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Control of cyclic variations by computing the cycle-to-cycle air-fuel ratio by neuro fuzzy technique

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Abstract

Purpose – The problem of cyclic variation has been an interesting area of research and has been investigated by many researchers. It is more severe in the case of two-stroke engines compared with four-stroke engines. One of the reasons for these cycle-to-cycle variations is the variations in the air-fuel ratios of individual cycles and, if these values of individual cycle air-fuel ratios are available by some means, they can be used for controlling the cyclic variations. The purpose of this paper is to find a technique to predict the air-fuel ratio of the individual cycles and use the same for reducing cyclic variations.

Design/methodology/approach – In this work, a neuro-fuzzy model was developed using MATLAB software to compute the air-fuel ratio of the individual cycles based on the relationship between the air-fuel ratio and the combustion parameters such as those indicating mean effective pressure (IMEP), crank angle occurrence of peak pressure, and angles of different percentages of heat releases. In-cylinder pressure traces of 1,000 continuous cycles were measured using a Personal Computer (PC)-based data acquisition system and an investigation was carried out. The readings were taken for two modes of operations, namely gasoline carburetion and electronic gasoline injection. The engine was loaded by an eddy current dynamometer. The air-fuel ratio was varied from rich to lean by adjusting the fuel quantity in the carburetion mode and adjusting the pulse width (measure of quantity of fuel to be injected) in the injection mode, at constant throttle. The cyclic variation was identified by the variations in the peak pressures and IMEPs of the individual cycles. The stored data were given as input to the developed neuro-fuzzy model and, using SIMULINK, the air-fuel ratios of individual cycles were obtained. These predicted values are fed to the electronic control module (ECM) (meant for injecting the fuel) for refining the pulse width to get cyclic variations reduced.

Findings – Results show that cyclic variation increases when the mixture becomes lean. It was also found that cyclic variation in an injected engine was less in comparison with the carbureted engine, as the precise control of air-fuel mixture was possible in the case of the injected engine.

Research limitations/implications – The technique used in this work may be modified to give more precise pulse width by incorporating various other parameters like exhaust temperature, etc. Future research may be focused to incorporate this system in a moving vehicle to get more fuel efficiency and fewer emissions.

Practical implications – The design of vehicle and engine should be slightly modified to incorporate the ECM and various sensors.

Originality/value – The originality in this paper is that a new technique was developed to find the air-fuel ratio of individual cycles. This will be useful for the engine manufacturers and for those researchers doing research on the engine side.

Keywords Variance, Internal combustion engines, Modelling

Paper type Research paper

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Introduction

Owing to its simple construction, compactness, low cost and superior performance, two-stroke engines are widely used. These two-stroke engines suffer from high-scavenge losses leading to high-hydrocarbon emissions. This increases the fuel consumption and creates serious exhaust emission problems (Blair *et al.*, 1989). Two-stroke engines also suffer from cyclic variations (Winsor and Patterson, 1973). To minimize the short-circuiting of fuel leading to less-fuel consumption and lower emissions, and to reduce the cyclic variations an electronic fuel injection (EFI) system was developed which was able to control precisely the quantity of fuel to be injected. The developed system actuates the EFI for the start of injection and quantity of fuel to be injected (pulse width) after taking the input signals from various sensors such as manifold absolute pressure (MAP) sensor, throttle position sensor (TPS), etc. The fuel injection system developed was made to run a single cylinder tow-stroke SI engine.

Cyclic variations

In an apparently steady running SI engine, there will be as much as 70 percent variation in peak pressure at certain operating conditions (Winsor and Patterson, 1973). This variation in cylinder pressures from cycle-to-cycle, that originate from many sources is termed as cyclic variations. This cyclic variation is a fundamental combustion problem. Cyclic variations are affected by many engine and operating variables like fuel properties, mixture composition, charge homogeneity, ignition, in-cylinder charge motion and exhaust dilution, etc. The important variables, which affect cycle variations, are air-fuel ratio and maximum flame speed. Higher burning speed is achieved in stoichiometric or slightly rich mixtures (Ozdor *et al.*, 1994). The problem of cyclic variation is more severe in two-stroke engines. It affects the performance and drivability of two-stroke SI engine of both carburetion and injection as lean misfire limit is approaching the predicted values are showing some deviation from the actual values (Yamashita, 1995). These cyclic variations increase drastically in lean operation of the engine. In-cylinder pressure is an important indicator of the cyclic variations. In this work, the cylinder pressure was measured for individual cycles at each crank angle interval by a pressure transducer flush mounted on the cylinder head. Many pressure related parameters were derived from the pressure history, which indicate the cyclic variations. Some important pressure related parameters are in-cylinder peak pressure (Pmax), crank angle at which Pmax occurs (CAPmax), and IMEP of individual cycles. Apart from this, the burn rate and heat release rate related parameters are also used to indicate the cyclic variations such as crank angle occurrence of 5 percent heat release, CAQ5, crank angle of occurrence of 10 percent heat release, CAQ10, crank angle of occurrence of 50 percent heat release, CAQ50, and crank angle of occurrence of 90 percent heat release, CAQ90.The cylinder pressure variation can be identified either in Pmax, or in the rate of pressure rise, or in indicated mean effective pressure (IMEP). Among these, IMEP was proved to be the best to represent the pressure variations (Nedunchezhian, 2000) and hence it was considered as one of the input parameters for the fuzzy model. The crank angle position of the heat release values indicates the combustion history (Nakagawa *et al.*, 1982). The variation in the early phase of combustion can be identified from the 5 percent heat release angle (CAQ5) and the 90 percent heat release angle (CAQ90) is the measure of combustion duration. For any variation in these parameters variation in air-fuel ratio may be one of the main factors. Thus, any variation in the air-fuel ratio will be reflected in these parameters and all the above parameters, namely IMEP, CAPmax, CAQ5 and CAQ90 were considered to be the input data for the developed fuzzy logic model.

Electronic fuel injection

EFI technology is as old as the carburetor itself. During the last 30 years or so, reductions in tailpipe exhaust emissions of more than 90 percent have been demanded of, and achieved by the automobile industry (CONCAWE, 2000), with one of the most important enabling technologies being low cost, series production EFI. Relative to carbureted fuel systems, the main mechanisms by which EFI has helped to reduce exhaust emissions are reduced wall wetting, improved fuel atomization, greater flexibility in air/fuel (A/F) ratio control and improved unit-to-unit repeatability. In addition to reduced exhaust emissions, EFI has also introduced other benefits such as reduced brake specific fuel consumption, increased full-load output and improved drivability (Norbye, 1985; Plohberger *et al.*, 1988). The quantity of fuel to be injected is determined by the electronic control module (ECM) by setting up the pulse width depending upon the different signals it receives from various sensors such as MAP sensor, TPS, etc. MAP sensor measures the pressure in the inlet manifold and TPS is used to measure the position of the throttle at a particular speed of the engine.

Neuro-fuzzy model

Neuro fuzzy technique refers to logic of approximation (Chin and Mital, 1999). Unlike Boolean logic, which assumes that every fact is either entirely true or false, fuzzy logic allows for varying degrees of truth. Computers can apply this logic to represent vague and imprecise ideas, such as "hot" and "tall." Fuzzy logic is a convenient way to map an input space to an output space. The basic concepts underlying fuzzy logic are membership functions, degrees of membership, logical operations, and IF THEN rules (Russell and Norvig, 1995). The Fuzzy Logic Toolbox is designed to work seamlessly with Simulink, the simulation software available from The Math Works (Jang *et al.*, 1997). Once the fuzzy system is created, it can be embedded directly into a simulation. One of the great advantages of the Fuzzy Logic Toolbox is the ability to take fuzzy systems directly into Simulink and test them out in a simulation environment.

In this work, the input parameters are IMEP of individual cycles, crank angle of occurrence of peak pressure (CAPmax), crank angle of occurrence of 5 percent heat release (CAQ5), and crank angle of occurrence of 90 percent heat release, CAQ90. And the output parameter will be the air-fuel ratio for individual cycles. Figure 1 shows the block diagram of the fuzzy model.

The MATLAB software package was used for developing the fuzzy model and for the simulation to get the results. Figure 2 shows one of the fuzzy input sets that were used in the model. The IMEP fuzzy set shown in Figure 2 used three trapezoidal membership functions for classes low, medium, and high. Similarly the other input variables and output variable were given with the membership functions for different classes. Some of the rules contained in the rule base are shown in Table I.

The first rule in the Table I, is, "If imep is low, and capmax, caq5 and caq90 are high then A/F ratio is low." The value of IMEP will be more for rich mixtures and less for lean mixtures. Hence, a low-IMEP value is due to lean mixture and the rule is formed.

Similarly if the crank angle occurrence of maximum peak pressure is closer to Top Dead Centre (TDC), it is found that rich mixture is present. When the value of CAPmax is more, it is away from the TDC and hence lean mixture. CAQ5 indicates the ignition delay and CAQ90 indicates the crank angle interval for complete combustion. In Table I, A/F ratio "low" means lean mixture. The control surface in Figure 3 shows the crisp value of the air-fuel ratio for different combinations of IMEP and CAPmax. Each of these intersecting points indicates the differing air-fuel ratio, which is determined by

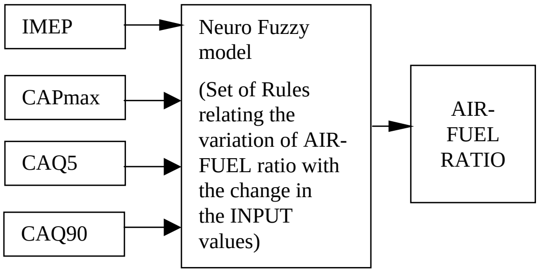


Figure 1. Block diagram of the developed fuzzy logic model

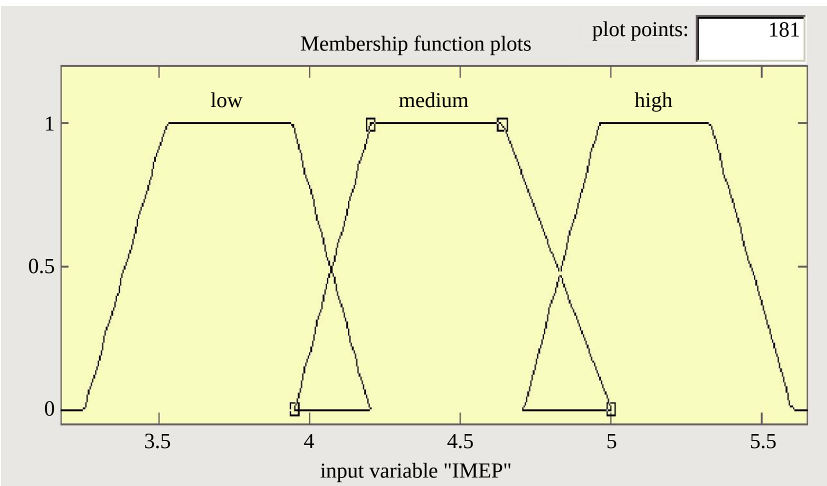


Figure 2. Fuzzy input set-IMEP, bar

	IF IMEP	IF CAPmax	IF CAQ5	IF CAQ90	THEN A/F ratio
1	Low	High	High	High	Low
2	Low	Medium	High	High	Low medium
3	Medium	Medium	Medium	Medium	Medium
4	Medium	High	High	Medium	High medium
5	High	Low	Low	Low	High
6	High	Medium	Low	Low	High medium

Table I. Rule base of the developed neuro-fuzzy model

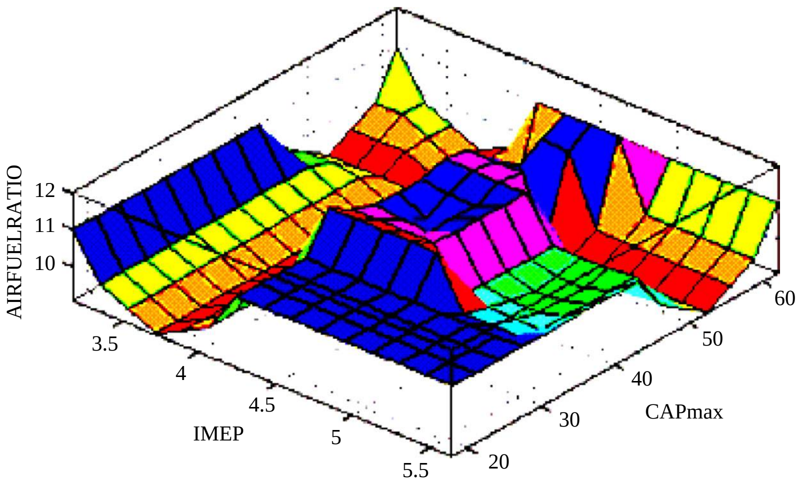


Figure 3.
Three dimensional fuzzy map

the design of fuzzy sets and membership functions. The control surface acts as a means of determining the variation in air-fuel ratio for each IMEP and CAPmax combination.

Similarly, other control surfaces also can be shown for other combinations. After framing the fuzzy model, it was exported to Matlab workspace and linked with the Simulink model. Figure 4 shows the block diagram of the Simulink model. In Figure 4, the first block represents the source of data. The stored data of IMEP, CAPmax, CAQ5 and CAQ90 were exported to the Matlab workspace from the stored location.

The second block represents the developed neuro-fuzzy model, which was explained in the previous section and it was exported to Matlab workspace. In this block, the different rules were analyzed and fuzzification and defuzzification of data were done. The third block represents the results of the model. The result can be exported and further analysis can be made.

Experimental setup and procedure

For the experimentation a 150 cc two-stroke engine was chosen. The specifications of the engine are given in Table II. The engine was set to run first in gasoline carburetion mode.

Gasoline carburetion

The engine was run for at least 30 min of warm up period before readings were taken. The engine was made to run at different constant speeds of 2,500, 3,000, 3,500 and 4,000 rpm. Atmospheric pressure, temperature and humidity were noted. The fuel flow

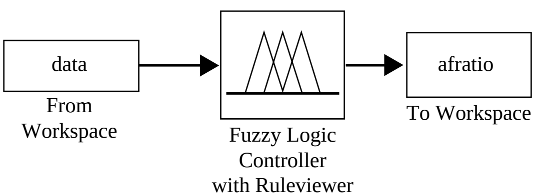


Figure 4.
Block diagram of the Simulink model

was varied to supply from rich to lean mixture. The load on the engine was varied by the dynamometer's control panel to keep the engine speed constant. The fuel flow meter is used to measure the rate of flow of gasoline. The instrument is calibrated for change in temperature and density variations. Commercially available petrol mixed with proper grade lubricant is used as fuel for base reading. As the air-fuel ratio is determined by the air and fuel flow measurements, enough care has been taken to measure the air flow precisely. A calibrated orifice flow meter is used in combination with U-tube manometer. A plenum chamber having sufficient volume has been fitted to suppress the air fluctuations. Air-fuel ratio was found by dividing the total fuel consumption by mass of air. After the engine was stabilized for a particular operating point, air flow, fuel flow, inlet vacuum, inlet air temperature were noted. Load and speed were noted from the dynamometer's control panel. At each operating point, the cylinder pressure traces of 1,000 continuous cycles were stored in the PC for post processing of the results.

Electronic control module

For injecting the fuel into the inlet manifold, a dedicated ECM was designed and developed. Virtual instrumentation software Labview was used to design the programme to be fused into the microcontroller. The system was tailored to Atmel AT89C51 microcontroller IC and injector was operated by the microcontroller. The software program was developed using Keil μVision2 for Windows™ software. A "C program" was compiled and converted to microcontroller mnemonics by the software and HEX code was generated. The HEX code was transferred to AT89C51 microcontroller using the flash programmer by interfacing the programmer to the computer parallel port. Initially, the pulse width is calculated by considering two parameters namely TPS and MAP. Later on the in-cylinder pressure data was used to refine the pulse width. Pulse width is nothing but the duration of injection, which determines the quantity of fuel to be injected. To refine the pulse width a feed back was given to the ECM and control of air-fuel ratio was achieved. To regulate the injection-starting angle, a crank angle degree marker was connected to the engine to measure the position of the piston with reference to the TDC. The block diagram of the developed ECM is shown in Figure 5.

Control of air-fuel ratio

Figure 6 shows the block diagram of the ECM long with the feed back it receives for the control of air-fuel ratio. Initially, the pulse width is calculated from the data it receives from MAP and TP sensor. Once the engine starts running the peak pressure developed inside the engine cylinder will be sensed by the piezo electric pressure pickup and through charge amplifier it is fed to the ECM. The ECM is programmed to adjust the

Engine make and model	Bajaj 150 cc, two-stroke, single cylinder, air cooled
Cylinder bore (mm)	57.5
Stroke length (mm)	58
Displacement (cc)	150
Power	4.5 kw @ 5,500 rpm
Connecting rod length (mm)	105
Compression ratio	7.4:1

Table II. Specifications of the engine

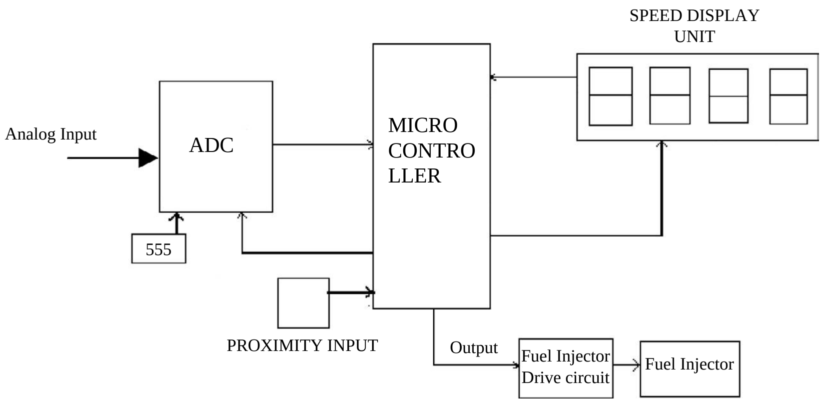


Figure 5.
Block diagram of the ECM

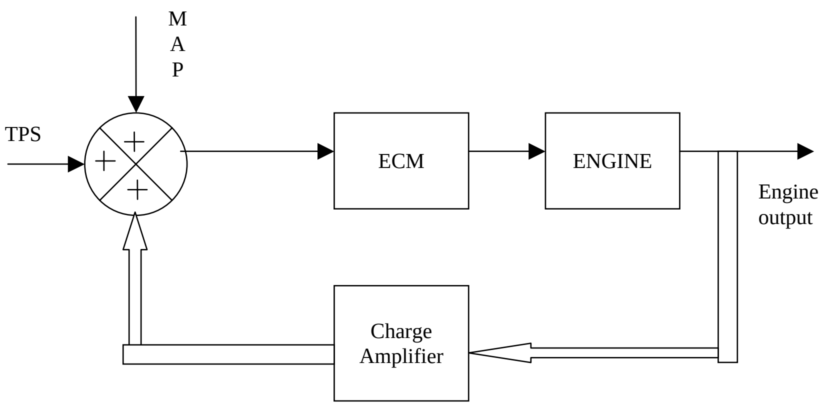
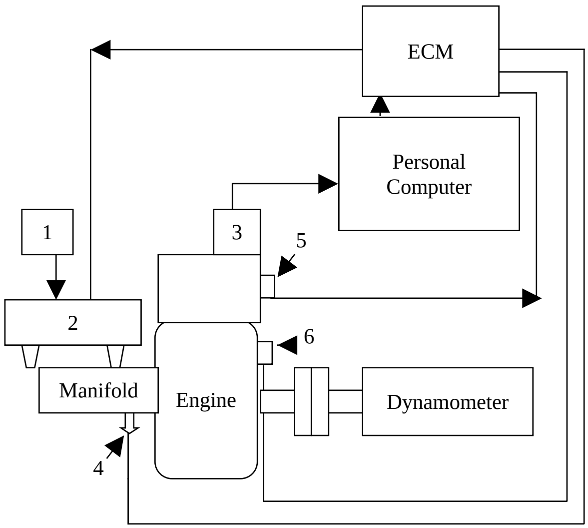


Figure 6.
Block diagram showing the closed loop feed back control

pulse width as per the signal received from the engine and refinement of pulse width leads to the control of air-fuel ratio of the individual cycles and thus cyclic variations are reduced.

Gasoline injection

Figure 7 shows the experimental setup for the gasoline injection mode. The same set up for gasoline carburetion was kept for this mode also, other than the supply and measurement of fuel. The fuel was electronically injected through the injector which was mounted on the inlet manifold. The location and inclination of the injector was optimized by a CFD analysis so that a better mixing is achieved. An electronic balance with high sensitivity was used to measure the fuel mass. This was due to the close loop fuel supply with gasoline injection system taking place at higher pressures. The exact quantity of fuel required for a particular point of operation was calculated by the ECM from the input signals received from the TPS and MAP sensors. Adjustment of pulse width is done as discussed earlier. The triggering for the start of injection was given by the proximity sensor. The same set of readings was taken in this mode as like



Notes: 1 – SMPS; 2 – Fuel rail with injector; 3 – Pressure pickup; 4 – MAP sensor; 5 – Proximity sensor; 6 – TP sensor

Figure 7. Schematic of the experimental setup for the injection mode

carburetion mode. After taking all the readings they were stored in the PC for further analysis. The obtained readings are critically analyzed in the following section.

Results and discussion

Figures 8 and 9 show the scatter plots of air-fuel ratios in the carburetion and injection modes, respectively. It can be observed from Figure 8 that the spread of air-fuel ratios are higher in comparison with the injection mode as can be observed from Figure 9.

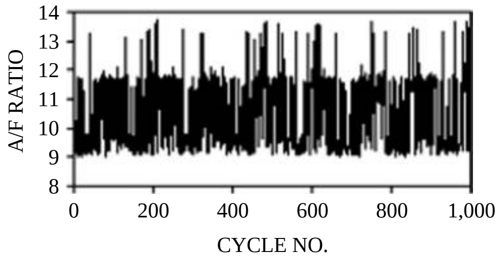


Figure 8. Plot of air-fuel ratio in carburetion mode (mean A/F ratio 10.32)

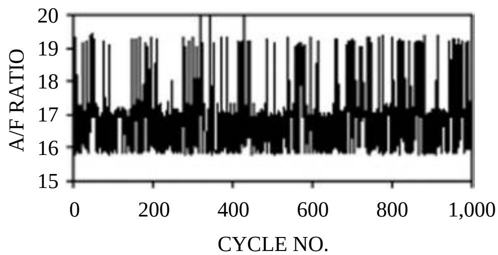


Figure 9. Plot of air-fuel ratio in injection mode (mean A/F ratio 16.9)

This trend reveals that the cyclic variations are less in the case of injection when compared with carburetion. But, even in the injection mode as the lean side is reached the cyclic variations are more as shown in Figure 10. Figure 11 shows the scatter plot of air-fuel ratio for the 1,000 cycles in carburetion mode. It can be observed that certain groups of cycles are having a wide variation of air-fuel ratios where as some cycles are having narrow band variation. But the mean values indicated in the figures do not represent the respective means of these groups of cycles. There are cycles having air-fuel ratios higher than the mean values and cycles having air-fuel ratios lower than the mean values. Also, certain groups of cycles have air-fuel ratios closer to the mean values.

Hence, the analysis of cyclic variation based on the mean values of entire cycles could be misleading. Hence, the entire cycles are grouped into three categories as follows:

(1) Upper mode cycles (UMC) = AFR > mean AFR + 10 percent of mean AFR.

(2) Lower mode cycles (LMC) = AFR < mean AFR-10 percent of mean AFR.

(3) Middle mode cycles (MMC) = All cycles between UMC and LMC.

These results are shown in Figures 12-14 for the carburetion mode and in Figures 15-17 for the injection mode. The IMEP variation is also shown in these figures. It can be observed from Figures 12-14 that more number of cycles belong to MMC group and mean value of overall cycles and mean value of MMC are almost similar. Here, the LMCs give a better IMEP values but they are nullified by the UMCs and by any means if these UMCs are brought to either MMC or LMC the overall cyclic variations will reduce. The same trend can be seen in Figures 15-17 where the cyclic variations of injected engine are still lower than the carbureted engine. UMCs of injection mode show larger variations when in comparison with other modes. Hence, it can be concluded from the above discussion that if air-fuel ratios of UMCs are brought to

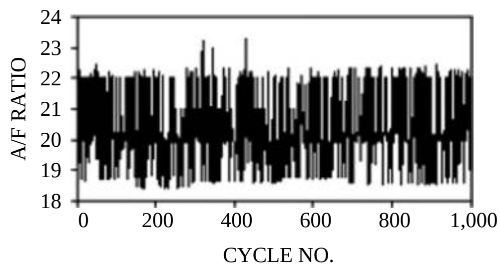


Figure 10.
Plot of air-fuel ratio in injection mode (mean A/F ratio 20)

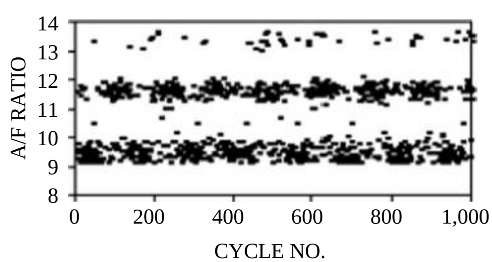


Figure 11.
Scatter plot of air-fuel ratio in carburetion mode

either as LMCs or MMCs the cyclic variations can be brought down and such provisions can be made in the ECM by adding individual cycle air-fuel ratios as one of the parameter for calculating the pulse width. For validating the results obtained from the fuzzy model, comparison was made between the calculated and predicted air-fuel

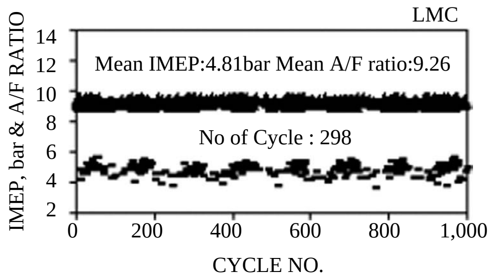


Figure 12.
Plot of IMEP and air-fuel ratio in carburetion LMC

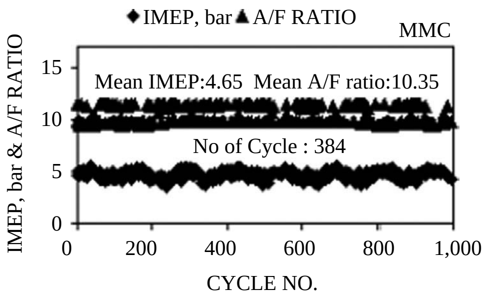


Figure 13.
Plot of IMEP and air-fuel ratio in carburetion MMC

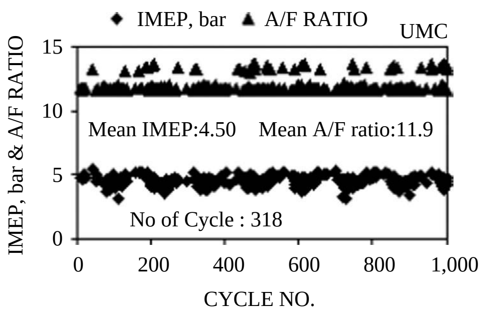


Figure 14.
Plot of IMEP and air-fuel ratio in carburetion UMC

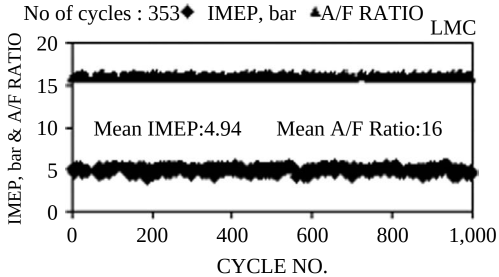


Figure 15.
Plot of IMEP and air-fuel ratio in injection LMC

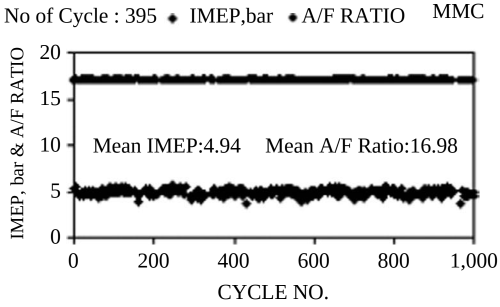


Figure 16.
Plot of IMEP and air-fuel ratio in injection MMC

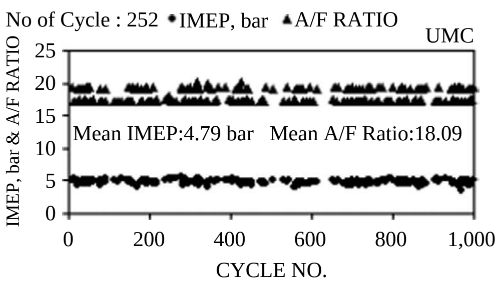


Figure 17.
Plot of IMEP and air-fuel ratio in injection UMC

ratios. Since, the measurement of air-fuel ratios for the individual cycles are not possible in practice, the average values are compared to check the accuracy of the predicted values. Since, the experiment was conducted in constant speed mode with varying air-fuel ratios, a plot of load and air-fuel ratio can be generated and one such plot is shown in Figure 18. From the experimental results for a constant speed of

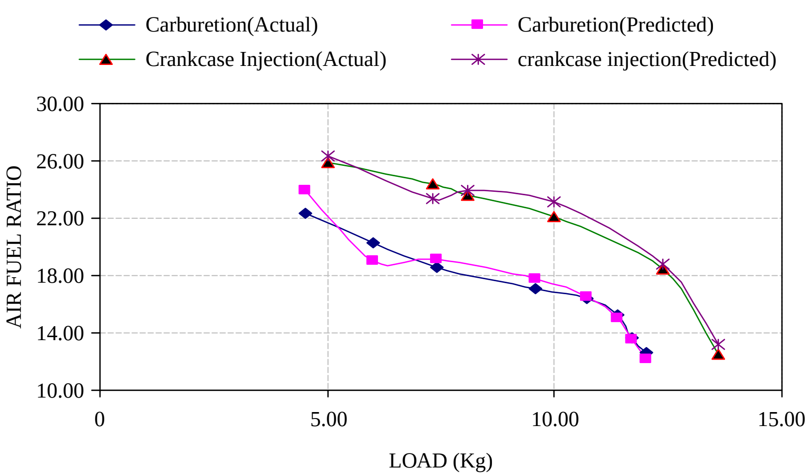


Figure 18.
Variation of air-fuel ratio with load at a constant speed of 3,000 rpm

3,000 rpm, and for different load conditions air-fuel ratios were calculated for both carburetion and injection mode of operation. For the same conditions the air-fuel ratios of the individual cycles are predicted from the fuzzy model and the average of those 1,000 cycle values are calculated and all these values are plotted in Figure 18. It can be observed from the figure that for the injection mode the predicted air-fuel ratios are more closer to actual values in comparison with the carburetion mode. This may be due to the better mixing characteristics of the injected engine, and hence the acquired data were precise.

Conclusion

- Prediction of air-fuel ratios of individual cycles is possible by fuzzy logic technique.
- The effect of variation of air-fuel ratios in cyclic variations in a two-stroke engine was analyzed and based on the analysis a program was developed to vary the pulse width so as to vary the air-fuel ratios of the individual cycles and found that cyclic variations are less in the case of injected engines when compared with carbureted engines.
- Injected engines also suffer from cyclic variations in the lean operation.

References

Blair, G.P., Sheaffer, B.L. and Lassanke, G.G. (Eds) (1989), *Advances in Two Stroke Cycle Engine Technology*, SAE PT-33, SAE Publications, Warrendale, PA.

CONCAWE (2000), *Motor Vehicle Emission Regulations and Fuel Specifications – Part 2 – Detailed Information and Historic Review (1970 − 1999)*, Concawe, Brussels.

Chin, L. and Mital, D.P. (1999), "Fuzzy logic and neural networks", *IEEE Region 10th Annual International Conference, Proceedings/TENCON*, Vol. 1, pp. 195-9.

Jang, J.Y.R., Sun, C. and Mizutani, E. (1997), *Neuro-Fuzzy and Soft Computing*, Prentice-Hall, Englewood Cliffs, NJ.

Nakagawa, Y., Nakai, M. and Hamai, K. (1982), "A study of the relationship between cycle-to-cycle variation of combustion and heat release delay in a SI engine", *Bulletin of the JSME*, Vol. 25 No. 199, pp. 54-60.

Nedunchezhian, N. (2000), "Experimental and theoretical investigations of catalytically activated lean burn combustion in a two-stroke spark ignition engine", PhD thesis report, CIT, Coimbatore.

Norbye, J. (1985), *Automotive Fuel Injection Systems – A Technical Guide*, Haynes, Yevoil, ISBN 0 85429 347 7.

Ozdor, N., Dulger, M. and Sher, E. (1994), "Cyclic variability in SI engines – a literature survey", SAE Paper 940987.

Plohberger, D., Mikulic, A.L. and Landfahrer, K. (1988), "Development of a fuel injected two-stroke gasoline engine", SAE Paper 880170.

Russell, S. and Norvig, P. (1995), *Artificial Intelligence: A Modern Approach*, Prentice-Hall, Englewood Cliffs, NJ.

Winsor, R.E. and Patterson, D.J. (1973), *Mixture Turbulence – A Key to Cyclic Variation*, SAE Paper 730086, SAE, Warrendale, PA.

Yamashita, H. (1995), "Drivability evaluation of two stroke SI engines at part throttle operation by torque map", SAE Paper 950226.

Web site

Introduction to Fuzzy Logic www-ugrad.cs.colorado.edu
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