

Power control of a spark ignition engine through the variation of the intake valve opening angle

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Abstract. The power control developed for a spark ignition engine, with indirect fuel injection, is made through the throttle valve, which regulates the air flow used by the electronic injection system to dose the amount of fuel to be delivered, maintaining the suitable air/fuel rate.
The FIAT 1580 cc 16V engine was modified to function with only one cylinder. The tests for performance evaluation were made on a dynamometric workbench for the engine using diverse load configurations. Seeking the reduction of fuel consumption, a mechanical device was designed that allows, with a working engine, variation of the angular position of one of the intake camshaft cams, maintaining the cam of the other valve in its normal synchronism. This process is characterized by the late intake valve closing. The results of the engine performance trials are presented operating with and without the throttle valve control system for many engine load configurations. The results achieved in the break tests show a considerable reduction in the fuel consumption in partial loads of 75, 50 and 25%.

***Keywords**. Internal Combustion Engine, Late intake valve closing.*

1. Introduction

Since the first petroleum crises, it was evident that petroleum was not a renewable resource. It was necessary to reduce petroleum use.

The unordinary growth of cities increased traffic jams that contributed to increased pollution. To control all environmental problems, vehicle emissions limits were established in the United States of America, and later in other countries.

The CO_2 from fossil fuel combustion became considered an atmosphere pollutant. The recent compromise of the European vehicle manufacturers is to launch, by 2008, vehicles that emit less than 140 g/km of CO_2. This corresponds to reduction of more than 25% in fuel consumption than in 1990 (JOST, 2002).

Nowadays, the technical solutions to reduce fuel consumption are: superchargers, turbochargers, variable valve actuation, direct injection and engine.

Superchargers and turbochargers promote an increase in engine power and the cubic displacement reduction makes the car lighter. Therefore the ratio power/weight rises, resulting in fuel economy. Direct injection engines save fuel because the cam works with lean mixture.

Variable valve actuations are systems that permit the variation of valve opening and closing for:

a) unthrottled engine load control (KREUTER et all, 1992; ANDERSON et all, 1998; PISCHINGER et all, 2000);

b) high performance engine because of its sluggish response in low and middle-speed with a heavy load (TITOLO, 1991);

c) low-speed cam with moderate lift and high speed cam with high lift under a wide range of power, increasing torque, power and fuel economy (HATANO et all, 1993; DEMMELBAUER-EBNER et all, 1991);

d) cylinder deactivation to control load composition and cylinder gas motion (PISCHINGER et all, 2000)

e) in compression brake augments of Heavy Commercial vehicles converting the engine into a compressor (MOKLEGAARD, STEFANOPOULOU, SCHMIDT, 2000).

2. Unthrottled load control

Unthrottled control is a system that permits control of engine power through variable valve train to modulate the valve timing that restrains the cylinder filling . The strategies to do it are: early intake valve closing, late intake valve closing and variable valve lift.

In the early intake valve closing, the intake valve is closed early during the suction stroke of the engine, after the cylinder is refilled with the required fresh charge. The late intake valve closing is characterized by the intake valve remaining open during the complete suction stroke. It cannot be closed before of the excess charge is pushed back into the intake manifold during the compression stroke of the piston. Variable valve lift limits intake flux that is similar to the early intake valve closing.

The first system of variable valve actuation was created four years after Otto presented his engine, with patent number 230470, in USA (PHOENIX, PHOENIX, 1991). Later, in1903, Cadillac launch a vehicle (Runabout model A) with an single cylinder engine, water cooled, with 7,5 kW. It used a variable valve system to control power without throttle (BUCHHOLZ, 2002). In recent days, BMW launched the Compact 316ti with an engine that uses a continuous variable lift system, to control power without throttle (JOST, 2002).

2.1. Pumping loss

As a result of this throttle load control, the pumping losses increase with decreasing load, and reduce in 30% the indicated mean effective pressure in low-load area as shown in Fig. 1 (STUMPF, 1983; KREUTER, HEUSER, SCHEBITZ, 1992).

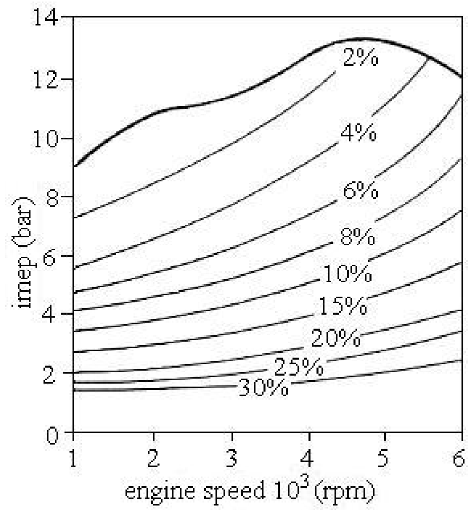

Figure 1. Pumping losses of a throttle-controlled 4-valve SI-engine λ=1 (KREUTER, HEUSER, SCHEBITZ, 1992).

In the low-load area, there is a great potential to improve fuel economy. It is the most strong indication of benefits in throttle-free load control (KREUTER, HEUSER, SCHEBITZ, 1992; PIERIK, BURKHARD, 2000).

Fig. 2 shows a typical PV diagram for a conventional throttled engine, enlarged to provide increase intake and exhaust details. The sum of the areas labeled “A” and “C” define quantity termed “Indicated Mean Effective Pressure” (IMEP). Area “B” plus area “C” is termed “Pumping Mean Effective Pressure” (PMEP). The net “Mean Effective Pressure” (NMEP) is the difference between IMEP and PMEP. It is equal to “A” minus “B” (NMEP) consequently “C” is canceled (PIERIK, BURKHARD, 2000).

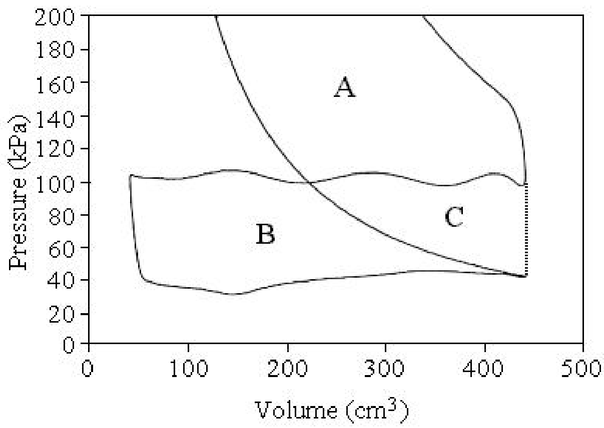

Figure 2. PV diagram enlarged at low-load (PIERIK, BURKHARD, 2000).

Fig. 3 shows that the area “B” becomes smaller with variable valve actuation in throttle-free partial load when compared with throttle load control (PISCHINGER et all., 2000).

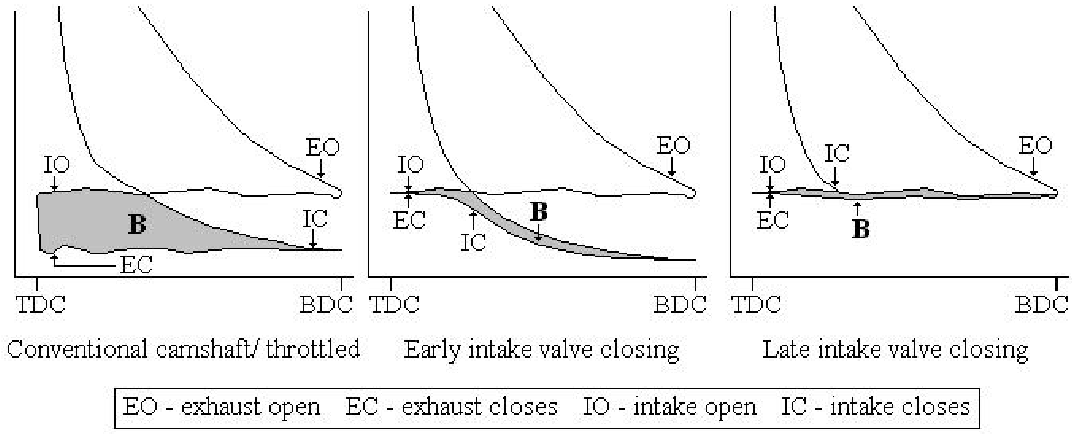

Figure 3. PV diagram for different load control strategies (PISCHINGER, 2000).

2.2. Internal exhaust gas recirculation (EGR)

Cylinder charge consists of the inducted air, the supplied fuel, the residual gas in the cylinder and the exhaust gas that returns to the intake manifold (PISCHINGER, 2000). While the air-fuel ratio is determined by fuel supplies, residual gas fraction is influenced by the duration and position of the valve-overlap, engine speed and intake manifold pressure (STUMPF, 1983; KREUTER et all, 1992; PISCHINGER et all, 2000). Fig. 4 shows the typical behavior of the residual-gas fraction as a function of engine speed and load.

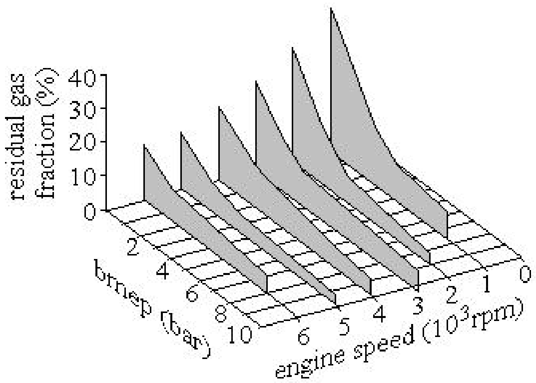

Figure 4. Residual gas fractions of a throttle controled SI-engine (KREUTER, HEUSER, SCHEBITZ, 1992).

The internal EGR dilutes the fresh mixture in low-load. It requires a richer mixture to balance this dilution. It is shown in Fig. 5 (TAYLOR, 1976, STUMPF, 1983).

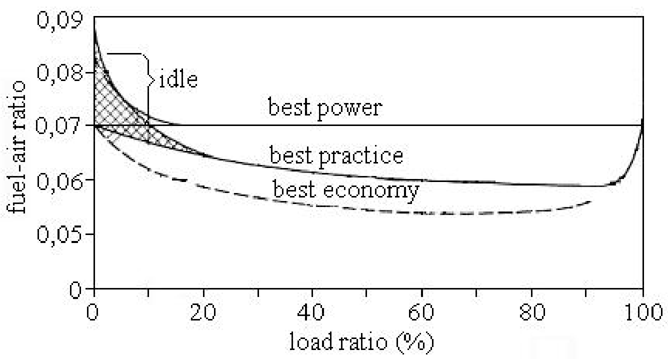

Figure 5. Air/fuel ratio and load ratio (TAYLOR, 1976)

2.3. Advantages and disadvantages of control strategies

The throttle-free variable valve actuation presents some advantages and some disadvantages as shown in the next topics.

2.3.1. Early intake valve closing

This kind of load control requires very short valve-lift period for light-load conditions as well as high accuracy and good repeatability of valve timing. These requirements are specially severe at partial load when the intake valve closes during near-maximum piston speeds (KREUTER, HEUSER, SCHEBITZ, 1992).

The intake valve closing before bottom dead center results in a nearly adiabatic expansion inside the cylinder. Because of this, the fresh charge cools down to 75 K. It is cooler than in a conventional engine. Cooler charge and higher pressure in the intake manifold are detrimental to the fuel atomization (URATA et all apud CUNHA et all, 2000; LENZ et all apud CUNHA et all, 2000; TUTLE, J. H. apud CUNHA et all, 2000). Low temperature in the end of intake stroke causes the subsequent compression phase to start in a polytropic rise at a lower temperature (FLIERL; KLÜTING, 2000).

A lower in-cylinder gas motion is a disadvantage because it contributes to a poor mixture formation.

The variable valve lift has a similar advantage and disadvantages as the early intake valve closing.

2.3.2. Late intake valve closing

The flow losses in the intake stroke with late intake valve closing are less than with early intake valve closing. But in subsequent compression strokes the flow losses tend to be greater as more fresh charge is pushed back to the intake manifold (KREUTER, HEUSER, SCHEBITZ, 1992).

The high intake manifold pressure is a disadvantage for mixture formation. The gas flows form intake manifold to cylinder. Then it pushes gas back to intake manifold. The temperature rises and increases the mixture formation. A disadvantage of the temperature rise is a decrease in the volumetric efficiency and increase engine knocking (KREUTER, HEUSER, SCHEBITZ, 1992).

2.4. Variable valve train

Variable valve train for unthrottled engine that use late IVC, early intake valve closing or variable lift strategies can be classified as hydraulic, electromagnetic or mechanical systems, as shown below.

The hydraulic actuator is equipped with a specially designed linear actuator that opens and closes the engine valves. A synchronized controller interfaces solenoid valves. The hydraulic fluid is the engine lubricating oil itself (ANDERSON et all, 2000). It is possible to use the hydraulic actuator to open the engine valve and the valve spring to close it (CUNHA et all, 2000).

Pischinger's electromagnetic actuator uses an armature regulated by a spring. It is moved between two solenoids, which hold it in the fully open/closed positions. The armature actuates over the engine valve (KREUTER, HEUSER, SCHEBITZ, 1992). This actuator permits great flexibility in control. Through this many control strategies are possible (PISCHINGER et all, 2000).

The electromagnetic actuator from Aura Systems for Valve Outside Rotating Armature Design (VORAD) is similar to Pischinger's and operates engine valve by means of an arm in a small engine. A Hall Effect Sensor feeds-back information to the controller (PODNAR, KUBESCH, 1998).

The BMW's double-VANOS is a mechanical system that uses two cams for variable lift. The arrangement of this system with a variable cam timing is called valvetronic. It permits the Compact 316ti, the first throttle-free nowadays, fuel to save up to 10 % in fuel, in normal driving (JOST, 2002). Another arrangement of the double-VANOS system was presented by PIERIK e BURKHARD, 2000. The test results demonstrated a brake specific fuel consumption improvement of approximately 12% at idle, 7 – 10 % at light to medium load, and 0 – 3% at medium to heavy load.

The mechanical system from HAUGEN et all, 1992, operates with late intake valve closing. It uses two intake camshafts, one for each intake valve in a 4 cylinder 16 valves engine. Load modulation is made through the controlled phasing of one intake camshaft, consequently one valve/cylinder.

STUMPF, 1983 proposed a mechanical system that used an extra-camshaft with a multi-dimensional cam (helical-cam) to operate a supplementary inlet valve. It is called "Third Valve" (at that time Brazilian's engines used only one intake valve/cylinder).

2.5. Engine and variable valve system proposed

In this work a FIAT 1580 cm^3 16V engine was used. Three cylinders were deactivated by means of a large hole in piston crow. A mass was added to piston pin to compensate the hole. In the deactivated cylinder the piston rings were removed and the lifters modified in order to maintain oil pressure and valves closed.

In the experimental engine the third cylinder was selected to operate with two new intake camshafts manufactured and uses two cams from the original camshaft, as shown in Fig. 6.

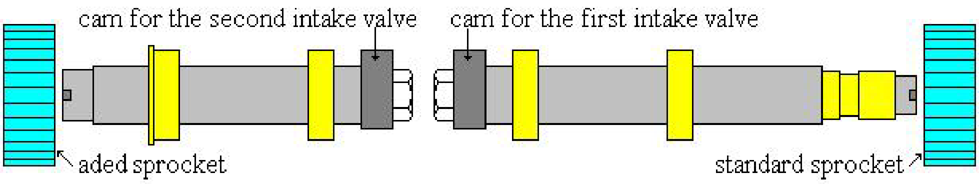

Figure 6. Intake valve camshaft

The first intake camshaft is driven directly to the crankshaft by the timing belt.

The exhaust camshaft was extended at the rear end to drive the second intake camshaft by a timing belt. As show schematically in Fig. 7, it runs on two adjustable wheels (one spring is loaded to resist belt tension under all conditions). The wheel movement changes the active length of the drive belt and thereby the phase angle between exhaust camshaft and the second intake camshaft.

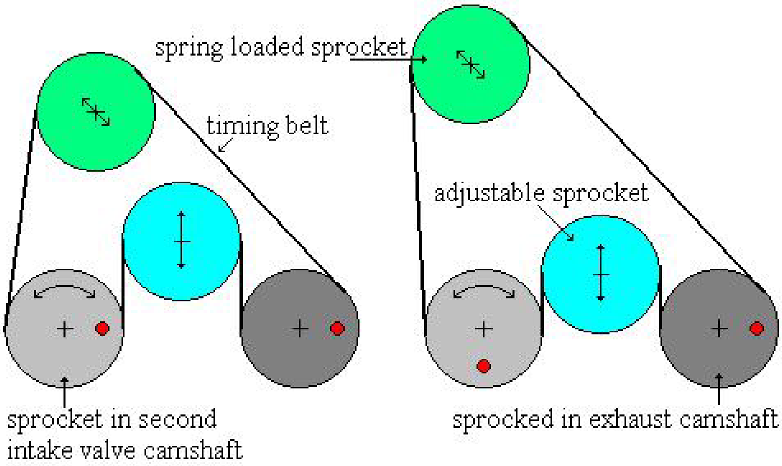

Figure 7. System with a variable drive belt length

In order to prevent interference in the flow, new intake and exhaust manifold were manufactured with a pipe that have the same length and cross section as the ducts of the third cylinder of the standard part.

The throttle was changed to a 1L FIAT engine throttle. It was necessary for better torque adjustment because the engine suction was for only one cylinder.

A new spark system was placed to allow an adjustment for the correct spark advance for maximum brake torque.

The fuel flow was set for λ = 0,87 at full load and λ = 1 at partial load. It was possible by the change of the sensors of intake pressure and throttle valve position with two potentiometers.

2.6. Tests

Tests were made in the test cell from Fundação Centro Tecnológico de Minas Gerais – CETEC. The phase adjustment system operated in all tests, throttled or unthrottled conditions.

The full load with throttle was used as reference test. At partial load of 75, 50 and 25%, the torque was calculated from a reference test.

At unthrottled part load, the engine torque was controlled by means the camshaft phase angle of the second intake valve in late intake valve closing.

2.7. Results

The fuel consumption test results at part load are presented in Tab. 1.

Table 1. Fuel consumption (g/h)

Load %	Throttle	Engine speed (rpm)						
		1500	2000	2500	3000	3500	4000	4500
75	Yes	975	1409	1793	2276	2677	3155	3529
	No	958	1383	1741	2209	2679	3152	3529
50	Yes	774	1098	1457	1862	2270	2704	2958
	No	748	1064	1375	1812	2186	2647	2831
25	Yes	610	842	1137	1455	1808	2177	2449
	No	539	771	1080	1370	1701	2105	2413

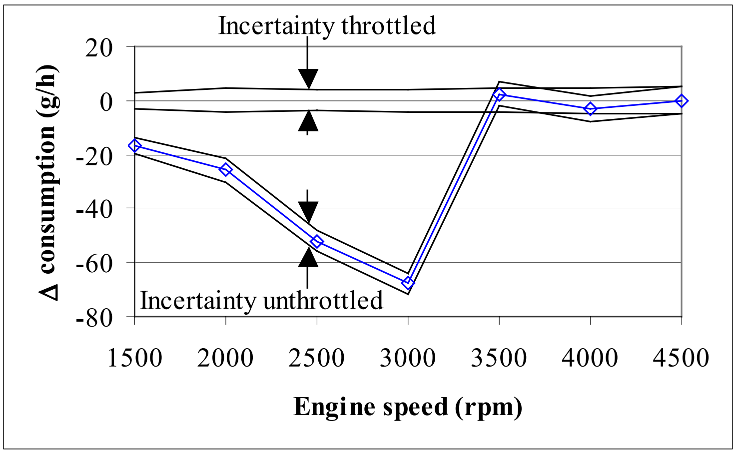

Figure 8. Fuel consumption (g/h) at 75% load

As shown in Tab. 1 and Fig. 8 at 75% load, in unthrottled mode, the mean fuel saving was 1.4%. The greatest reduction was 3.1% at 3000 rpm and decreased to zero over this speed.

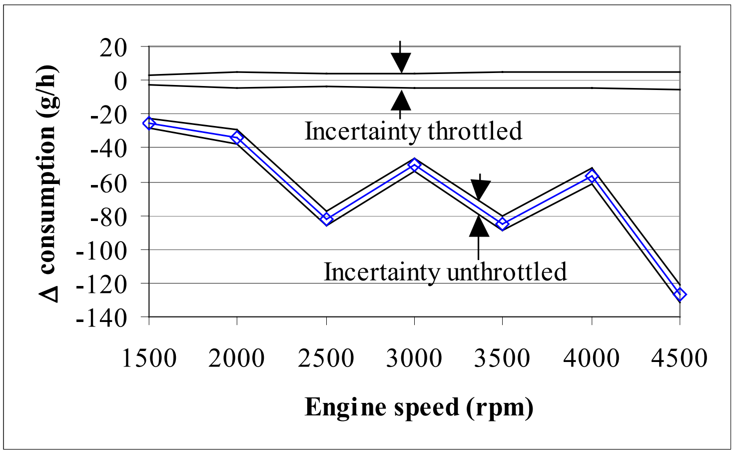

Figure 9. Fuel consumption (g/h) at 50% load

Tab. 1 and Fig. 9 show that at 50% load in the unthrottled operation, the fuel economy presentes a mean value of 3.7% and the greatest reduction was 6% at 2500 rpm.

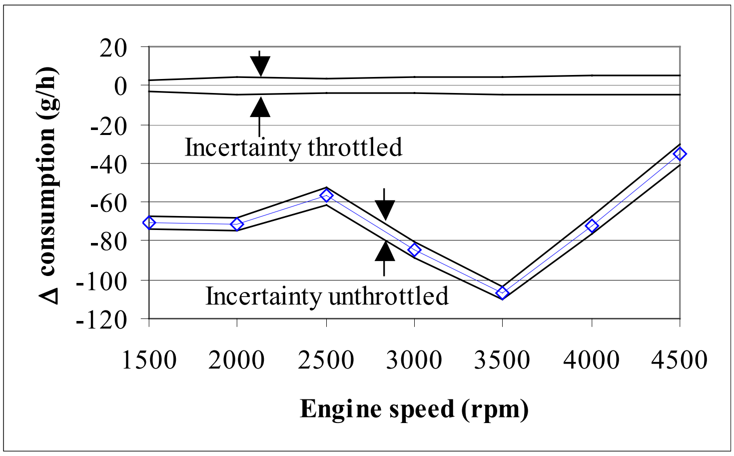

Figure 10. Fuel consumption (g/h) at 25% load

In unthrottled operation mode and 25% load, the mean value of fuel economy was 6.4% and the greatest reduction was 13.1% at 1500 rpm.

3 Conclusions

Late intake valve closing, in unthrottled operation mode, presents possibilities of fuel saving. A mean reduction of 6.4% at 25% load, 3.7% at 50% load and only 1.4%. at 75% load was observed.

Unthrottled operation mode, with late intake valve closing, permits a reduction in pumping loss and contributes to fuel saving

The intake pressure with throttle-free is greater than in throttle controlled engine. Because of this, internal EGR, in partial load is smaller, which requires less enrichment and results in fuel economy.

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