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FUZZY LOGIC CONTROL SYSTEM FOR FUEL MIXTURE QUALITY IN SPARK IGNITION ENGINES

نظام تحكم بالمنطق المبهم لنوعية خليط الوقود في محركات الإشعال بالشرارة

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الملخص العربي :

من المعروف أن أداء محركات الإشعال بالشرارة والعوادم المنبعثة منها تتأثر بشكل مباشر بنسبة الخليط (الهواء / الوقود) لذا يتركز جهود معظم الأبحاث لهذا المجال على إمكانية استنباط نظام تحكم لمتغيرات مثل توقيت الإشعال ، نسبة الخليط ، نظم تدوير العادم وغيرها للحفاظ على أداء المحرك وتقليل نسبة الانبعاثات الضارة منه .

لذا استهدفت هذه الدراسة استنباط نموذج يعمل بالمنطق المبهم للتحكم في نسبة الخليط وذلك بوضع مجسات حرارة للعادم وتحويل هذه الإشارة إلى نظام إدخال مبهم لتخرج إشارة تتحكم في دوران موتور خطوي الذي يتحكم بدوره في صمام الإدخال لوقود المحرك .

تم تجهيز نموذج اختبار معملي لمحرك وتزويد التجهيزة بمجموعة من المجسات للحرارة والسرعة والعزم ونسب الانبعاث و ربط التجهيزة بالحاسب الآلي من خلال دائرة موائمة لتحويل الإشارات التناظرية إلى إشارات رقمية والعكس .اجريت مجموعة من التجارب المعملية لإيجاد العلاقة بين السرعة ودرجة حرارة العادم عند نسبة خلط مختلفة وكذلك العلاقة بين نسبة انبعاث أول أكسيد الكربون والسرعة بنسب خلط مختلفة لتكون قاعدة بيانات لنظام التحكم المبهم .

اقترحت الدراسة عناصر الإدخال والإخراج للمنطق المبهم وكذلك قواعد العلاقات وعليه تم تطويرنظام تحكم يعمل بالمنطق المضيب يتعامل مع الخطأ في درجة حرارة العادم وكذلك معدل التغير في الخطأ وتم محاكاة أداء المحرك . وبمقارنة أداء المحرك التجريبي باستخدام طرق التحكم التقليدية ونظام المحاكاة للتحكم بالمنطق المبهم المقترح وجد أن هذا النظام ساهم في تحسين أداء المحرك بنسبة في حدود 8 % .

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ABSTRACT

Spark ignition engine performance and exhaust emissions are strongly affected by the fuel/air ratio used. A considerable amount of investigations have been carried out by engine manufacturers to control engine performance and meet exhaust emission standards of governmental ageneies by developing control systems for some operating variables such as ignition timing(IT), Fuel/Air Ratio(FAR), and Exhaust Gas Recirculation (EGR)

This paper presents a fuzzy control system that measures exhaust temperature and operates a needle valve on the engine earburetor jet that enables the fuel to air ratio to oscillate about a desired value. A group of experiments have been carried out to obtain the relationship between fuel to air ratio or (Φ), Exhaust temperature and exhaust emissions. A group of fuzzy logic rules which relate exhaust temperature, to the desired speed with the position of a needle valve actuated by a stepping motor are proposed. A beneficial of fuzzy control method was that the rules determined the characteristics of control system are interpreted by the operator. Experimental and simulated results show that the proposed fuzzy system improves the fuel/air mixture quality.

KEYWORDS

Fuel to air ratio- Exhaust temperature – Gas emissions – Fuzzy logic control –Fuzzy rules.

INTRODUCTION

With the increasing demand for an efficient use of the available world energy sources and for reduction the level of atmospheric pollution, a considerable amount of investigation have been carried out to improve the combustion of the fuel/air mixture in spark ignition engines. This is to achieve a higher engine performance with the lower level of exhaust emissions over a wide range of engine operating conditions, researches have examined the effect of some operating parameters such as mixture strength, mixture preparations, ignition timing and exhaust gas recalculation[1,2]. The results obtained from these investigations indicated that combustion in spark ignition engines is greatly affected by the fuel air ratio used. The control strategy of this ratio allows the engine to operate at higher efficieney[2].

Many investigations have been reported in the literature describing fuel air ratio control systems for spark ignition engines [3]. A fuel air ratio control system using a self tuning regulator to eliminate or minimize the fuel air ratio oscillation about stoichiometry was presented in ref[3]. The system operates with a feedback signal from an exhaust gas oxygen sensor. Ref.[4] reviewed the work carried in the area of fuel air control and presented a control model that takes into account the manifold wall wetting and throttle - torque identification. The model also deals with engine transient operation. An adaptive engine control system using burning rate as a feedback signal for fuel air ratio control was presented in ref. [5].

Cylinder pressure sensor is used to control the fuel air ratio in spark ignition engines. In this system statistical methods were applied to the detected peak pressure and crank angle position [6]. A nonlinear control method for automotive fuel injection system was also presented in ref. [7].

Representation of 3-D mapping for automotive control applications using neural networks and fuzzy logie was proposed [8]. Engine Control Unit(ECU) using a 3-D mapping in a form of look up tables to represent the nonlinear behavior of the engine was presented. The major disadvantages of a look up table representation is the time taken to determine the values it should contain for optimal engine operation.

The aim of this paper is to develop tools and techniques in fuzzy control with applications to engine and ECU's as a mechatronics system. In the short term the objective was to develop a fuzzy control system based on previous knowledge base to regulate engine earburetor jet that will enable the fuel air ratio to oscillate about a desired value according to exhaust gas temperature.

FUZZY LOGIC CONTROLLER

A generalized block diagram of fuzzy logic controller is shown in figure (1). This controller includes knowledge base element, rule base element, crisp-fuzzy interface input, inference engine, and finally fuzzy-crisp interface output. The design of a fuzzy controller begins with the choice of linguistic variables (inputs, output, process states) followed by the selection of linguistic rules and fuzzy inference process. Appropriate interfaces may be needed to interact with the environment [9].

The inference engine computes the effect of the rules in the rule base under the prevailing input(s). It selects the implication operator (mostly Mamdani or Larsen) and makes the choice of the fuzzy reasoning method and aggregation of rules (sup/max, Takagi-Sugeno).The design of the knowledge base [10] is composed of:

-selection of scaling factors for mapping the inputs

-choice of linguistic variables (usually: state, state error and its derivative)

-definition of the term sets for the linguistic variables

-choice of "shapes, distribution and parameters" of membership functions

The Design of the Rule base comprises the choice of the source and the contents of the set of rules such as:

-Modeling the knowledge of the control engineer

-Modeling the human operator's actions and experience

-Fuzzy modeling of the controlled plant

-Data driven modeling (Learning); rule based modeling

The fuzzy-crisp interface assigns a crisp value to the aggregation of modified fuzzy sets given by the evaluation of the rules. This process has been called "*defuzzification*". As shown in figure (2) the most used method calculates the abscissa of the center of gravity of the area of the fuzzy set resulting after aggregation of the rules.

$$C = C_1(c) \cup C_2(c), \text{ or}$$

$$\mu_C(z) = \max(\mu_{C1}(z), \mu_{C2}(z))$$

Where;

$C_1(c)$ is the area of aggregated membership fuzzy function C_1 weight μ_{c1}

$C_2(c)$ is the area of aggregated membership fuzzy function C_2weight μ_{c2}

C is the area of membership fuzzy function of union

μ_{c1},and μ_{c2} are weights of membership functions C_1 and C_2

then the crisp value assigned to the aggregated fuzzy set is given by:

$$Z^*_{.} \approx \frac{\sum_{J=1}^{J=n} Z_J \mu_C(Z_J)}{\sum_{J=1}^{J=n} \mu_C(Z_J)}$$

where;

$\mu_c(Z)$ weight of union,

Z is the value of membership function, and

Z* is the crisp value of membership function

EXPERIMENTAL STUDY

In order to obtain a relationship knowledge base data between Fuel air ratio or (Φ), exhaust temperature, and exhaust emissions an experimental study

has been carried out using a ford engine test bed shown in figure (3). The engine specification and parameters are summarized in Table (1). The test bed is equipped with measuring devices and sensors for speed, power output, air flow rate, fuel flow rate and temperature thermocouple for cooling water and exhaust gas temperatures. A PC data acquisition system utilizing A Data Acquisition (DA/ADQ), Das-1600/1400 series by KEITHLEY Instruments, analog to digital converter (12 bit AD/DAC) card was adopted.
A sample of engine exhaust gases was fed to a gas analyzer (model] SUN SGA 9000} which accurately measures the carbon monoxide (Co%) and unburned hydrocarbon (HC ppm) concentration.

Table 1 Engine parameters and specifications

Bore diameter	80.98 mm
Stroke length	53.29 mm
Engine capacity	1098 cc
Compression ratio	8.0:1
Speed range	1500-3000 rpm
Maximum power	22 kw
Oil pressure	0-7 bar
Oil temperature	20-150 C°
Max. cooling water temperature	75 C°

Experimental Results

The engine was tested after all measuring devices were calibrated and the engine reached the steady state operation as specified in the instruction sheet [11]. The engine was tested at constant speed and the carburetor main jet oscillates to compensate the variation of fuel flow rate.

The results obtained are shown in figures (4,5). Figure (4) shows the variation of carbon monoxide (Co%) with the mixture equivalence ratio (Φ) at constant speed full throttle and fixed ignition timing. The results show an increase in Co% with the rich mixture. The exhaust temperature variation with (Φ) at constant speed is also presented in figure (5). Exhaust temperature increases with both the increase of equivalent ratio and the increase of engine speed.

PROPOSED CLOSED LOOP FUZZY CONTROLLER

Figure (6) shows a proposed closed loop fuzzy logic system for fuel to air ratio control system. In this system it is convenient to represent fuel air ratio by the equivalence ratio (ϕ)

$$\phi = \frac{Fuel\ /\ Air_{(actual)}}{Fuel\ /\ Air_{(stoichiometry)}}$$

In the fuel metering actuator for the engine control system inlet manifold dynamics represent fast fuel flow in the form of vapor or droplets, and slow fuel flow in the form of liquid film on the manifold walls. To regulate the fuel flow into the engine exhaust gas temperature at specified speed were used to define an output equivalence ratio. The temperature sensor generates an electrical signal, which were converted into fuzzy membership input functions. The fuzzy sets showed in figure (7) were used in fuzzy controller.

The first controller input is feedback temperature error and the second controller input is feedback rate of change of temperature error as given in the following equations

$$e_T(t)=T_r-T_{F.B.}$$

$$\frac{de_T(t)}{dt} = e(t) - e(t-1)$$

where;

T_r is set point reference temperature,

$T_{F.B.}$ is feedback Temperature, and

t is a current time discrete sample

In order to write the control rules, three fuzzy sets have been chosen for temperature error, and three fuzzy sets for rate of change of error as shown in figure (7-1) and figure (7-2). The fuzzified values for the outputs rules were classified into membership sets similar to the input values An output functions illustrated in figure (7-3) was used. This function was fuzzified to crisp value of stepping motor pulse width which proportional to fuel pulse width. The final sets of rules contained in the rules base is shown in Table (2)

Experimental adjustment of limits of memberships enable the response of the control system to be adopted to physical characteristic of the engine. An output membership fuzzy sets illustrated in figure (7) were defuzzified to a crisp value of stepper motor pulse. Stepper motor pulses adjust main jet needle valve installed in the fuel line to produce a desired fuel pulse.

Table (2) Fuzzy Control Rules

	A variable input sets				A variable output sets
	Error		Rate of change		Stepping Motor Pulse
IF	Low (L)	AND	Rising (R)	THEN	Medium Pulse (MP)
	Low (L)		Slight change (SC)		Large Pulse(LP)
	Low (L)		Falling (F)		Very Large Pulse(VLP)
	Medium M)		Rising (R)		Small Pulse(SP)
	Medium M)		Slight change (SC)		Medium Pulse(MP)
	Medium M)		Falling (F)		Large Pulse(LP)
	High (H)		Rising (R)		Very Small Pulse(VSP)
	High (H)		Slight change (SC)		Small Pulse(SP)
	High (H)		Falling (F)		Small Pulse(SP)

DISCUSSIONS

The performance of the engine running with conventional carburetor jet was experimentally compared with that of the engine using fuzzy logic control and stepping motor as actuator. The comparison was done at different engine speeds of (2000, 2400, 2800, and 3000rpm) versus different throttling carburetor jet valve of (20%, 40%, 60%, and 80% opening). The results are shown in figure (8) to figure (11). Results demonstrated improvements of about 8% of engine performance. The difference in performance between the conventional and fuzzy logic was reduced with the increase of throttling percentage. The reason may be due to nonlinear behavior of carburetor main jet valve at conventional performance which produce rich mixture at small throttling value, and weak mixture at large throttling.

CONCLUSIONS

Results from experimental and simulated models have led to the following conclusions

1-The exhaust emissions concentrations are strongly affected by fuel air ratio and have their minimum values at stoichiometry. Operating with a ratio greater than stoichiometry will cause high carbon monoxide in the exhaust gases, so fuel/air ratio needs to be controlled around stoichiometric value.

2-One of the most significant factor that affect engine exhaust gas temperature is fuel/air ratio and can be used to indicate the concentration of CO%.

3-The variation in exhaust temperature is correlated with fuel/air ratio through a group of fuzzy rules and used to control the engine needle jet valve.

4-Fuzzy logic is useful tool for use in controlling fuel/air ratio. An about 8% improvement in output torque was achieved compared with conventional carburetor.

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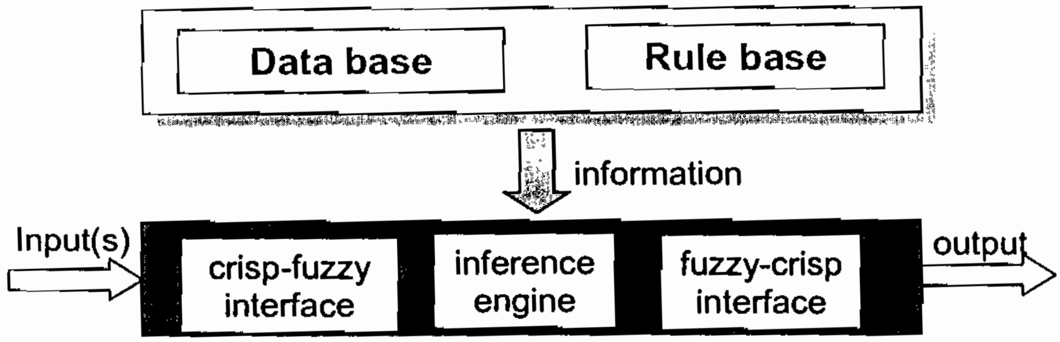


Figure (1) Generalized block diagram of fuzzy logic controller

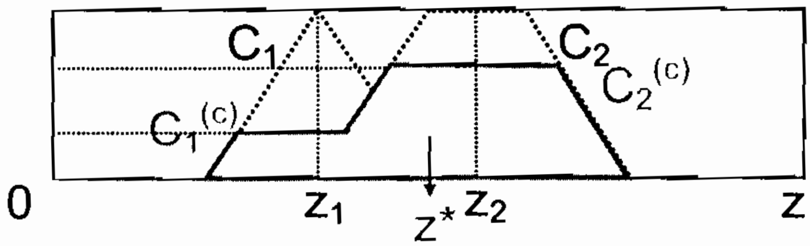


Figure (2) Center of gravity defuzzification process

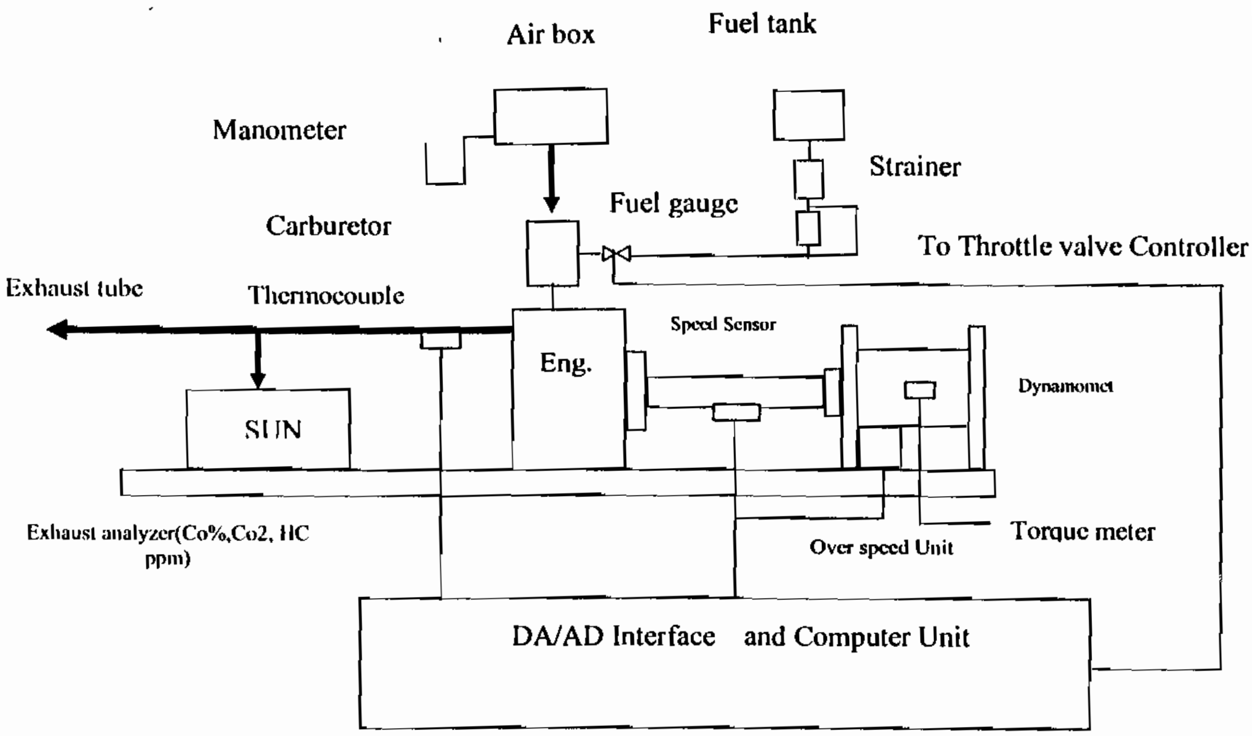


Figure (3) Test Rig Layout

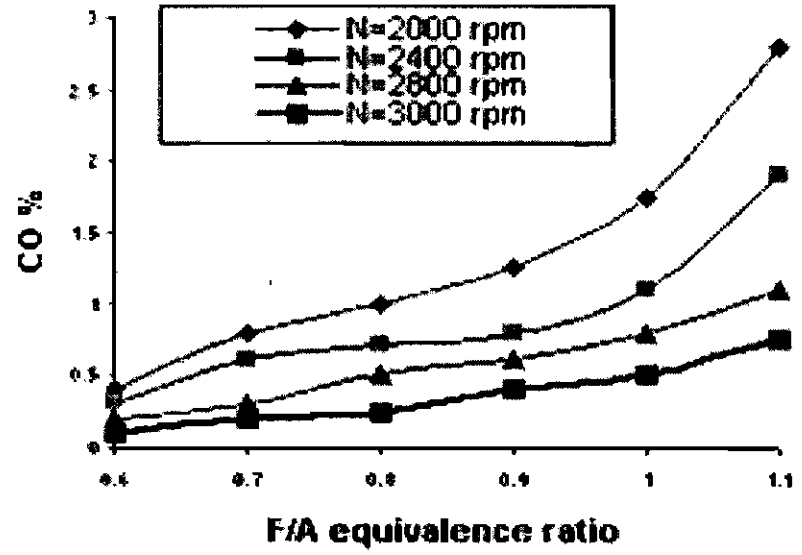


Figure (4) **Effect of F/A equivalence ratio on CO concentration [Ford C.R.8]**

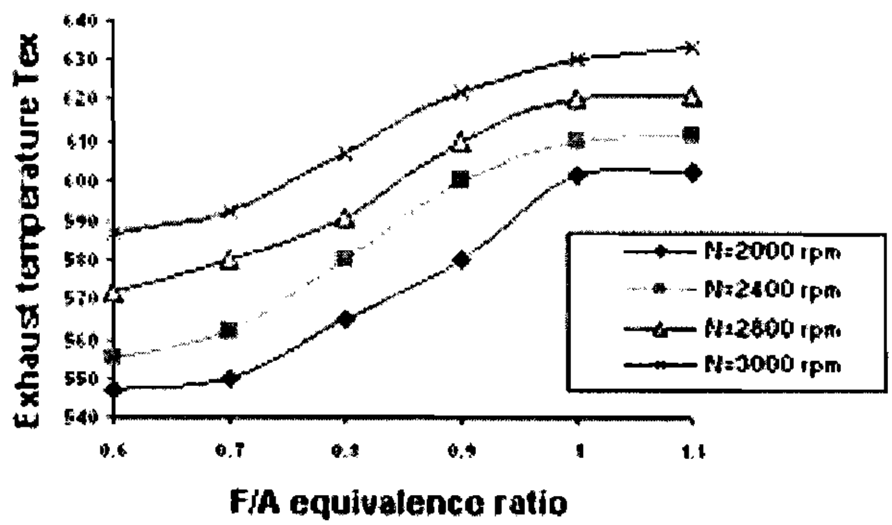


Figure (5) **Effect of F/A equivalence ratio on engine exhaust temperature[Ford C. R. 8]**

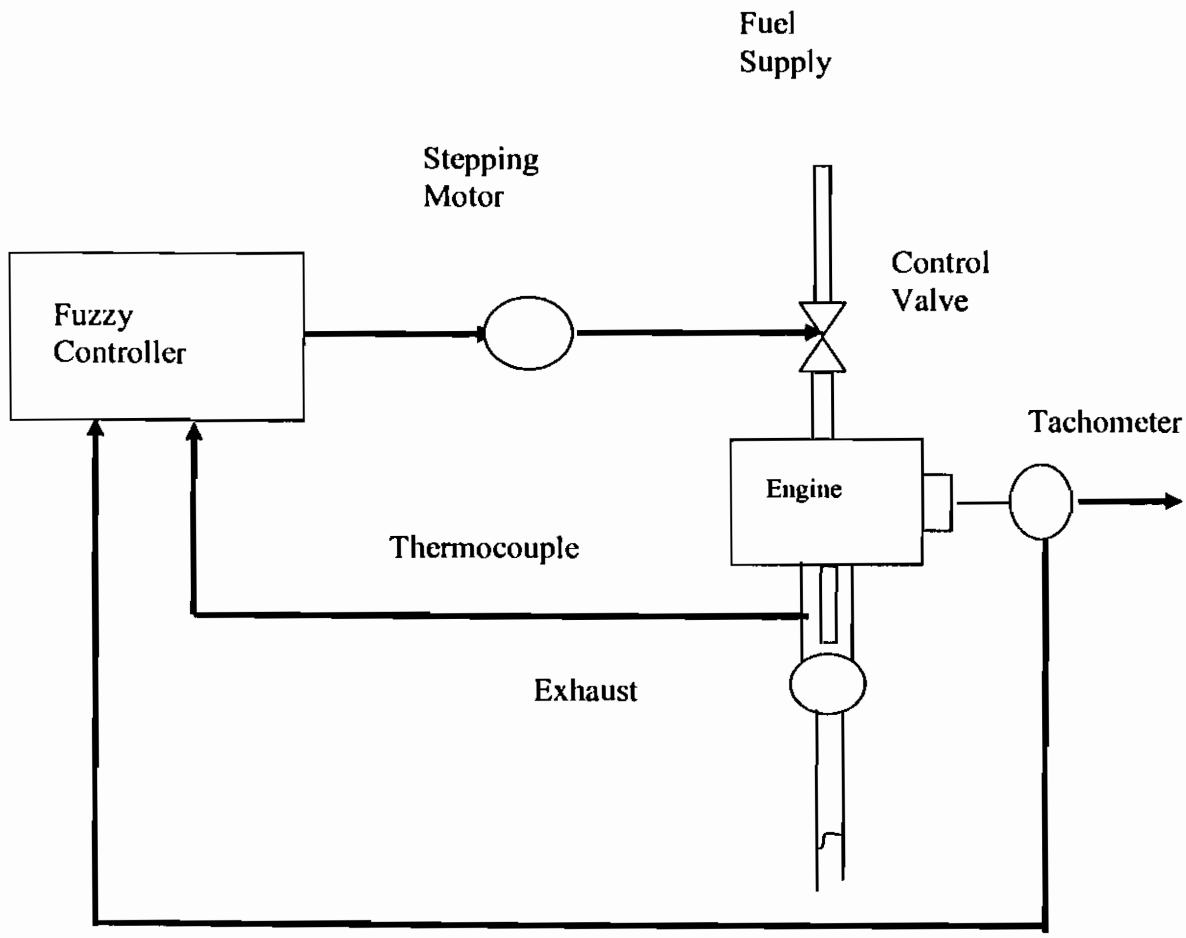


Figure (6) Proposed fuel-air ratio fuzzy control loop

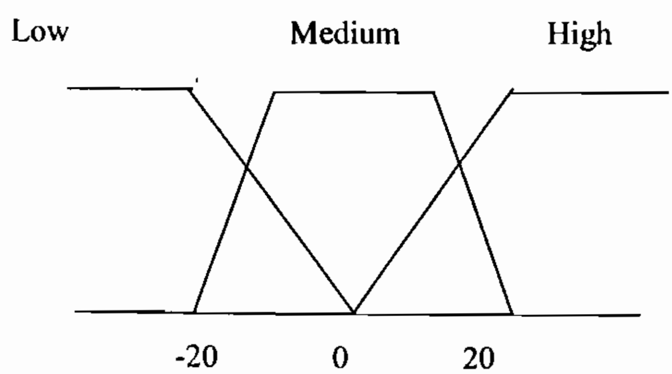


Figure (7-1) Membership function of exhaust temperature error

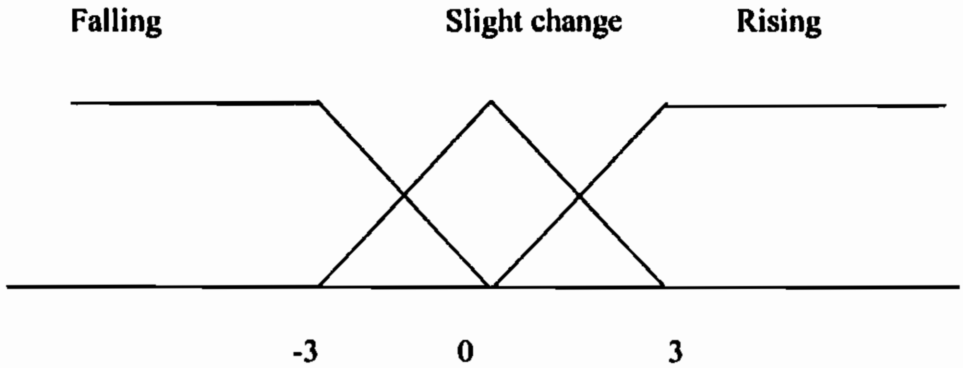


Figure (7-2) Membership function of rate of change of exhaust temperature error

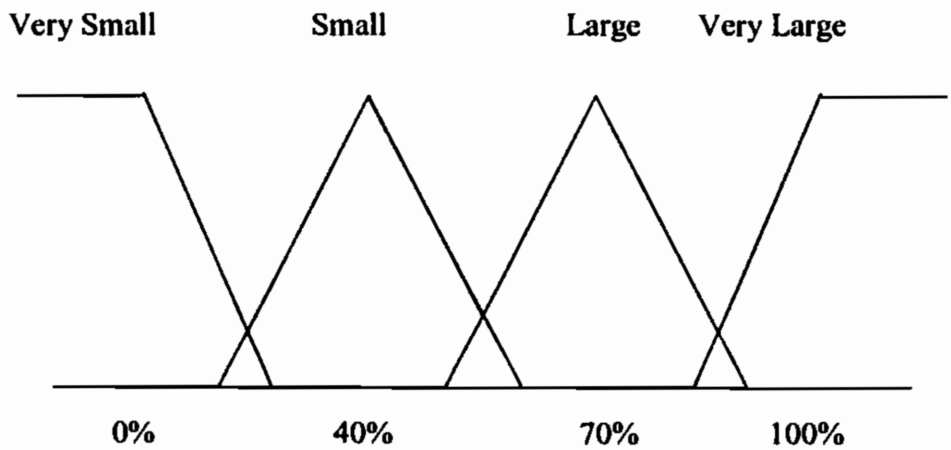
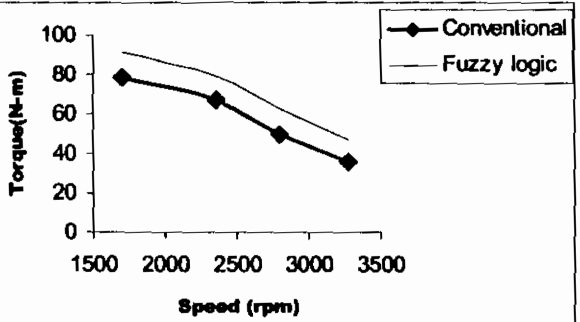
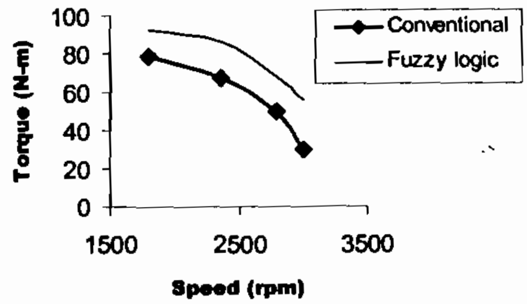


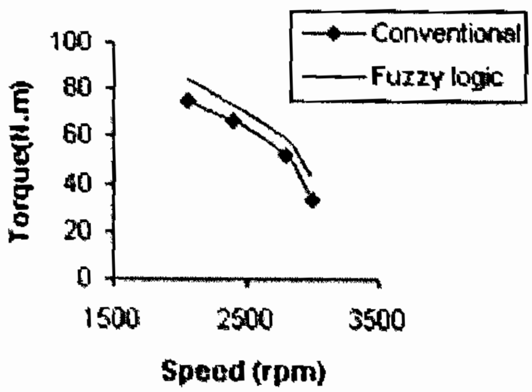
Figure (7-3) Membership function of stepping motor pulse width



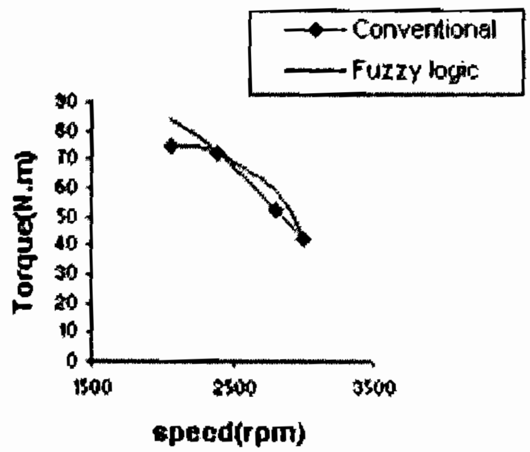
Figure(9)Variation of engine torque versus speed at 40% throtling



Figure(8) Variation of engine torque varsus speed at 20% throtling



Figure(10) Variation of engine torque versus speed at 60% throttling



Figure(11)Variation of engne torque versus speed at 80% throttling