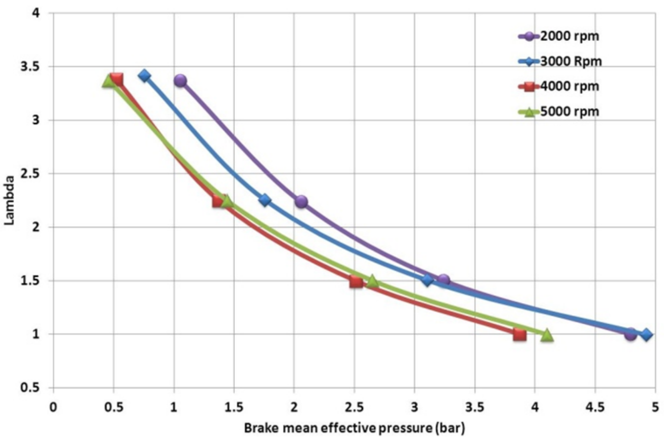

Figure 10: Computed lambda vs. brake mean effective pressure at various engine speeds

with load, but the new engine shows an ability to achieve high 20% and above 30% efficiencies over a significant portion of the speed and load range, due to the higher compression ratio (from 12 to 15) and especially the coupled DI and JI of the gaseous fuel.

Worthy of note, combustion is the Wiebe function of 50% mass fuel burned 7.5 degrees crank angle after top dead center and combustion duration 10...90% of 12.5 degrees crank angle. Properly developed jet ignition well coupled to direct injection may produce even shorter combustion durations of bulk confined premixed mixtures and the efficiency does not vary too much as this parameter changes.

4. Conclusions

This paper presents a novel combustion system that is being considered for two stoke engine design. The design couples high pressure direct injection with jet ignition. The paper reports on the preliminary design of the jet ignition device and the selection of the direct injector and the main chamber injector to be used for the prototype of a two stroke gasoline engine converted to compressed natural gas.

Preliminary results of engine simulations show the ability to run the engine throttle less by changing the load through the quantity of fuel injected, achieving improved top fuel conversion efficiencies and reduced penalties when changing the load or the speed.

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