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Experimental Investigation on Electronic Fuel Injection in a Two-Stroke SI Engine by Virtual Instrumentation Technique*

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This paper presents the results of experimental work conducted on a two-stroke spark-ignited engine to reduce emissions and to enhance performance using electronic fuel injection. A virtual instrumentation program developed using LabVIEW software controls the fuel injection system. A comparative study was carried out with a base engine for determining the effect of electronic fuel injection. The injector was mounted on the inlet manifold to get a better mixing of the fuel and air. The in-cylinder pressures were recorded for 1,000 continuous cycles using a piezo-electric pressure pickup and PC-based data acquisition system. The results show that the accurate and precise control of fuel injection achieved by virtual instrumentation techniques results in improved engine performance, reduced emissions, and cycle-to-cycle variations.

NOMENCLATURE

MAP—Manifold Absolute Pressure
TPS—Throttle PoSition
LabVIEW—Laboratory Virtual Instrument Engineering Workbench
VI—Virtual Instrumentation
SMPS—Switch Mode Power Supply
AFR—Air Fuel Ratio
CDM—Crank angle Degree Marker
DAQ—Data AcQuisition

INTRODUCTION

IN THE FACE of the twin crisis arising from fossil fuel depletion and environmental degradation, it has become essential to invent new technologies to improve fuel efficiency and reduce pollution in the automobile sector. Many countries have abandoned the usage of two-stroke engines in automotive applications due to their high level of emissions and poor fuel efficiency. But the inherent advantages of the two-stroke engine as compared to the four-stroke engine have been understood for more than a century [1–4]. Over the years, various methods have been suggested to improve power output and to reduce the exhaust emissions from two-stroke petrol engines. Of the various methods available for reducing emissions, fuel injection has proved to be the most efficient [5, 6]. Various aspects of fuel injection, such as timing control [7, 8] and the impact of fuel injection control [9], have been studied. The effect of using computers to control fuel injection has also been studied [10, 11].

The technique used in this work is to develop a control system for fuel injection based on virtual instrumentation techniques using LabVIEW software. The system monitors the various aspects of the system by receiving data from various sensors in real time and regulating the quantity of fuel to be injected into the engine. The PC-based virtual instrumentation program using LabVIEW software sets the timing through the pulse width for the injector and the start of fuel injection. The above system was used to control a 150 cc, Indian-made, two-stroke production engine. The necessary modifications carried out in the engine to adopt the fuel injection system along with measuring instruments and experimental results are discussed here.

SENSORS AND SIGNAL CONDITIONING

The requirement of the developed virtual instrumentation program was to control the quantity of fuel injected into the inlet manifold of the engine. Various parameters like throttle position, manifold absolute pressure, amount of oxygen in the exhaust gas, engine speed, etc., can be used to determine the quantity of fuel to be injected. For the developed program it was decided that throttle position, manifold absolute pressure and speed data were sufficient to calculate the fuel quantity. The 12 volts DC output from the engine was used as input supply for the working of all the sensors discussed below.

1. TPS (throttle position sensor): This is basically a potentiometer used to sense the position of the throttle. Wide-open throttle requires more fuel to be injected. Closed throttle requires only the

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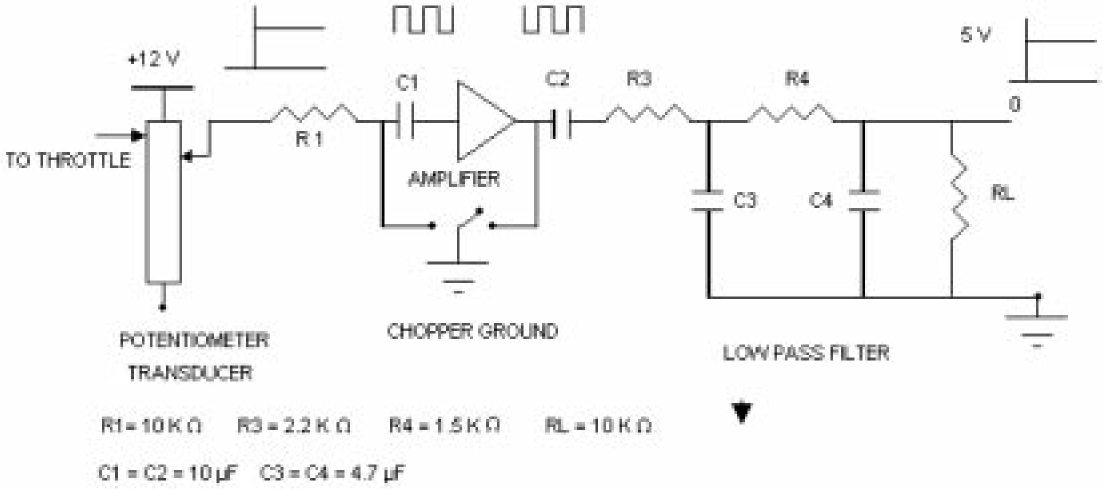


Fig. 1. Circuit diagram showing the signal conditioning of the signal from TPS.

minimum quantity of fuel to keep the engine in idle running condition for no load. Closed throttle was set to 0 volts and wide-open (full) throttle was set to a maximum of 5 volts in the potentiometer. The output signal from the potentiometer was conditioned by passing it through an amplifier and filter before it is given to the data acquisition card of the PC. Figure 1 shows the circuit diagram of the signal conditioning of the signal from the throttle position sensor.

2. MAPS (manifold absolute pressure sensor): An electrical strain gauge attached to a diaphragm was used to measure the pressure depression in the inlet manifold of the engine. Change in resistance of the strain gauge on account of the pressure change was calibrated in terms of voltage and given to the input of the data acquisition card after the required conditioning, by passing it through a bridge, amplifier and low pass filter. Figure 2 shows the circuit diagram of the conditioning of the signal from the MAP sensor.

3. Proximity sensor: To calculate the speed of the engine and to inject the fuel for every individual cycle, a proximity sensor was connected to the engine in such a way that it could get the signal whenever the piston comes to the top dead centre. This signal was used to trigger the injector and to perform the rpm calculation. The signal from the proximity sensor was given directly to the PC through the data acquisition card.

CALIBRATION OF THE FUEL INJECTOR

A fuel injector calibration test bench was developed to calibrate the fuel injector for different load and speed conditions. The test bench has a DC variable speed motor to generate different speed conditions to simulate the engine speed, which is sensed by a proximity sensor. The test bench also includes the VI program and a fuel injector with the required power supply for running the motor and operating the injector. The solenoid-controlled fuel injector [12] was used with a 12 volt input DC

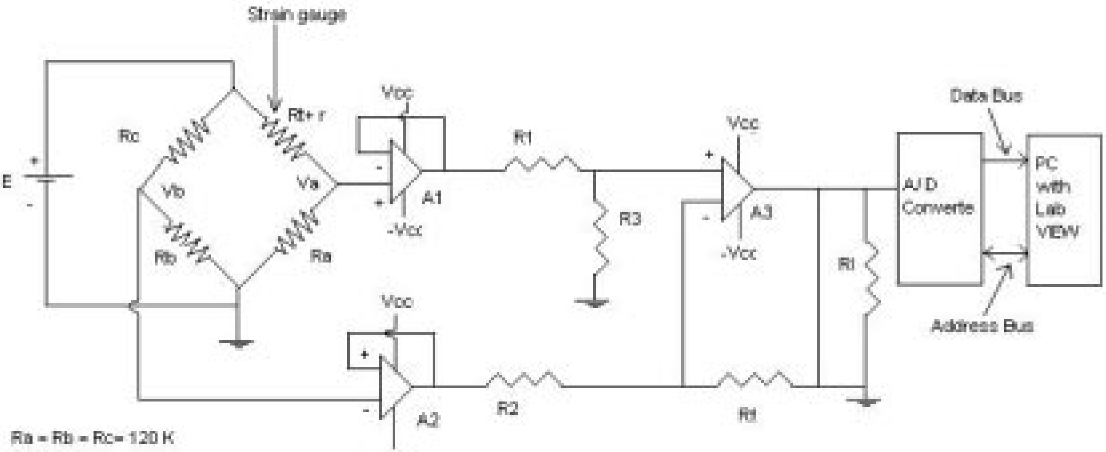


Fig. 2. Circuit diagram showing the signal conditioning of the signal from MAP sensor.

supply. The fuel injector was connected to a 12 volt DC fuel pump and pressure regulator to supply the fuel at 2 bars of pressure through the injector. The LabVIEW program gives a 5 volt output, which was amplified to 12 volts by a transistor circuit and was given to the fuel injector, as it needs a 12 volt supply. The injector was calibrated to meet the minimum and maximum fuel requirements of the engine. A controller was created in the front panel of the VI program to set the load conditions. By adjusting the pointer of the controller, the desired load conditions can be provided for the VI program for the calculation of pulse width. Pulse width is the time duration for opening the fuel injector, which controls the amount of fuel injected into the inlet manifold of the engine.

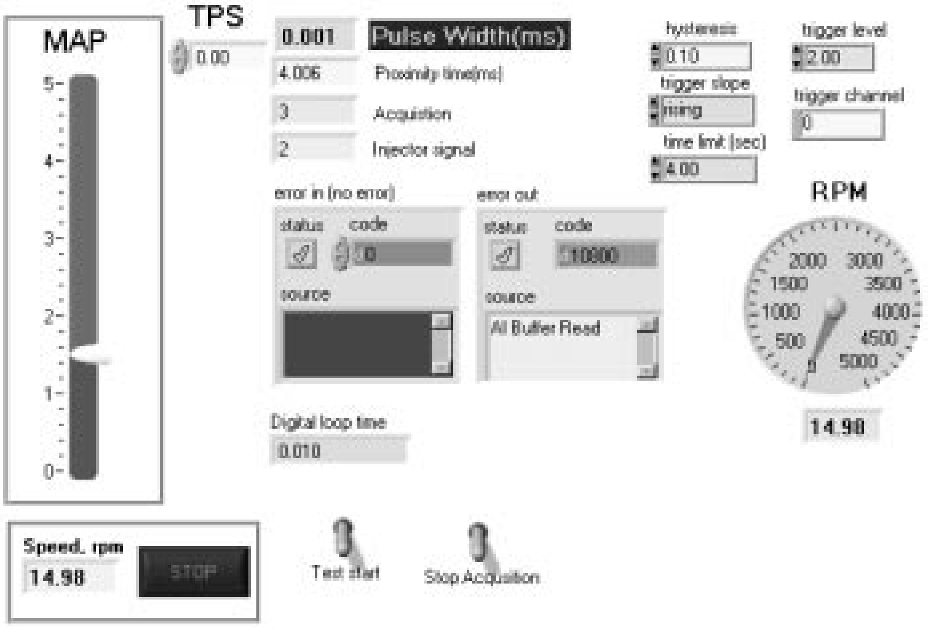
VIRTUAL INSTRUMENTATION PROGRAM

Initially, a VI was developed to calibrate the fuel injector. The requirement of the VI was to give one output (basic pulse width) from two input signals. The two input signals are from the manifold absolute pressure sensor and the proximity sensor. The basic pulse width can be modified to meet any sudden change in the throttle position by multiplying an appropriate factor available from the corresponding signal from the TPS sensor. For the calibration test, TPS and MAP signals were developed as virtual controls in the front panel of the VI. Thus the advantage of controlling the parameters as per the desire or requirement of the user was ensured, indicating the advantage of using the virtual instrumentation technique. The signal from the proximity sensor connected to the DC motor was taken as the reference for the start of injection, and pulse width was calculated. The fuel metering was based on the signals from the MAP, TPS, and proximity sensor. The program was developed initially to inject the fuel quantity according to the pulse width, which can be adjusted to vary the voltage pulses applied to the solenoid coil of the injector. Figure 3 shows the front panel of the VI.

The dynamic flow characteristics of the injector were one of the main aspects of the tests [13]. It is difficult to measure the fuel quantity per injection, due to the high speed of operation. The calibration results were generated for integrating flow over 500, 1000, 1500, 2000, 2500, 3000, and 3500 injections per minute. The different speeds were achieved by the DC motor and the developed program was run for the appropriate pulse width, based on the signals from the MAP, TPS, and proximity sensor signals. Table 1 shows the lookup table for the basic pulse width.

The above procedure was repeated for various conditions of the engine to generate a lookup table to optimize the pulse width. The injector response characteristic is a crucial factor for the efficient operation of the engine. The response time of the injector depends on various parameters, such as the physical size of the solenoid, the power output, the drive circuitry, the mass and travel of the armature, and the fuel injection pressure [14].

To run the engine, a separate virtual instrumentation program was developed. To calculate the pulse width, real-time signals from the proximity sensor, MAP sensor and TPS sensor by running the engine were considered. The basic pulse width was obtained just by considering MAP and proximity sensor (speed) values. The difference between the virtual instrumentation programs developed for the calibration of the injector and to run the engine in real time is given below.



TPS 0.00

0.001 Pulse Width(ms)

4.006 Proximity time(ms)

3 Acquistion

2 Injector signal

hysteresis 0.10

trigger level 2.00

trigger slope rising

trigger channel 0

time limit (sec) 4.00

error in (no error) status code 0 source

error out status code 10000 source All Buffer Read

Digital loop time 0.010

RPM 14.98

Speed, rpm 14.98

Fig. 3. Front panel of the developed VI program.

Table 1. Lookup table for the pulse width in milliseconds

	SPEED, RPM								
MAP, Pa	500	1000	2000	2200	2400	2600	2800	3000	3500
50	4	3	2.1	2.1	2.1	2.2	2.1	2.1	2.1
55	4	3	2.1	2.15	2.16	2.17	2.18	2.19	2.2
60	4	3	2.1	2.15	2.16	2.18	2.19	2.2	2.3
65	4	3	2.15	2.17	2.17	2.19	2.2	2.25	2.32
70	4	3	2.2	2.19	2.18	2.20	2.26	2.28	2.34
75	4	3	2.2	2.2	2.19	2.21	2.3	2.34	2.36
80	4	3	2.2	2.21	2.2	2.22	2.4	2.36	2.38
85	4	3	2.2	2.23	2.25	2.26	2.44	2.38	2.42
90	4	3	2.25	2.24	2.3	2.3	2.48	2.4	2.5
95	4	3	2.25	2.26	2.35	2.35	2.51	2.44	2.55
100	4	3	2.28	2.28	2.36	2.4	2.54	2.46	2.58
110	4	3	2.28	2.3	2.37	2.46	2.55	2.48	2.61
120	4	3	2.29	2.4	2.38	2.5	2.56	2.52	2.65
130	4	3	2.3	2.41	2.39	2.52	2.57	2.59	2.9
140	4	3	2.32	2.43	2.41	2.54	2.6	2.64	3.2
150	4	3	2.33	2.45	2.43	2.56	2.62	2.69	3.4
160	4	3	2.35	2.46	2.47	2.59	2.68	2.74	3.6
170	4	3	2.36	2.47	2.49	2.62	2.7	2.9	3.8
180	4	3	2.4	2.48	2.52	2.68	2.74	3.2	4.2

In the calibration program, the sensor signals were given as per the fuel mapping done between MAP, speed and fuel quantity required. A test run was given in the carburation mode to generate the data for fuel requirement for different TPS , MAP and speed conditions. By setting up those values in the virtual controls (not the signals from the sensors by running the engine) developed in the front panel, the required pulse width for injecting the particular quantity of fuel was obtained. But, in the case of the virtual instrumentation program developed for running the engine, the real-time signals obtained from the engine while running were given as input for calculating the pulse width. Therefore in the second program the virtual controls were replaced with the real input signals by configuring the MAP sensor and TPS sensor. The fuel injection control is basically a speed density system [15]. The proximity sensor was fixed in the engine such that it could sense the position of the piston for injecting the fuel in every cycle for every revolution. These three sensors were interfaced with the computer by means of a PCI-6035E data acquisition card used for acquiring signals after the required signal conditioning discussed earlier. A CDM was used to regulate the injection-starting angle by measuring the position of the piston head with reference to the top dead centre of the cylinder.

FUEL SUPPLY SYSTEM

An electrically driven roller-cell pump pumps the fuel from the fuel tank through a filter into the fuel rail. From the fuel rail, fuel lines diverge to the injection valve. At the end of the fuel rail is a pressure regulator, which maintains the pressure at a constant level of 2 bars. More fuel circulates in the fuel system than is needed by the engine, even under the most extreme conditions. The excess fuel will return to the fuel tank by the pressure regulator. The constant flushing of the fuel system enables it to be continually supplied with cool fuel. This helps to avoid the formation of fuel vapor bubbles and guarantees good hot-starting characteristics.

EXPERIMENTAL SETUP AND SCHEME OF EXPERIMENTATION

The experiments were carried out on a single-cylinder, air-cooled, two-stroke SI engine. The engine details are given in Table 2. The schematic of the experimental setup is shown in Fig. 4. Air was admitted to the engine by means of an air damper, which was also used to measure the airflow rate and acted as a pressure damper. The fuel flow measurement was done by an automatic fuel flow meter for the base engine and a test injector and stopwatch for the injected engine.

The engine was loaded by means of an eddy current dynamometer. An infrared exhaust gas analyzer was used for measuring the exhaust emissions including CO (in % vol) and HC (in ppm). The cylinder pressure was measured using a piezo-electric pressure transducer flush mounted on the engine in such a way that its bottom surface

Table 2. Engine specifications

Type	Single cylinder, air-cooled
Model	Bajaj Super FE
Cylinder Bore	58 mm
Stroke	57.5 mm
Displacement	150 cc
Power	4.7 kW @ 1500 rpm
Compression Ratio	7.4:1

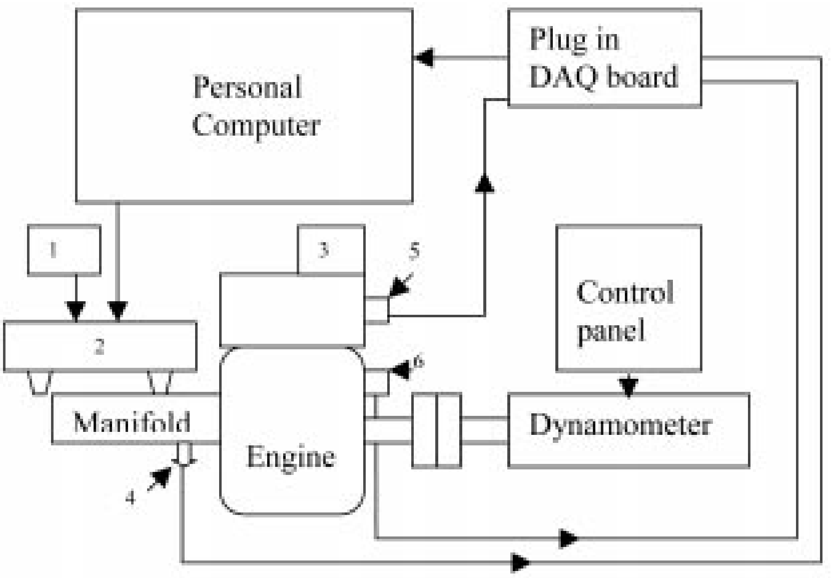


Fig. 4. Schematic of the experimental setup. 1) SMPS; 2) fuel rail with two injectors; 3) pressure pickup; 4) MAP sensor; 5) proximity sensor; 6) TP sensor.

coincided with the inner surface of the cylinder head of the engine.

Pressure data was recorded using a high-speed AVL data acquisition system timed by an optical encoder mounted on the engine crankshaft. Sampling intervals of 0.1 degree, 0.5 degrees and 1 degree were examined and the interval of 1 degree was found to be sufficient for the study. This is in agreement with Evan [16]. Pitterson [17] proved that a sample size of more than 1000 cycles produced fairly repeatable results, whereas less than 1000 cycles could be misleading. Hence a sample size of 1000 cycles was selected for further analysis. The necessary modifications were made to the engine to mount the fuel injector in the inlet manifold, enabling it to inject the fuel so that it mixes properly with the incoming air. The other end of the fuel injector was attached to a fuel rail, which supplies the fuel. A test injector was mounted on the fuel rail to measure the fuel consumption in injection mode.

The engine was started and the necessary load conditions were set by the control panel of the eddy current dynamometer. The volume of fuel consumption was set to 25 cc on the dynamometer control panel. The time taken for the consumption of 25 cc of fuel was measured using a test injector in the injection mode. Manometric pressure difference, exhaust gas temperature and emission readings were recorded.

RESULTS AND DISCUSSION

Air-fuel ratio is one of the important factors used to compare the performance of the engine running with different modes. It gives an idea about the fraction of fuel and air available for combustion. Hence, in the following discussion, air-to-fuel ratio is compared with the other performance characteristics of the engine. From Fig. 5, it can be seen that, for the same air-fuel ratio, the engine develops more brake power in the injection mode when compared to the carburation mode. This is because of the stable ignition, due to the precise quantity of fuel supplied by injection through the virtual instrumentation technique. From Fig. 6, it can be seen that, for both carburation and injection,

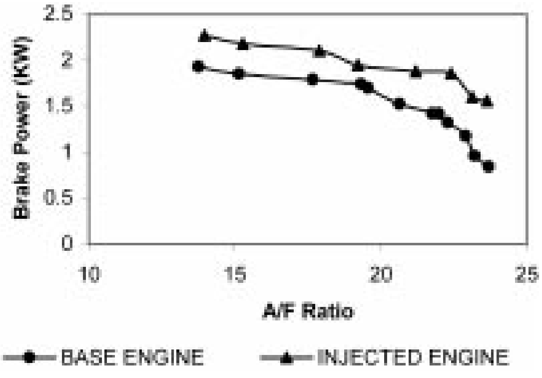


Fig. 5. Air-fuel ratio vs brake power at 2000 rpm.

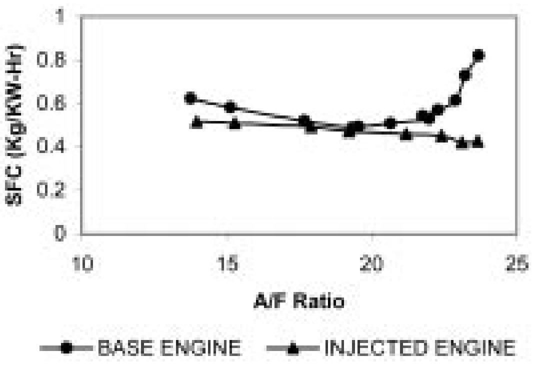


Fig. 6. Air fuel ratio vs specific fuel consumption at 2000 rpm.

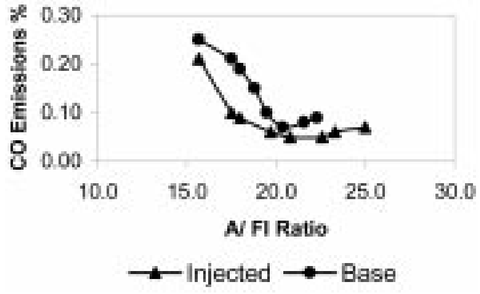


Fig. 7. Air fuel ratio vs CO emissions at 2000 rpm.

the specific fuel consumption decreases with an increased air-fuel ratio up to a particular limit, after which specific fuel consumption starts increasing. This is because, after this limit, the decrease in brake power outweighs the decrease in fuel consumption. It is also observed that, for the same air-fuel ratio, the specific fuel consumption is less with fuel injection because more power is developed, even with the same amount of fuel supplied.

Recent research on engines is concentrated around reduction in tail-pipe emissions from automobiles, in order to avoid global warming and air pollution. The following results reveal the usefulness of virtual instrumentation techniques for reducing pollution levels. The exhaust emissions CO and HC are plotted in Figs 7 and 8. The CO emissions of the injected engine are well below the carbureted engine, even in a leaner (more air and less fuel) operation. The HC emissions are also too low for the injected mode. However, in the lean limit, HC emissions show a sudden increase, which is due to inefficient combustion. Since in real time the engine will be running closer to a stoichiometric air-fuel ratio, there will not be any increase in HC emissions.

Effect on cycle variation

There are many methods for analyzing combustion variation in SI engines [17, 18]. A widely used parameter is the peak pressure measured inside the cylinder during combustion. Figures 9 and 10 show the density plot of peak pressure for both the base engine and injected engine. The cycle-to-cycle combustion variation should be minimized and/or combustion rates maximized so as to reduce cycle-to-cycle pressure variation.

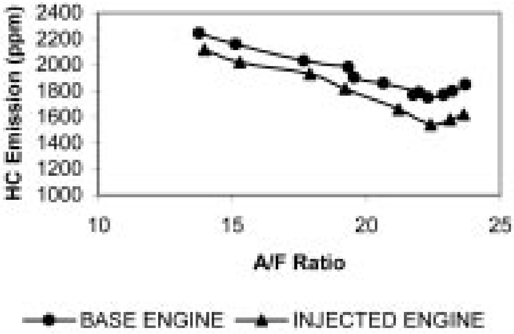


Fig. 8. Air fuel ratio vs HC emissions at 2000 rpm.

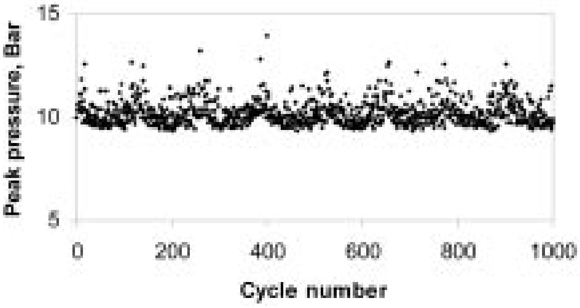


Fig. 9. Density plot of peak pressures in carburetion mode, load 10 kg, speed 2000 rpm, air-fuel ratio 16.

Closer observation of Figs 9 and 10 will reveal the unstable variation of peak pressures in the carburation mode and a stable level of peak pressures in the injection mode. Since the charge in an injection system burns at a high rate, the gas force developed by combustion of the charge is more compared to that developed with a carbureted system.

Educational uses of the present work

From the above-discussed results, it is evident that a VI program can be used for engine control. Laboratory experiments on engine performance can be conducted using the developed program with slight modifications to find out the performance characteristics of the engine online. Since the software is user-friendly, quick programs can be made to check various parameters of the engine, such as brake thermal efficiency, indicated thermal efficiency, fuel consumption, etc. These parameters can be found online, resulting in a reduction of time over conventional methods. The students can be educated on the working of fuel injectors in the laboratory using the VI program.

CONCLUSION AND FUTURE WORK

The elimination of fuel waste and emissions has been intensively studied over the past few decades. One of the best methods for solving the above problem was identified as electronic fuel injection. In this work, a successful virtual instrumentation program was developed using LabVIEW software to run a two-stroke SI engine in injection mode.

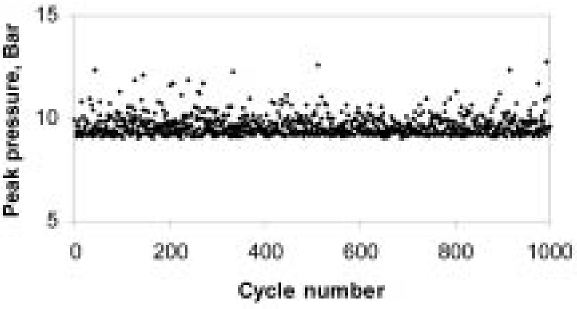


Fig. 10. Density plot of peak pressures in injection mode, load 11 kg, speed 2000 rpm, air-fuel ratio 16.7.

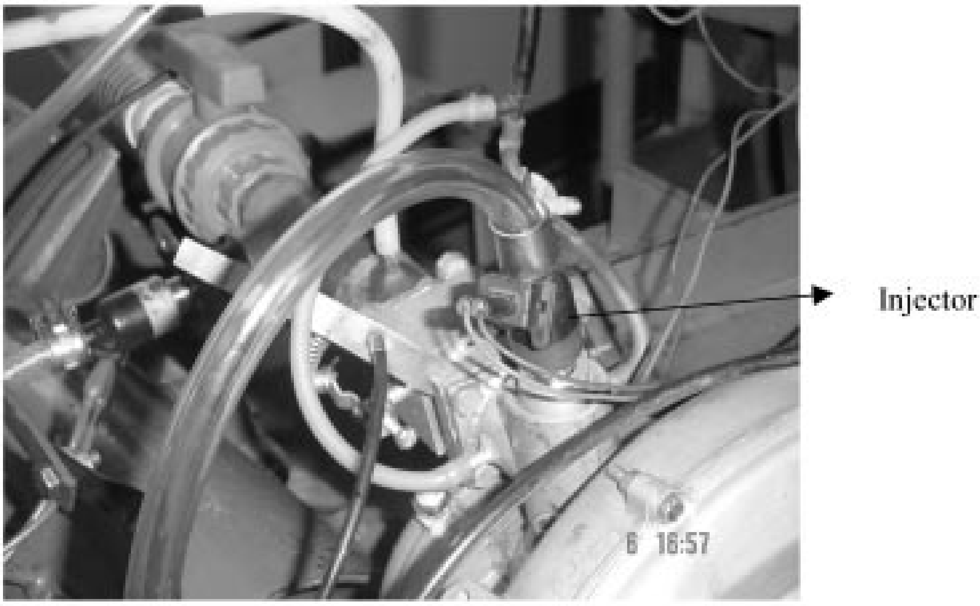


Fig. 11. Photograph showing a view of the experimental setup.

The injected engine shows an overall performance improvement compared to the base engine. The injected engine shows very good improvements in brake power when compared to the base engine. The injected engine shows less fuel consumption. The brake thermal efficiency of the injected engine was higher when compared to the base engine. The CO and HC emissions were less in comparison with the base engine and the injected engine produced higher peak pressure.

The present work can be extended by considering more input parameters, such as coolant temperature, and oxygen content in the exhaust, etc., for calculating the pulse width to precisely inject the fuel. The VI program that was developed can be used for stationary engines (mostly for research engines) only where a computer is required to control the engine operation. After optimizing the program in LabVIEW software, this program can be fed into a micro-controller and used as an embedded system for real-time applications.

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