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Research Article

Smart PC Based System to Control the Air-Fuel Ratio in S I Engines for Best Performance

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Abstract

A smart mechatronic system was developed in this work to control a Spark Ignition, SI, engines. A self-regulative control system was proposed to run the engine at the optimum thermal efficiency whatever the loading value is. An experimental test rig was developed to apply and verify the present control system. The test rig consists of a speed sensing, engine loading, and air and fuel metering hardware modules. A software program was developed by the authors to control the engine speed very near to the design speed value, while applying the best economy air to fuel, A/F, ratio on the engine. Off-line and on-line self regulation techniques were developed, and implemented by the control soft ware to decide the air and fuel rates corresponding to the optimum efficiency. The speed signal and the fuel and air control commands are exchanged via an I/O digital data acquisition card, DAQ, connected to a host personal computer. Off-line self regulation technique is faster but needs updating from time to time due to the engine ageing. The on-line technique is always up to date but takes a relatively long time to decide the best A/F ratio. Experimental results showed that, the present smart control system improves the thermal efficiency in a range from 8 to 10% compared to the stochiometric engine operation.

Keywords: *A/F Ratio Control, Best Economy A/F ratios, Improvement of SI Engines Efficiency, PC Based Feedback Control, Smart Mechatronic Control Systems.*

1. Introduction

Regarding the essential need to enhance overall efficiency and to reduce hateful exhaust emissions, (Piltan, *et al*, 2013), optimized internal combustion engines, ICE, to meet exhaust emission requirements with the best fuel economy. The control target is to maintain the fuel ratio at stoichiometry. A control oriented cycle-to-cycle engine model, containing engine combustion information for each individual engine cycle as a function of engine crank angle is performed.

Adaptive neural network model-based control is applied to A/F ratio control of automotive engines by (Zhai, *et al,* 2011). Their simulation results validated that the developed method can control the A/F ratio to track the set-point value under disturbance of changing throttle angle.

There have been considerable efforts to improve the performance of spark-ignition engines over the past years (Bidan, *et al*, 1995), (Guzzella, *et al*, 1995), (Hendricks, and Sorenson, 1990). Matching between the severe exhaust emissions limits, decreasing specific fuel consumption, increasing engine performance and getting fast response time is the real challenge in the modem SI engines industry. These requirements depend mainly on how the air/fuel ratio is optimum. A precise control of air/fuel ratio may not be easy because the requirements tend to be incompatible as reported by (Hendricks, and Sorenson, 1993), (Hendricks *et al, 1993*). The feedback control showed a delay and stability problems when accelerating or decelerating the throttle angle as concluded by (Khalil, 1993).

(Kim, *et al***,** 1992) suggested a robust sliding mode control method for the design of a fuel injection control system. They used an electronic control unit with 16 bit microcontroller. Their experimental results showed that the sliding mode fuel injection controller can make the engine to operate in the neighborhood of stoichiometric air-fuel ratio, 14.7 ± 0.3. This improved the efficiency of 3-way catalyst by more than 90%, so strict regulations for the exhaust emission can be satisfied.

(Schook,R., 1992) developed an air-fuel ratio control system for more effective emission control and acceptable performance. Medium and high speed stationary stoichiometric engines were employed. He concluded that accurate closed loop control is particularly beneficial with engines subjected to load and speed variations.

(Solimann, *et al* , 1993) introduced the vaporizing carburetor for providing the engine with a high quality A/F ratio, which allowed it to operate at maximum power with lower level of exhaust emission. The result obtained from their investigation showed that the exhaust emission can be reduced over a speed range of 1500-3000 rpm by using the vaporizing carburetor.

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Therefore, the A/F ratio controlled variable must be determined by more sophisticated means than before. The recent technical developments in microelectronics allow the rapid and accurate solutions of complicated real time problems. With the microchips controlled electronic fuel metering, it is possible to use more sophisticated strategies to compensate for the transient air/fuel fluctuations and therefore controlling the performance of the SI engine. The first generation control strategies, microprocessors and sensors are used to attain the engine performance improvements necessary to meet recent emissions requirements. This becomes a difficult task if no new techniques and advanced dynamic modeling are made available for engine controller design.

Beside the steady state condition, the transient air-fuel ratio control is taken into consideration since it is essential for meeting low emission targets. It is worth noting that the conventional compensation forms are not suitable at all for transient modes. This is due to stability problems and the delay in acceleration and deceleration of the air throttle angle with feedback control. With the advent of wide band air-fuel ratio sensors, nonlinear and more sophisticated control schemes become possible. However, cost and reliability of these sensors do not yet meet large-scale production requirements. Also, the modern electronic engine controls are not robust with respect to modeling errors resulting from engine aging, wear, and lack of maintenance. It is therefore, alternative methods for running controlled SI engines on the optimum A/F ratio become an important issue.

The present paper is organized as follows. In the following section, an overview of the present work is presented. All modules of the present test rig are described in the next section. The control software program, developed in this study, is illustrated afterward. The results of the present experimental work are consequently discussed. Conclusions, nomenclatures and references are presented at the end of this paper.

2. Overview of the present work

The present work is dedicated to the area of engine speed control keeping the optimum A/F, ratio for best economy. The best-economy is achieved by selecting the A/F ratio at any operating load in order to maintain higher thermal efficiency. The scheme of the present work is detailed below:

1- Preparation of a single-cylinder, spark ignited, internal combustion engine, coupled with an AC electric generator to be digitally controlled. A personal computer equipped with a multi I/O digital data acquisition card, DAQ, is used to handle the engine speed measured data. The speed data is processed by the control software to decide the air and fuel control actions. Control actions is sent, as digital and analog voltage signals, using the data card through interface electronic circuits, designed by the authors, to adjust for the optimum air and fuel rates.

2- Design and construction of the required, measurement, control and interfacing electronic circuits.

3- Construction of the control software required to achieve the following tasks:

A. Control the engine speed fixed at 3000 rpm, whatever the load value is, through controlling the fuel rate to the engine.

B. Storing a look-up table for air-fuel ratio against load, prepared by the authors for the optimum engine efficiency. The engine load is changed by sending a voltage signal to the light turn on/off circuit, and according to its value, the optimum A/F ratio is selected. Given that fuel rate is known from (A) above, the optimum air rate is calculated. Control signal is thus sent to adjust the air orifice area for the new rate.

C. Executing different pre-planned operating load cycles to check how successful is the present control system in controlling the engine speed while the maximum thermal efficiency is achieved.

A schematic block diagram for the present engine PC based control system is shown in Figure1.

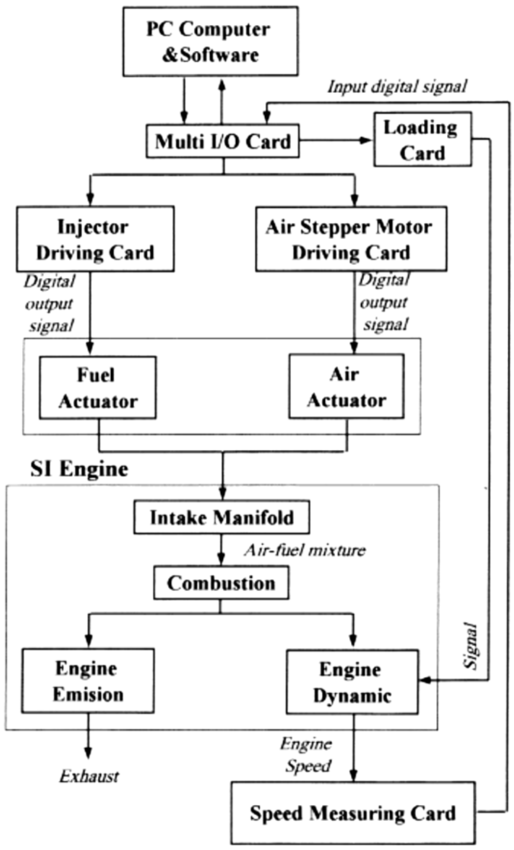

Fig.1 Schematic block diagram of the present engine control system

Inputs to the engine are mainly air and fuel rates. Outputs are the mechanical power, engine dynamics in the figure, speed, and exhaust emissions. The A/F ratio is the main control key parameter. Engine speed is measured by the present speed sensor. Speed signal is fed to a personal computer through a multi I/O data acquisition card, DAQ.

The engine is coupled by AC electric generator loaded by electric lamps each of 100 W. The engine is loaded using a loading electronic circuit to be activated by digital signals from the personal computer. The load signal decides the lamps number to be lighted. Control signal to decide the fuel rate, according the measured engine speed, is sent to the fuel injector driving electronic circuit. Another control signal is sent to air orifice driving circuit to decide the air rate corresponding to the fuel rate, decided for the current control time, to attain the optimum A/F ratio for the best engine efficiency.

All of the speed measuring, load assigning, air throttle, and fuel injector driving electronic circuit are designed and constructed by the authors. The processing of the speed signal and the control signals for the load, air and fuel rate are decided by the control soft ware constructed by the authors.

The control software is designed to maintain the engine speed constant at 3000 rpm, irrespective of engine load changes and the external disturbances. The error in the measured speed, deviation than the desired value, is processed by the software using control law of the PID controller. A control signal is thus decided and sent to the fuel injector to compensate for the speed error. A corresponding control signal is also sent to air stepper motor to change the air flow rate so that the A/F ratio for the best engine efficiency is maintained.

The present control software is designed to implement two methods for engine self regulation as it will be detailed later in this paper. Engine self regulation are designed and applied, in this work, for self selecting the best economy A/F ratio as the applied loads changes.

3. The present test rig

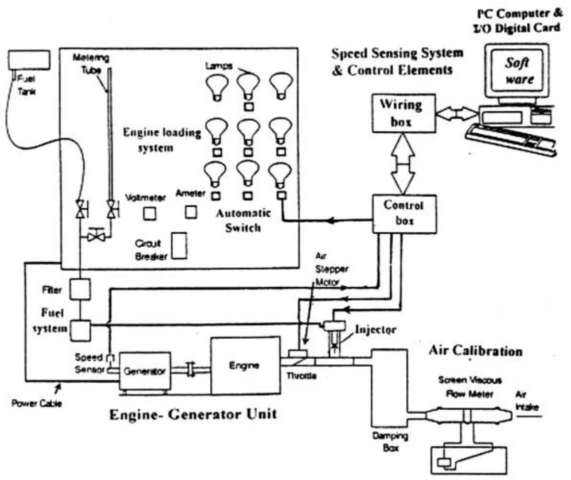

Fig.2 Schematic diagram of the present test rig

A layout of the present test rig is shown in Figure 2. It consists of a small SI engine unit, loading system, and control hardware modules, included in the control box shown in the figure, fuel and air metering hard-wares. The test rig is connected to a personal host computer through an I/O data acquisition card, DAQ, using wiring network. The present engine-generator unit consists of a Honda engine, GX 340 model, single cylinder, air cooled, spark ignited, 4 cycles, 337 cc, coupled to an AC electric voltage generator, 220 AC volts at a design speed of 3000 rpm.

The fuel and air feeding systems have been modified to enable the present calibration and control systems. In the present work, the original conventional carburetor system of the engine was replaced by an electronic fuel injection system to achieve a precise control of the fuel rate

4.1 Speed sensing system

Engine speed is measured in two steps. The engine crankshaft rotation speed is first converted to a train of pulses of the same engine rotational frequency using an optical proximity sensor as shown in Figure 3.

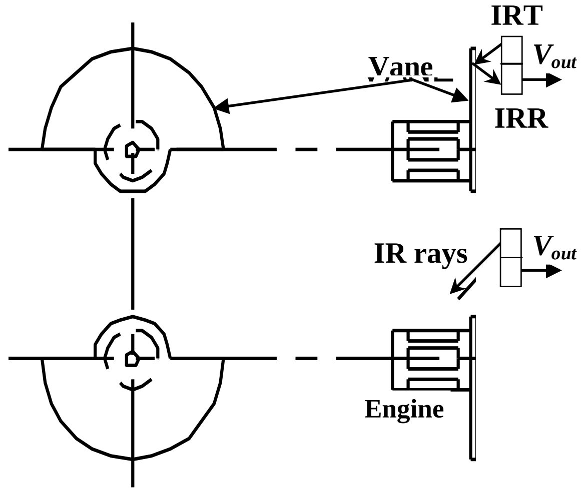

Fig.3 The optical proximity sensor used to measure the present engine speed

Infrared rays are emitted by IRE, infra red emitter, to be reflected or not to an infra red optical receiver, IRR. The IRR is an infra red photo transistor connected so that it gives 1 or 0 digital outputs, V_{out}, if the optical rays is allowed or not to be reflected. An unsymmetrical vane of large diameter in one halve and a small diameter in the other halve, as shown in the figure, is mounted to the engine axis so that the optical rays is allowed to be reflected in one revolution halve and to be prevented in the other halve. V_{out} is thus generated as a periodic square pulse wave of the same frequency as the engine rotational motion.

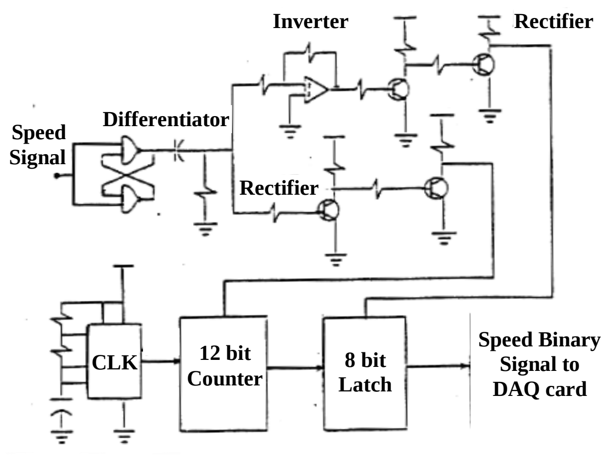

Fig.4 Engine speed periodic time measurement circuit

In the second speed measurement step, the periodic time, *T*, of the pulse signal generated by the first step mentioned above, is precisely measured using the electronic circuit shown in Figure 4. It is clear that, T is the reciprocal of the engine rotational speed, revolutions per seconds RPS, The idea is to generate a high frequency square signal train, f_{clock} = 40 kHz, and to count its pulse number, N_{speed}, that pass during each engine periodic time, T. N_{speed} is sent to the computer memory through the data acquisition card. The engine speed, RPM, is then calculated by the control software using the relation:

$$RPM = \frac{60}{T} = \frac{60}{(N_{speed}/f_{clock})} \quad (1)$$

4.2 Fuel metering system

The present engine fuel feeding system is shown in Fig. 5.

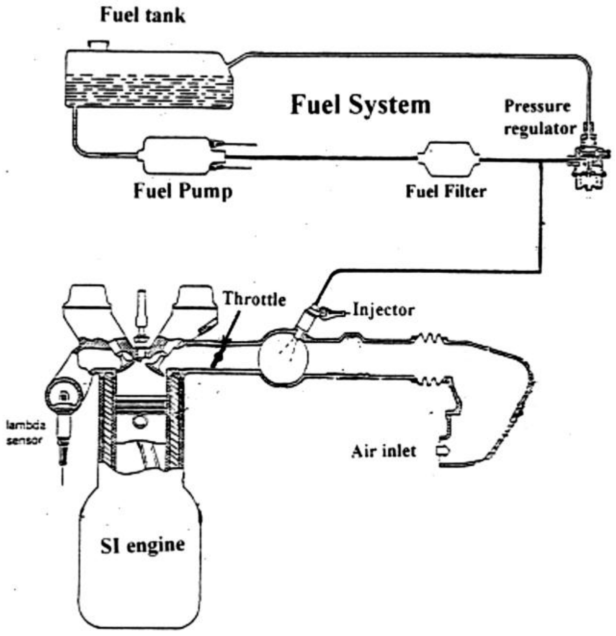

Fig.5 The present fuel feeding system

It is mainly consisted of a fuel tank, 25 micron fuel filter, electric fuel pump, pressure regulator and solenoid-operated injector. 25 cm^3 metering tube is connected to the fuel system through a bypass valve system to enable the calibration of the fuel rate.

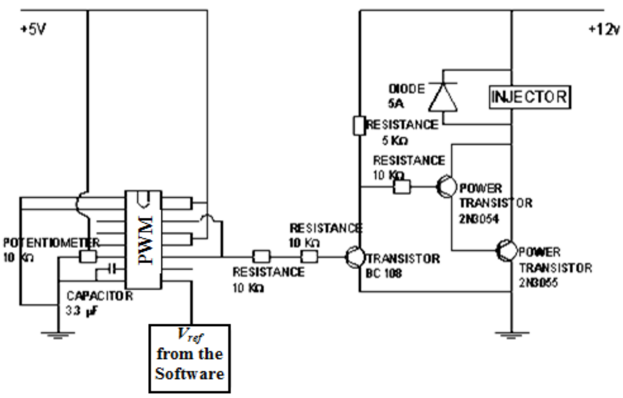

Fig.6 Injector driving circuit

A solenoid type injector is used to spray fuel from its nozzle into the air stream going to the intake manifold. The injector is energized using the PWM technique, its nozzle is fully opened then fully closed according to a certain duty, in a pulse cyclic mode of a periodic time of 0.1 s, operation frequency =100 Hz. The operation duty, the ratio between opened to the closed periods of the injector, is controlled using the driving circuit shown in Figure 6. The input to the circuit is an analogue reference voltage, V_{ref},. V_{ref} is generated by the control software in 12 bit binary form to be converted into analogue by the data acquisition card. V_{ref} range is from 0 to 5 V which is corresponding to PWM duty range from 0%, fully closed injector, to 100%, fully opened injector.

Calibration of the fuel rate against V_{ref} is experimentally carried out and is presented in Figure 7.

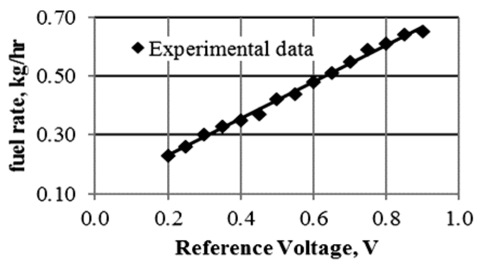

Fig.7 Calibration of fuel rate against V_{ref} value

The best fit line of the calibration experimental data is concluded as:

$$M_f = 0.625\, V_{ref}(V) + 0.105 \quad \text{(kg/hr)} \quad (2)$$

$$V_{ref} = 1.60\, M_f(\text{kg/hr}) - 0.164 \quad (V) \quad (3)$$

4.3 Air metering system

The present air metering system is shown in Figure 8. It is equipped with a bellows flow meter, and damping box to enable the offline calibration of air consumption against the air throttle angle. An electronic air metering actuator, shown in Figure 8, is designed to control the air flow rate with digital signals generated by the control software.

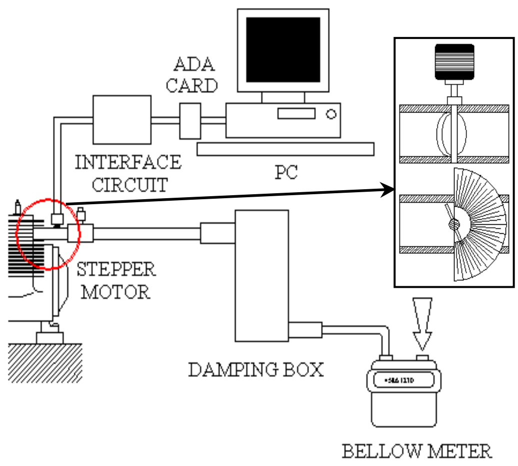

Fig.8 Schematic diagram of the present air metering system

It consists of a butterfly valve driven by a stepper motor of 1.8°/step. The direction and number of rotational steps of the stepper motor determine the butterfly valve angular position, θ, and thus the cross sectional area of the air flow. The air flow rate is experimentally calibrated with the angle θ with engine speed is controlled to be fixed at 3000 rpm.

Air calibration is presented in figure 9.

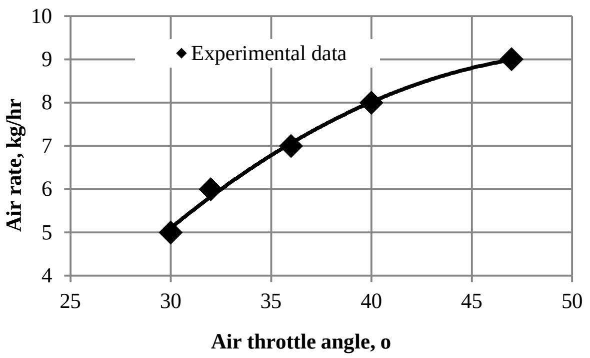

Fig.9 Calibration of air rate against throttle angle θ value at 3000 rpm engine speed

The best fit curves of the calibration experimental data are given below:

$$m_{air} = -0.009\,\theta^2 + 0.914\,\theta\,(o) - 14.3,\ \text{kg/hr} \quad (4)$$

$$\theta = 0.7143\, m_{air}{}^2 - 5.80\, m_{air}(\text{kg/hr}) + 41.17,\ \text{deg} \quad (5)$$

$$n_{pulse} = \frac{\Delta\theta}{1.8} \quad (6)$$

Figure 10 shows the electronic circuit used to drive the stepper motor. A direction digital signal, n_d, is sent to the motor driver to decide the rotational direction, n_d =1 for CW, increasing θ, and n_d = 0 for CCW, decreasing θ,. Another signal for the number of rotational steps is sent as a train of square pulses of equal number of pulses, one step for each pulse.

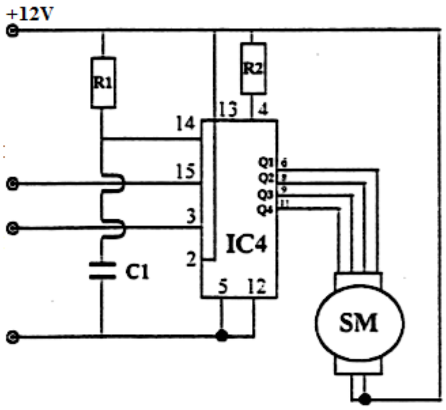

Fig.10 Air stepper motor driving circuit

The control software decides and sends a suitable direction signal and a 4 bit binary digital number, n_{pulse}, equal to the rotational steps corresponding to the required change in the air valve angle, $\Delta\theta$. New value for m_{air} is calculated from the new m_{fuel} and the best A/F ratio decided by the control software. θ_{new} corresponding to new m_{air} is calculated using equation (5). $\Delta\theta$ is calculated as the difference between θ_{new} and θ_{old}. The required n_{pulse} is calculated from $\Delta\theta$ using equation (6). If $\Delta\theta$ is of positive value, CW, $n_{direction}$ =1, direction is decided to increase θ, and vice verse.

The n_{pulse} binary digital number is converted to a square pulse train of the same pulse number using the binary to pulse circuit shown in Figure 11. The stepper motor control signals are sent to the motor driver through the data acquisition card.

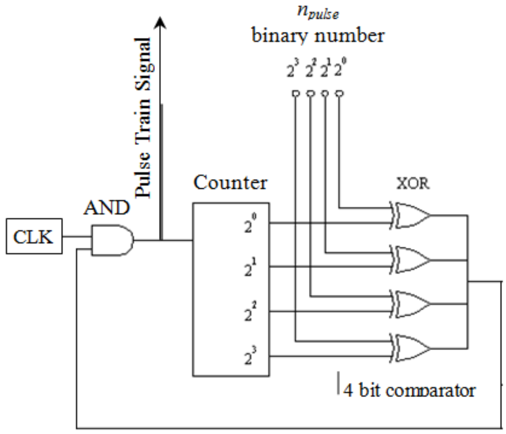

Fig.11 Binary to pulse circuit

4.4 Engine loading system

The engine loading system is shown as in Figure12. An electric 220 AC/ 3000 rpm, generator, coupled to the present engine, is used to supply the power to lighting system consists of nine electric lamps, 100 watt for each. The nine lamps are arranged in five groups, two groups of one lamp and three groups of series connected lamp, two groups of two lamps and one group of three lamps.

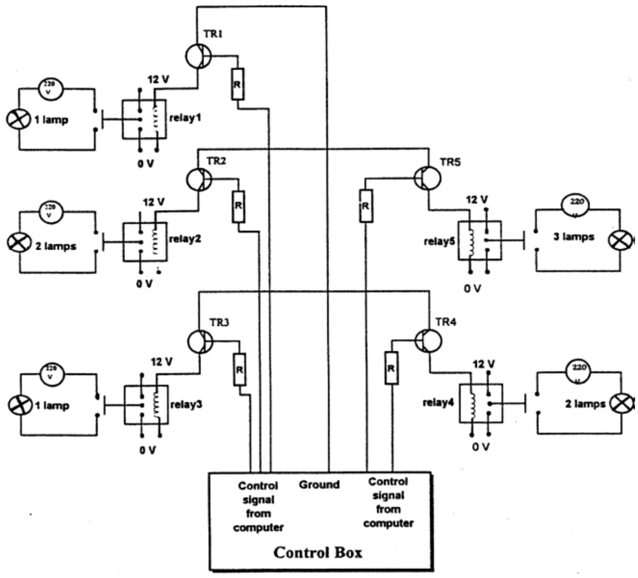

Fig.12 Schematic diagram for the present loading system

Each lamp group is triggered using a solid state transistor switch which can be switched ON or OFF by a digital signal decided by the control software. The engine load is thus determined as the number of loaded lamps, n_{lamp}, multiplied by a 100 W value. Triggering a combination of these lamp groups enables the engine loading by a load from 100 W to 900 W, 10% to 90% of the full load, through 100 W increments.

4. The present control software program

A software program to control the present engine system was designed and constructed by the authors. The engine speed is controlled to be kept very close to a reference value of 3000 rpm. The control software is designed to send fuel and air command signal so that the best economy A/F ratio is applied. Figure 13 shows a block diagram for the present feedback control system. Figure 14 shows how the control loop is applied on the present engine.

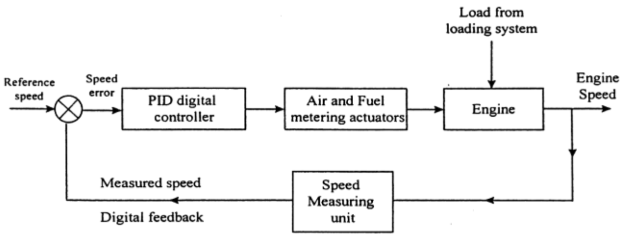

Fig.13 Block diagram for the feedback speed control system

The program was written in QBASIC language. Control hardware electronic circuits were designed and constructed to acquire the engine speed and to control the engine load, fuel and air flow rates. Communications between the control soft and hard wares are done via wiring network using an I/O digital data acquisition card connected to a host personal computer

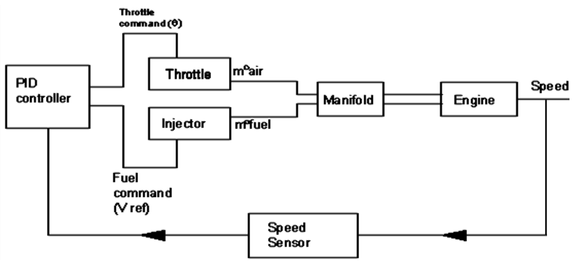

Fig.14 speed control system applied to the present engine system

The air throttle angle is manually set to zero and the control program is used to send a predefined reference value to the injector driving circuit = 0.23 V, $V_{ref} = 0.23$ V, and stepper motor commands to set the throttle angle, θ, at 30°. This is decided to enable the engine to start at a suitable rich A/F ratio of about 14. The load is increased manually from the no load condition gradually to 30% full load through a 10% increment to ensure a smooth engine starting.

4.1 Engine speed control

Figure 15 shows the flowchart of the present engine speed control software.

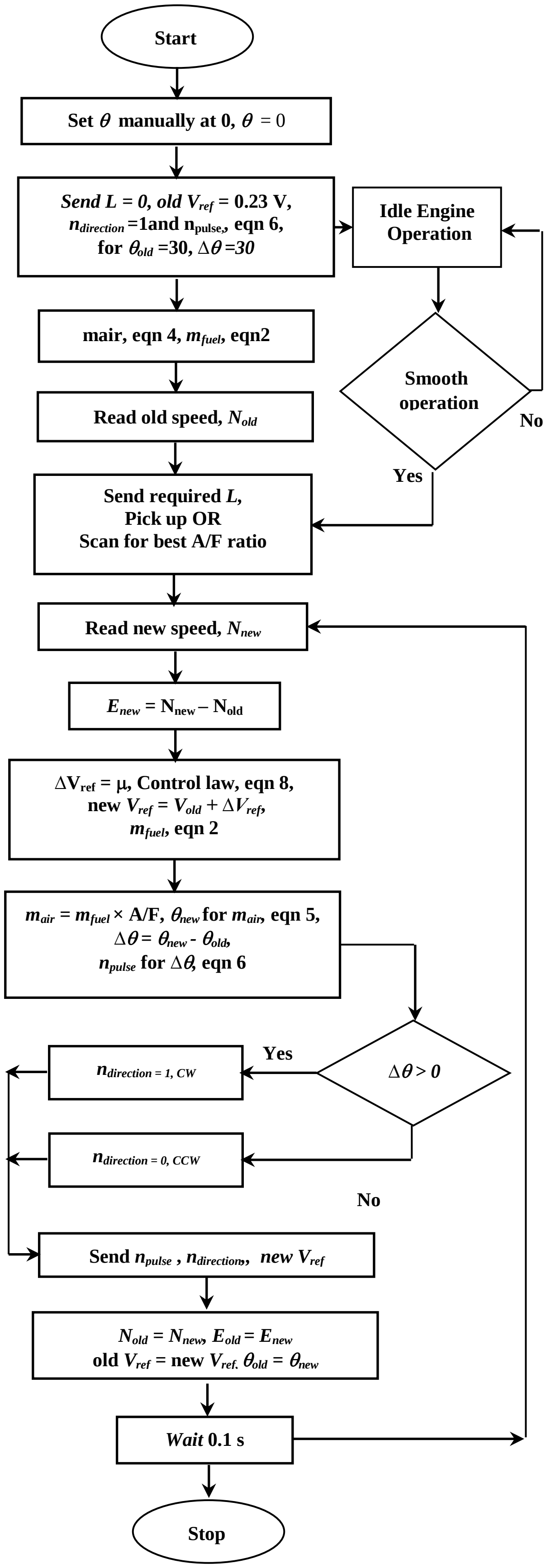

Fig.15 Flow chart of the present control software

After the engine smooth operation is ensured, the speed control program is started. A feed-back control is run to maintain the engine speed very close to a certain desired speed of 3000 rpm regardless of load fluctuations. While controlling the engine speed two self-regulation alternative techniques are applied to select the best-economy air-fuel ratio corresponding to the load applied on the engine. The speed control is detailed in the next 4.2 section.

The control process is achieved by a continuous sampling of engine speed and continuous corrections of the air and fuel mass flow rates according to the PID controller law. A measured value for the current speed is gotten by the speed measurement circuit mentioned in section 3 above. The speed signal is sent to the computer memory through the data card.

Speed error signal, *e*, deviation than the desired speed value, is processed by the controller law, equation 7, to get the control action, μ which is considered as the change in the fuel rate command, ΔV_{ref}. Knowing the previous value for V_{ref}, the new value for it is thus calculated and sent to the fuel injector driving circuit. The new fuel rate value is calculated using the injector calibration, equation 2. The best economy A/F ratio is decided by the soft ware, as it is detailed in section 4.3 below, and the new air rate is thus calculated. The change in the air flow than the previous value is determined and the required direction and number of rotational steps of the air stepper motor is calculated and sent to the motor driving circuit.

Another speed sample is acquired after 0.1 sec sampling time period to repeat the sequence mentioned in the paragraph above.

Typical results for the engine speed control are shown in figure 20. The figure shows that the speed is of very short settling time with negligible fluctuation around the desired value and of maximum over shoot of about 10%, when the load value is suddenly changed, which is of allowable value. Sudden change of the A/F ratio, for a fixed load, does not affect much the engine speed as it is shown in the figure.

4.2 The PID controller software

The control low of the PID controller is shown in equation 7 below:

$$\mu(t) = K_c \left[e(t) + \frac{1}{T_i}\int_0^t e(t)\,dt + T_d \frac{de(t)}{dt}\right] \quad (7)$$

It is a three terms controller where the control action, μ, is the summation of a proportional action, K_c *e(t)*, an integral action, $\frac{K_c}{T_i}\int_0^t e(t)\,dt$, and a derivative action, $K_c\,T_d\,\frac{de(t)}{dt}$.

Where: *e* is the error in the engine speed, $N - N_{ref}$, *t* is the current control time, K_c is the controller gain, T_i and T_d are the integral and derivative time constants respectively.

The integration and derivative of the error signal is numerically computed by the control software. The control action is considered as the change in the command, ΔV_{ref}, to correct the fuel rate for the speed error compensation at the current control time. The error signal is updated, using the actual engine speed, *N*, measured every sampling time of 0.1s. The measured speed value is kept unchanged over each sampling period using electronic latching attached to the speed measuring circuit.

The optimum values of the controller parameters, K_c, T_i, and T_d, is experimentally determined for a best combination of the considered control measures, namely, the steady state error, settling time, minimum root mean square of the error signal and the peak overshoot. The optimum controller parameters are experimentally determined as mentioned in the experimental results presented below.

4.3 The present engine self regulation techniques

Two alternative self regulation techniques are applied by the present control software to determine the most economic A/F ratio while controlling the engine speed. Using the first technique, the best A/F ratio is picked up from a stored look-up table for the optimum air-fuel ratio against engine load. The lock-up table is experimentally offline created at 3000 rpm, the desired speed value in this work. It is worth noting that when the engine is speed controlled, speed is almost kept at the desired value except for very few periods when load disturbance happens. The creation of the lock-up table is detailed in the experimental work section presented below. The best A/F ratio lock up table technique is schematically shown in Figure 16.

Engine ageing is being taking into consideration in the second regulation technique. An online selection of the optimum A/F ratio corresponding to the current load is carried out. Air to fuel ratio was scanned, over a wide range, through suitable increments.

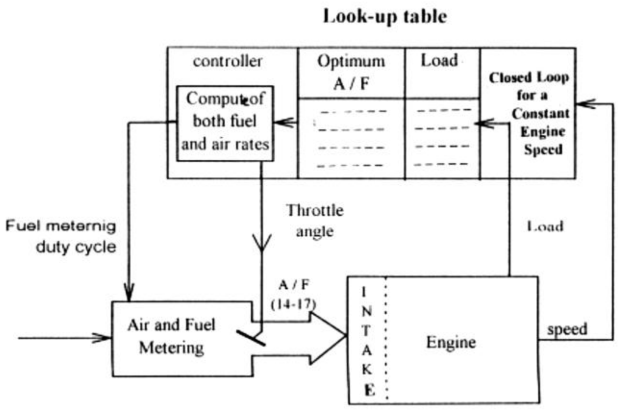

Fig.16 Applying the best A/F selection using the off line lock-up table technique

At each step the thermal efficiency is calculated as the ratio between the applied load, W, and the energy of fuel rate, using equation 8 presented below:

$$\eta_{engine} = \frac{Load}{m_{fuel} \times CV} \quad (8)$$

Where: CV is the fuel caloriated value. The optimum A/F ratio corresponding to the highest thermal efficiency value is thus chosen and applied to the engine.

5. Results of the present experimental work

Experimental test runs were carried out on the present internal combustion engine utilizing the test rig presented in details above. The control hard and soft wares were designed and constructed to achieve the engine speed control along with keeping the best economy A/F ratio.

A PID controller was chosen to the speed control task. The controller optimum parameters were experimentally determined as presented in 5.1 subsection below.

The engine is kept running with the best economy A/F ratios, corresponding to the applied loads. This is achieved by applying self A/F ratio regulation techniques suggested by the present study. This is outlined in the control software section presented above. The results of the present self regulation techniques are presented in 5.4. The effect of applying the best economy A/F ratios on the engine thermal efficiency is presented at the end of this section

5.1 Determination of the optimum parameters of the PID controller

Control measures are considered in this study as the steady state error, settling time, minimum root mean square of the error and the peak overshoot. Control measures were used to qualify the PID controller parameters, namely, are the gain, K_c, and the integral and derivative time constants, T_i and T_d. Their optimum values are experimentally determined for a best combination of the considered control measures.

The optimization process is carried out using the trial and error concept, according to which, only one parameter is changed while keeping the other two at constant values.

The load is suddenly changed while the control measures are evaluated. The optimum value for this parameter, under consideration, is thus determined and kept unchanged while another parameter is studied in return. This procedure is repeated until the optimum values of the three parameters are determined.

The experimental results showed that increasing of the controller gain, K_c, reduces the steady state error but increasing it above some maximum limit increases the system relative instability represented in the maximum overshoot value. Increasing the integral control action, $1/T_i$, reduces the steady-state error but results in an oscillatory response around the steady state speed value. The derivative control provides a damping action to reduce the peak overshoots and to compensate for the sudden changes in the engine disturbance.

Average values for the optimum controller parameters are obtained over all the applied load conditions as; K_c = 0.017, T_i = 8 s, and T_d = 0.73 s.

5.2 Engine load characteristics results

The engine load characteristics are defined as the relationship, at different applied loads, between the engine thermal efficiency, η_{engine} equation 8, and the A/F ratio while keeping the engine speed and the spark timing unchanged. The load characteristics of the present engine is experimentally determined and showed in Figure 17.

While the engine speed is controlled at a 3000 rpm reference value, the A/F ratio is changed from 14 to 17 through 0.2 increments. Experimental runs are repeated for applied load values changed from 100 W to 900 W through 100 W increments. The fuel rate is decided by the control law, to compensate for the speed error, and thus engine efficiency is calculated according to the current applied load value.

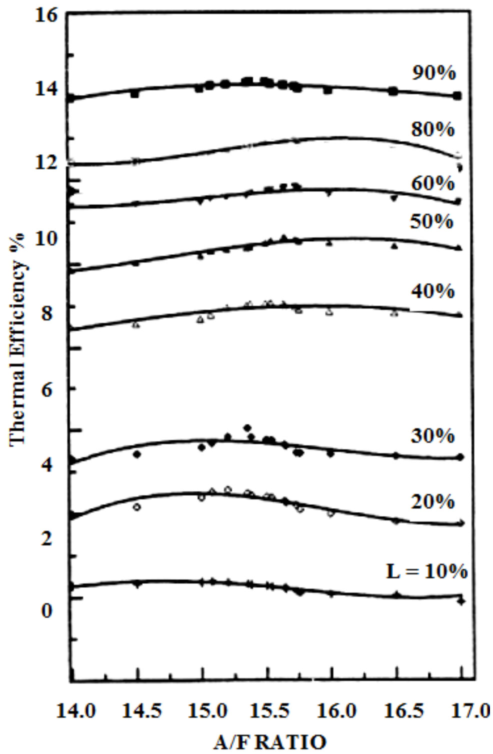

Fig.17 Effect of A/F ratio on the engine thermal efficiency at engine speed of 3000 rpm

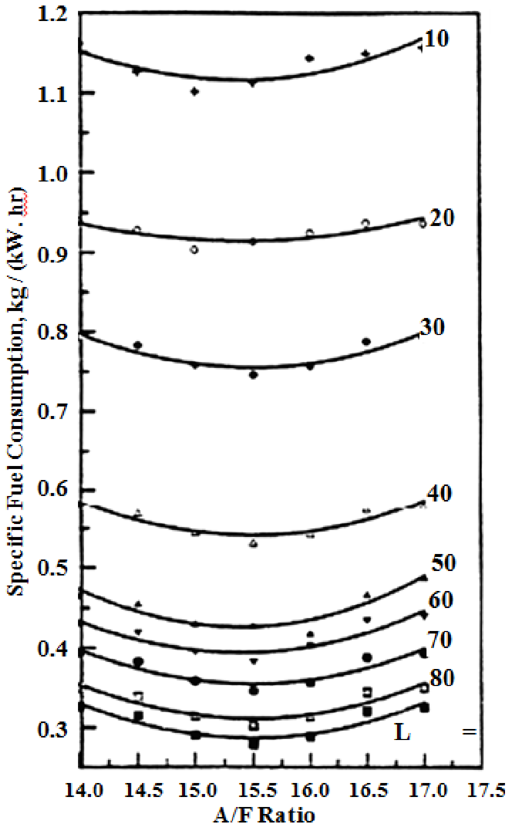

Fig.18 Effect of A/F ratio on specific fuel consumption, at engine speed of 3000 rpm

Figure 17 shows that engine thermal efficiency is significantly improved with increasing engine load for a constant value of A/F ratio. The efficiency at a certain load value increases as the A/F ratio is increased up to a certain maximum value. For any further increase in the A/F ratio, the engine thermal efficiency decreases lower its maximum value. The figure shows also that, the maximum thermal efficiency occurs at a point slightly leaner than the chemically correct A/F ratio. This is expected because of the imperfect air-fuel mixing process. A little excess air is needed to ensure the complete fuel combustion. Similar experimental runs were carried out for the effect of A/F ratio on the specific fuel consumption, SFC. The experimental data are presented in figure 18.

The figure shows similar results as those extracted from figure 17, taking into account that the maximum engine efficiency is matched with the minimum SFC. The change of the optimum A/F ratio value, corresponding to the highest engine efficiency, minimum SFC, with load is shown in figure 19.

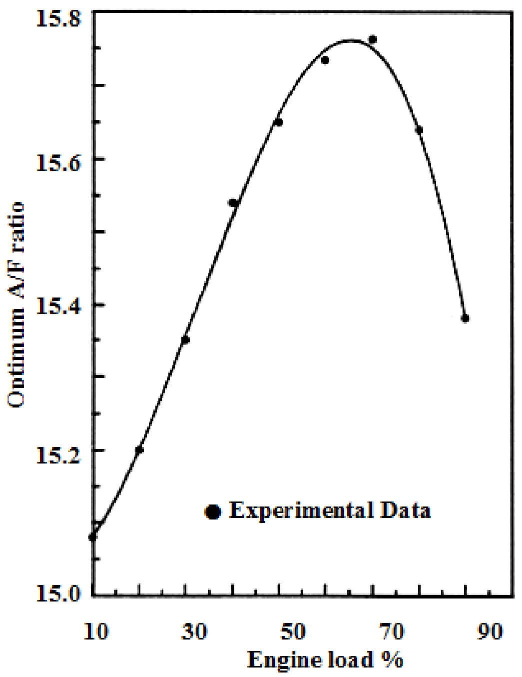

Fig.19 Effect of engine load on the optimum A/F ratio

5.3 Determination of the best economy A/F ratios lock-up table

The most economy A/F ratio are decided by the present work by applying two alternative self regulation techniques. According to the first technique, a look-up table for the optimum A/F ratio against engine load is experimentally offline created at 3000 rpm engine speed.

The best economy A/F ratios corresponding to the highest engine efficiency at different applied load values are extracted from Figure 19, mentioned in section 5.2 above.

Table 1 presents the lock-up table, for the best A/F ratio values against load values. The table is stored in the present control software, by which, the optimum value of the A/F ratio is picked-up according to the applied load value. The best A/F ratio is thus applied to ensure keeping running the present engine at the most economic conditions.

Table 1 Lock-up table of the best economy A/F ratios

Load %	Best A/F ratio	Maximum Efficiency%
10%	15.08	2.38
20%	15.20	4.55
30%	15.35	6.02
40%	15.54	9.06
50%	15.65	10.63
60%	15.73	11.83
70%	15.76	12.38
80%	15.64	13.60
90%	15.38	14.35

5.4 Results of the present two self regulation techniques

Using the first technique, mentioned above, it is essentially needed to update the best A/F ratios stored in the lock-up table every suitable engine operation periods. This is because that, the engine performance is changed with time due to the engine ageing.

Engine ageing is considered in the second regulation technique. An online selection of the optimum A/F ratio corresponding to the current load is thus carried out. Air to fuel ratio was scanned over the range from 14 to 17 through 0.2 increments. At each step the thermal efficiency is calculated, equation 8. The optimum A/F ratio corresponding to the highest thermal efficiency value is thus chosen and applied to the engine. Engine efficiency scanning is operated for a noticeable change in the engine load not less than 10% of the full load.

Experimental results showed that second technique takes a relatively long scan period before determining the optimum A/F ratio. It took about 2 minutes, compared to the first technique processing period which almost takes no time.

It is therefore, this technique is modified to reduce its processing time as follows; the predetermined lock-up table showed that the best A/F ratio is bounded by a range from 15 to 16 values for load changed from 10% to 90% of the full load. So scanning for best A/F ratio is modified to be for the above mentioned range, 15 to 16, through 0.2 increments. The processing time is reduced to about 50% using the modification mentioned above.

Another modification is proposed and applied as follows. It was found that engine ageing results in a maximum deviation in the best A/F ratio value in a range of ± 0.4 from that of a new engine. It therefore the scanning process is performed, through 0.2 increments, in a range from -0.4 to +0.4 of the lock-up table value corresponding to the applied load. Reduction of about additional 50% in the processing time of the second regulation technique is resulted using this last modification.

Typical speed control results with applying the second self regulation technique for the most economy A/F ratio are shown in figure 20 in the next page. The control sequence shown in the figure is presented as follows:

1. The load is changed according to a pre-specified plan.
2. The control software picks up the optimum A/F for the current load value from the saved lock up table.

3. The soft ware sends signal to the engine to change the actual A/F ratio in a range of ± 0.4 from the picked value through 0.2 increments.
4. The soft ware saves the engine efficiency calculated at each A/F ratio, equation 8.
5. The software decides the A/F ratio at which the maximum efficiency is reached and sends signals to apply it on the engine.

The figure shows that applying this technique needs a relatively long time compared to the lock up table technique, about 25 seconds, to reach the optimum A/F ratio. The fixed load value shows a slight fluctuation, as shown in the figure. This is due to that although the number of loaded lamps is fixed, the applied voltage is not fixed because of the fluctuation in the engine-generator speed. The control software takes this into consideration to calculate an accurate value for the applied load.

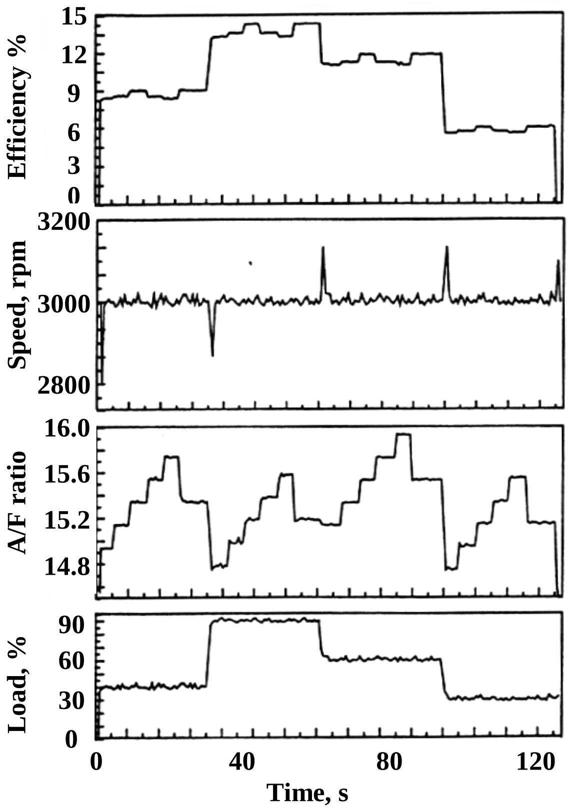

Fig.20 Typical results for the speed control with applying the 2nd self regulating technique for the optimum A/F ratios

Other experimental work were done for other pre-specified load plans and shows similar results.

Advantages and disadvantages of the two self regulation techniques are summarized as follows:

1. The first one is fast but its best economy A/F ration data needs to be updated to compensate for the engine ageing.
2. The second techniques takes the engine ageing into consideration but take a relatively long time to scan for the best economy A/F ratio. It is preferred if control settling time is not crucial.

5.5 Effect of applying the present self regulation, to get the best A/F ratio, on the engine efficiency

Figure 21, presented in the next page, shows a comparison for the engine thermal efficiency when it is operated on the present self regulation technique and the stoichiometric operation. The figure shows that an improvement of about 8 to 10% in the thermal efficiency is achieved by running an aged engine on the best A/F ratio.

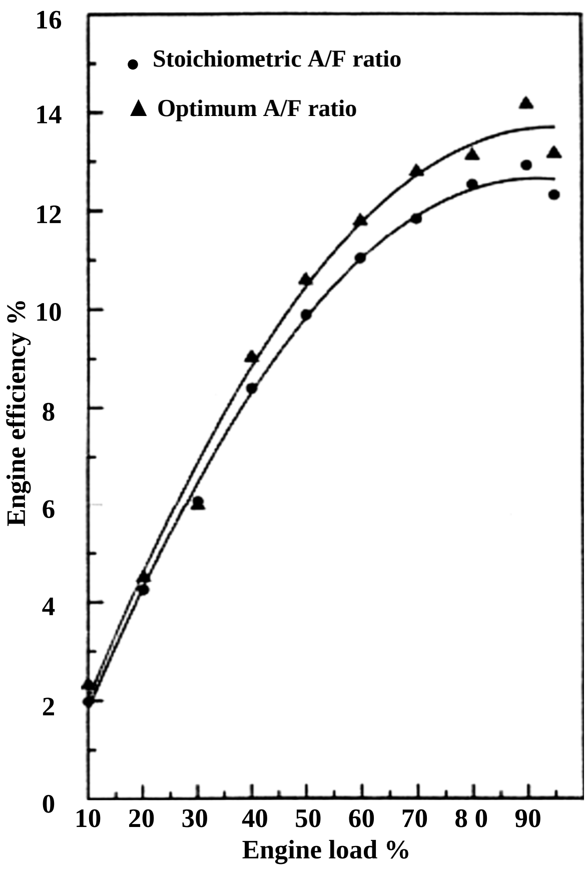

Fig.21 Effect of applying the present optimum A/F ratio self regulation technique on the engine efficiency

Conclusions

An SI engine is controlled in this work using a smart mechatronic system developed by the authors. Two self regulation techniques for deciding the best economy A/F ratio corresponding to different applied load values are proposed and applied in this work. Two, offline and online techniques are proposed for finding out the optimum A/F ratio.

The hard and soft wares of the present control system are designed and constructed by the authors. All the electronic circuits required for signal conditioning and interfacing are developed by the author.

Offline technique is fast but its best A/F ratio data needs to be updated from time to time to compensate for the engine ageing. The online technique takes into consideration, the engine ageing, but it takes a relatively long time to scan for the best economy A/F ratio. It is thus preferable if control processing time is not crucial.

Compared to the stochiometric operation, the thermal efficiency of the present controlled engine showed an improvement from 8 to 10% when applied the self regulation techniques proposed by the present study.

Further studies are needed to take into consideration, the effect of spark timing on the engine efficiency as well as the engine exhaust pollution control.

Nomenclature

AC	Alternating current.
A/F	Air to fuel.
DAQ	Data acquisition.
e	Error signal.
CLK	Clock.
CCW	Counter clock wise.
CW	Clock wise.
CV	Fuel calorated value.
IC	Integrated circuit.
ICE	Internal combustion engine.
I/O	Input / Output.
IR	Infra red.
IRE	Infra red emitter.
IRR	Infra red receiver.
K_c	Controller gain.
L	Load, W.
m_{air}	Air mass flow rate, *kg/hr*.
M_{fuel}	Fuel mass flow rate, *kg/hr*.
N	Engine rotational speed, *rpm*.
$n_{direction}$	Direction command to the stepper motor driver, 1 for CW and 0 CCW.
new	New value calculated at the current control time.
n_{lamp}	Number of loaded lamps.
n_{pulse}	Number of the rotational steps of the stepper motor.
N_{speed}	Number of CLK pulses passed during the engine periodic time.
old	Old value calculated at the previous control time.
PID	Proportional integral derivative.
PWM	Pulse width modulation.
R	Electric resistance.
RPS	Revolutions per second.
RPM	Revolutions per minute.
SI	Spark ignition.
SFC	Specific fuel consumption.
SM	Stepper motor.
t	Current control time, s.
T	Periodic time, s.
T_d	Derivative time constant, s.
T_i	Integral time constant, s.
TR	Transistor.
V_{ref}	Reference voltage command to fuel injector driver, V.

Greek letters

θ	Air throttle angle, degree
η	Engine thermal efficiency %
μ	Controller control action

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