بسم الله الرحمن الرحيم

"In the name of God, Most Gracious, Most Merciful."

ETHANOL AND METHANOL BLENDS WITH GASOLINE: AN EXPERIMENTAL APPROACH TO ENGINE PERFORMANCE AND EMISSIONS

By

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KEY TO SYMBOLS

ϕ = Equivalence ratio

A/F = The mass ratio of air to fuel

RPM = Revolutions per minute

WOT = Wide open throttle

CO = Carbon monoxide

HC = Hydrocarbons

CHO = Aldehyde

MTBE = Methyl tert-butyl ether

BTDC = Before top dead center

ABDC = After bottom dead center

ASTM = American Society of Testing Materials

OEM = Original equipment manufacturer

GC = Gas chromatograph

FID = Flame ionization detector

TCD = Thermal conductivity detector

BSFC = Brake specific fuel consumption

BSEC = Brake specific energy cons.

T = Torque

HP = Horsepower

UNC = Uncertainty

PPM = Part per million

injs = Inject sample

S = Spark timing

M = Per cent of alcohol in the alcohol-gasoline blend.

A = Ratio of methanol to ethanol in the alcohol.

$\dot{m}_f$ = Fuel mass flowrate

$\dot{m}_a$ = Air mass flow rate

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The effect of mixing methanol and/or ethanol with gasoline in fuel blends on brake specific fuel consumption, brake specific energy consumption, and exhaust gas emissions (CO, HC, and CHO) has been studied. Tests were conducted on a OEM 4-cylinder engine running at different conditions of equivalence ratio, spark timing, per cent of alcohol in alcohol-gasoline blends, and mixture of methanol and ethanol in the fuel. Results of this investigation indicated that fuel consumption increased as the percentage of alcohol was increased above 5% in an alcohol-gasoline blend. Fuel consumption also increased by 2 to 5% with retarded spark timings. Brake specific energy consumption was found to decrease by up to 8% with an increase of alcohol up to 15% in the blend. Minimum specific energy consumption was found to occur with normal spark timing and with equivalence ratios on the lean side of stoichiometric air-fuel ratios. No significant differences in brake specific fuel consumption or brake specific energy consumption were observed when different alcohols were used. Presence of alcohol in blend fuels was observed to reduce the concentration of carbon monoxide in the exhaust emissions (up to 40 to 50%) compared to gasoline only). Minimum carbon monoxide emissions were observed to occur with equivalence ratios in the lean range (A/F ratios of 1 to 1.2). Methanol-gasoline blends were found to be slightly more effective than ethanol-gasoline blends in reducing CO. Hydrocarbon emission was also decreased by increasing the alcohol content of the fuel. Minimum HC production was found to occur with 10% alcohol-gasoline blends in conjunction with near stoichiometric air-fuel ratios. Retarded timing was found to increase HC by as much as 60%. However, aldehyde emissions were found to be markedly higher with alcohol-gasoline blends. The 10% percent alcohol-gasoline blends were found to provide 1 1/2 times the aldehyde emissions from pure gasoline.

CHAPTER I

INTRODUCTION

The fear that energy from petroleum in the future will be available neither in sufficient quantity nor at reasonable prices has focused the world's attention on the need to conserve this limited resource. This concern has led to numerous studies of optimum use of crude oil and the development of renewable substitutes for petroleum products.

To achieve reduced energy consumption in engines, studies have been done in three principal areas. The first area concerns remodeling existing engines to include the design of peripheral equipment (such as fuel injectors, turbochargers, emission control systems, etc.) to achieve better performance and consequently lower fuel consumption. The second area considers the replacement of gasoline engines by diesel engines, or by some form of hybrid, running on wide cut fuel encompassing much of the gasoline and diesel fuel range. The third area of study seeks renewable sources of fuel that can be produced from local raw materials (agricultural residues, grain, food products, etc.). Examples of possible substitute fuels include hydrogen, methane, and alcohols.

Alcohols have been used as motor fuel almost since the automobile was invented. By definition alcohols contain the hydroxyl (OH) group. This gives the alcohols certain common characteristics which include high latent heat of vaporization and high solubility in water.

These characteristics can be advantageous or disadvantageous, depending on what function the alcohol is to serve. The wide flammability limits and high latent heat of methanol make it attractive as a racing fuel. The partitioning of isopropyl alcohol between water and gasoline and its good freezing-point depression make it an effective carburator anti-icing agent. The high motor octane number and modest water affinity of tertiary butyl alcohol make it attractive as an octane-blending component. However, none of the alcohols has ever been used as a primary energy source on a wide scale because they were both too expensive and have other disadvantages relative to gasoline. But as the world petroleum situation has changed, alcohols have become an increasingly viable fuel and have been under increasing study as potential alternative fuels. As a result of such investigations in the seventies, it has been found possible to develop efficient engine vehicle designs based on alcohol fuels. These designs can be expected to be superior to today's gasoline engines in the following aspects:

Better thermal efficiency.

Higher power output.

Improved exhaust emissions.

The increasing world-wide problem of air pollution further increases interest in alcohol fuels as they offer the hope of reduction of undesirable emissions.

Only methanol and ethanol appear to be practical candidates for alcohol fuels at present. Higher alcohols may be viable for other specific uses but are generally far too expensive for general use. In

Brazil, ethanol fuel has been used extensively for some time, where as in the USA and Europe, there is a clear preference for methanol over ethanol. This distinction arises from the expectation that it will soon be economical to derive methanol from coal.

The use of methanol-gasoline and/or ethanol-gasoline blends in spark ignition engines can increase thermal efficiency as alcohol boosts the octane number of the fuel blend and, accordingly, allows an increase in the compression ratio. As an oxygenated fuel, alcohol-gasoline blends enhance operation of spark ignition engines on the lean side. With both types of alcohol blends there is a decrease in carbon monoxide emissions.

Studies done on methanol and ethanol blendings with gasoline indicate that mixing ethanol with methanol-gasoline blends could outweigh some of methanol's disadvantages and thus produce a better blending fuel. The following reasons are cited:

1- Ethanol has a higher motor octane number (92 ON) than methanol (91 ON).

2- The heating value of ethanol (27 MJ/kg) is higher than that of methanol (20.1 MJ/kg).

3- Heat of vaporization of ethanol (390 kJ/kg) is less than that of methanol (500 kJ/kg).

4- The boiling point of ethanol (78.3°C) is higher than that of methanol (65°C).

5- Vapor pressure of ethanol (17 kPa at 38°C) is less than that of methanol (32 kPa at 38°C).

6- Ethanol is less corrosive to the materials conventionally used in present-design vehicle fuel systems than is methanol.

This study was carried out to evaluate ethanol-methanol-gasoline, in different proportions, as fuel blends, compared to pure gasoline. A Ford 2.3 liter 4-cylinder engine, mounted on an engine dynamometer was used for all tests. The independent variables equivalence ratio, ignition timing, and percentage (by volume) of ethanol and methanol in alcohol-gasoline blend were varied systematically. The dependent variables-torque, brake specific energy, fuel consumption, and the exhaust emissions- were studied at each different running condition. Chemical analysis was performed on combustion products to study hydrocarbon, aldehyde, and nitrogen oxide emissions. Statistical analysis of the data was carried out to check the influence of the independent variables on the dependent variables.

CHAPTER II

LITERATURE REVIEW

For thousands of years man has known the chemical process which produces alcohol (1). The ancient Egyptians and Mesopotamians produced alcohol through the natural fermentation of grapes and malt in the manufacture of wine and beer. The ancient Egyptians used alcohols in many chemical products such as dyes. The ancient Chinese are believed to have discouraged the art of distillation in view of the flammability of alcohol. Thus its known potential as a fuel is older than the written history.

The potential use of alcohol fuels for internal combustion engines (ICE) was established a long time ago (2-6). In 1826, Samuel Morey, of Oxford, listed alcohol, along with vaporized turpentines, as fuel for the newly-developed internal combustion engine. Some of the very earliest SAE papers were devoted to alcohol's fuel properties. The Cooperative Fuel Research Subcommittee published an extensive report in 1933 covering the use of a 10% alcohol-gasoline blend as a fuel for internal combustion engines (1).

Sir Harry Ricardo (7) in 1941 tested a single-cylinder engine with variable compression ratios with 198 proof ethyl alcohol blended into the fuel He reported that the mean effective pressure (MEP) of the engine was higher for all mixture ratios (20-40%) than it was for gasoline. This increase was due to the greater volumetric efficiency which results from the high latent heat of vaporization of alcohol and the greater mass of fuel per unit mass of air. The intake manifold temperature was reduced, causing an increase in the air density and engine volumetric efficiency. Maximum MEP of the engine when using alcohol occurred at over 40% excess fuel, while the maximum MEP for the engine when using pure gasoline occurred at over 20% excess fuel. To get a maximum power output from an engine one should exceed the above ratios and run the engine with over-rich mixtures. However, this would result in additional incomplete combustion and thus lower thermal efficiency. The maximum thermal efficiency can be achieved at approximately 15% excess air. At ratios above 15% the flame propagation speed of the combustion process will be dramatically decreased and thermal efficiency will decrease.

Lichty and Ziury (8) tested a multi-cylinder engine in 1936 with 190 proof ethyl alcohol and air at 100°F. Their study showed that the power increase was much lower than in the case of the above-noted single cylinder engine for the same air-fuel ratio. The authors concluded that the decrease in the output power of the multi-cylinder engine, compared to the single cylinder-engine, was due to fuel distribution problems and/or to differences in the combustion chamber design.

Many other tests have been done on multi-cylinder engines using alcohol as fuel. Brooks (9) concluded that 190 proof alcohol used in a multi-cylinder engine is not efficient without a special intake manifold. Bolt (2) tested 200 proof ethyl alcohol and pure gasoline in a 6-cylinder engine with high intensity light directed through glass windows set in the manifold runners and risers. He reported that more liquid alcohol fuel condensed inside the inlet manifold compared to gasoline fuel. This indicates difficulty in obtaining a uniform mixture distribution. In the normal type of spark-ignition (SI) engines, operation is satisfactory only if the various cylinders receive approximately the same fuel-air ratio and if nearly all the fuel is evaporated before ignition. The effects of alcohol-gasoline blend on engine performance and emissions will be discussed in the following paragraphs.

The octane number (ON), or the knock rating, indicates the anti-knock quality of fuels used in spark ignition engines. It is defined as the percentage of iso-octane fuel in a mixture of normal heptane and iso-octane to match the knock of the tested fuel at the same testing conditions (compression ratio, inlet temperature, cooling temperature, and RPM). In normal heptane, C_7H_{16}, the carbon atoms are connected together as a chain, and it has much greater tendency to knock than the average motor fuel. In iso-octane (2,2,4 trimethyl pentane) the carbon atoms are connected as branched chains, and it has much less knocking tendency than average motor fuel. There are two different international systems used for determining the octane number, the Research octane number method (ASTM D2699, DIN 51756) and the motor octane method (ASTM D2700, DIN 51756). In both ratings the higher the octane number, the more knock resistant the fuel is. The motor octane number needs more severe testing conditions (higher inlet temperature and higher engine speed) than the Research octane number. The difference between the Research octane number and the motor octane number is defined as the fuel sensitivity. The sensitivities of methyl and ethyl alcohols are 14(106-89) and 17(106-89) octane numbers, respectively (10). This indicates that these compounds are sensitive to changes in engine condition and are desirable as octane boosters in gasoline blends.

Porter and Wiebe (11) reported the influence of alcohol additions on four base stocks: straight run, catalytically cracked, thermally cracked, and polymer gasoline (Fig. A-1, Appendix A). The greatest improvement in octane number from alcohol addition was obtained with gasoline stocks of the lowest octane number (straight run). Southwestern Research Institute (12) has reported the Research and Motor octane ratings of three regular and three premium commercial leaded gasolines blended with 5,10, and 25% of anhydrous ethyl alcohol by volume (Figs. A-2 and A-3 Appendix A). The study indicated that addition of up to 25% ethanol to regular gasoline improved the Research and the Motor octane numbers in a near linear manner. For the premium fuels the Research octane number showed less improvement, as would be expected.

Since the heating value of ethyl alcohol is 60% of that of gasoline, blends of these liquids also have lower heating values than gasoline. The energy content of alcohol-gasoline blends decreases in direct proportion to the volume percent of alcohol in the mixture (13). In order to compensate for the decrease of energy per unit volume in the alcohol-gasoline mixture a proportional increase of the rate of fuel flow through the metering system (the carburetor and inlet manifold) of an engine is required. The efficiency of the metering system depends on the viscosity and specific gravity of the fuel. Ethyl alcohol has higher specific gravity and viscosity than gasoline, so that ethanol-gasoline blends have higher specific gravities and viscosities than gasoline only. The alcohol-gasoline blend has a slightly lower specific gravity than the ideal solution linear model would predict. The volume of mixing of this solution is slightly positive and the heat of mixing is slightly negative. For a given carburetor condition, the increased specific gravity of the blend will tend to increase the flow rate through the metering system, but the increased viscosity will tend to reduce the rate of flow. Accordingly, the rate of flow of a mixture can not be trivially computed from the flow of pure gasoline under the same conditions. Therefore it is normal practice to experimentally calibrate each metering system for the intended fuel blend (2).

Brown and Christeneen (14) conducted experiments on SI engines to compare fuel consumption of pure gasoline and 10% ethanol-gasoline blend by volume and found that consumption for both fuels was identical for the same carburetor.

Lichty and Phelps (15) tested 5,10 and 20% ethanol gasoline blends, using a single cylinder CFR (Cooperative Fuel Research) and a 6-cylinder Chevrolet engine. The CFR engine was run at several compression ratios. The conclusion was that the power output, thermal efficiency, and heat loss to the cooling system did not change appreciably with alcohol-gasoline blends, when compared to pure gasoline at different comparable conditions (same load, timing, speed and environment and without altering the spark setting). The only difference noted, however, was that, when the engines were returned to optimum spark advance, there was a reduction in detonation. For the CFR engine, specific fuel consumption was increased by 7% with a 10% alcohol-gasoline blend and increased by 13% with a 20% alcohol-gasoline blend. For the 6-cylinder Chevrolet engine, the specific fuel consumption was increased by 5% with a 10% alcohol-gasoline blend and increased by 9% with a 20% alcohol-gasoline blend compared to pure gasoline.

The Coordinating Research Council, Inc. (CRC) conducted two programs to study effects of using ethanol-gasoline and methanol-gasoline fuel blends on vehicle performance and vapor lock. In the first phase program (16), fourteen 1980 model-year cars (seven with open loop and seven with closed-loop emission control systems) were selected to represent a variety of engine and emission control designs. The parameter used for the analysis of drivability performance was the total weighted demerits on the CRS Intermediate-Temperature, Cold-Start and Drivability Test. The parameter used for analysis of vapor lock was the percent increase in critical acceleration time in the CRC Vapor Lock Test at 100°F. According to the findings, only a few of the cars in this program had severe drivability problems. However, the range of volatility characteristics in this program was much narrower than is typical of CRC drivability programs. The two fuel-injected vehicles had excellent drivability and showed no loss of drivability when ethanol-containing fuels were used. For the fourteen cars in this test, addition of 10% ethanol resulted in a statistically significant increase in average energy economy (mi/MBtu). The decrease in average fuel economy (mpg) was not significant.

In the second phase program (17), methanol-gasoline blends had oxygen contents ranging between 1 and 8% by weight, and included fuels with and without isobutanol co-solvent. Ten of the fourteen 1980 model cars were re-used in phase 2. Drivability demerits were significantly higher with all the alcohol fuels than with the base fuel. While there was no statistically significant difference between the 5 and 8% by weight oxygen-content fuels, this group of fuels deteriorated drivability more than the 2% by weight oxygen fuels. In all instances, co-solvent did not affect drivability demerits. None of the cars showed vapor lock on these fuels at 100°F on a chassis dynamometer. No general trend of fuel economy versus alcohol content was found

Ebersole and Manning (18) ran tests on a single-cylinder engine operated at maximum power spark timing using iso-octane and methanol fuels. They reported that the lean misfire limits with methanol were approximately 0.2 equivalence ratios leaner than with iso-octane. The maximum engine output with methanol was approximately equal to that obtained with iso-octane. The leaner limit associated with methanol permitted engine operation at considerably lower imep's (indicated mean effective pressure) than with iso-octane. Indicated specific fuel consumption with methanol was 2.15 times greater than with iso-octane at the same power outputs and equivalent ratios.

Brinkman (19) operated a Waukesha single cylinder engine on ethanol at compression ratios (CR) ranging from 7.5:1 to 18:1, and on gasoline at CR 7.5:1, with equivalence ratios ranging between rich and lean limits. He obtained about 3% increase in the engine thermal efficiency with ethanol over that of gasoline at the same engine conditions. He related this increase to faster burning and decreased heat transfer to the cylinder wall with ethanol. Using a higher compression ratio and operating under leaner conditions with ethanol provided additional efficiency gains. Due to ethanol's low heating value, mass specific fuel consumption was greater with the ethanol than with gasoline.

Starkman et al. (20) ran a comparative analysis of alcohol fuels (ethanol and methanol) and hydrocarbon (benzene and iso-octane) fuels using a CFR engine equipped for supercharged operation. The engine was run at a constant airflow rate, a nominal 1800 rpm, 100°F, and 14.7 psia inlet conditions and CR 9:1. Their results illustrated that iso-octane and benzene are not appreciably different from each other concerning engine power. However, ethanol is slightly superior to methanol if used at quite rich mixtures, and methanol is significantly superior, particularly at very rich mixtures, such as 50% more fuel than chemically correct. Starkman et al. also reported that ethanol produced about 6% more power output and methanol about 12% more than the two hydrocarbon fuels. Gross output can be increased by 6% through the use of ethyl alcohol but approximately twice the fuel flow rate is necessary. Similarly the output may be increased by 12% if methanol is used, but this will require about three times the fuel flow rate.

Ito et al. (21) tested methanol as fuel in a 6-cylinder engine equipped with an oxygen sensor, feed-back control system, and 3-way catalytic converter. A 4-cylinder engine with a carburetor was also used. The authors stated that thermal efficiency of the engine increased by about 16% when the engine was fueled with methanol as compared to gasoline. They explained such increase by the undecreased pressure of the combustion chamber and decreased temperature of the combustion gas since the moles of the methanol burned gas increase compared to those of gasoline. They also reported that the WOT torque was increased by about 15% by raising CR from 8.8 to 10 with cold-type spark plugs which prevent preignition. They mentioned that cold startability is possible by using the dual fuel system, where the fuel is injected into the engine while cranking, and for some time after the engine has started. There is no problem of drivability in hot weather as the fuel pump has increased capacity for fuel feed. They also pointed out that many problems with materials (like alumninum, copper, zinc, and rubber) will occur if methanol is used for current gasoline-fueled cars.

Another advantage of using alcohol as a substitute for or as a blend with gasoline is the reduction of the regulated emission products (hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x)) and the control of unregulated emissions (aldehyde (CHO), particulates, etc) in exhaust gases.

When running diesel or pure gasoline in internal combustion engines emissions are principally hydrocarbons, but when using alcohols or alcohol-gasoline blends (methanol or ethanol), emissions are principally alcohols, hydrocarbons, and aldehydes. Aldehydes and alcohols, technically, are not hydrocarbons; it is, therefore, more meaningful to name these emissions unburned fuel (UBF). For gasoline fuel, UBF and HC are the same (22).

The dependence of hydrocarbon emission from internal combustion engines on fuel composition is well established (23-26). The effects of engine air-fuel ratio and emission control systems (catalytic converter) were studied and recognized as the dominant variables affecting both allowable fuel composition and components of exhaust emissions (22,27-35).

When using alcohol-gasoline blends, emissions of unburned hydrocarbons in the exhaust gases are reduced in the absence of an exhaust system control, as compared to gasoline, because of the leaning effect of alcohol. It is known that the best way to reduce hydrocarbon emissions is by adjusting the metering system to run the engine in a lean condition (equivalence ratio between 0.8 and 1.0) in conjunction with the use of a catalytic converter on the exhaust system (33,36,37).

Furey and King (38) tested two different 8-cylinder engines fueled with gasoline containing ethanol or methyl tert-butyl ether (MTBE) to study the effects of blended fuels on exhaust emissions. MTBE is produced from methanol and isobutylene. It was developed to replace methanol as a blending component with gasoline to avoid some of the technical disadvantages of adding methanol directly to gasoline. They found that evaporative emissions were as much as 51% higher with 10% ethanol fuel blends than with gasoline. The increase in emissions was related primarily to the higher fuel volatility (Figs. A6, A7, Appendix A) and partly to an increase in hose permeability caused by the ethanol. Evaporative emissions as much as 15% higher with the 15% MTBE fuel than with gasoline were observed. The authors also recorded that tailpipe emissions of HC, CO, and NO_x from the engine without closed-loop fuel control were significantly lower with fuel blends than with pure gasoline, due to the leaning effect of ethanol and MTBE. On the other hand the tailpipe emissions from the engine with the closed-loop carburetors were very low and the differences in emissions among the various fuels were quite small.

The fuel preparation (heating the manifold, air pump) before the combustion process had a strong effect on CO emissions (39-42). Improving fuel preparation by using a heat exchanger after the fuel injector to increase vaporization of the alcohol fuel reduced CO emissions by 70% for pure methanol and by 50% for pure gasoline in a single cylinder engine (43).

Alcohol has a considerable advantage over gasoline with respect to emissions of nitrogen oxides (NO_x) at stoichiometrically correct and lean fuel mixtures, as well as under spark retard conditions (44-46). The use of an exhaust gas recirculation system (EGR) is also a successful method of control for NO_x emissions (47,48).

Nitric oxide is produced from the reaction of atomic nitrogen and oxygen with molecules of nitrogen and oxygen.

N + O2 -----> NO + O

O + N2 -----> NO + N

It is a slow reaction with a half-life on the same order as the time for an expansion stroke under typical conditions in internal combustion engines. The formation of NO_x is thus governed by kinetics rather than equilibrium considerations, and consequently it has an exponential temperature dependence (39). The lower flame temperature and consequently lower peak cycle temperature, when burning alcohol in internal combustion engines, provides conditions less favorable for the formation of NO_x (44,49).

Experiments showed that NO_x emission increased when the compression ratio was increased to a maximum after which further increases in the ratio resulted in a decrease in NO_x emissions (50,52). This indicates that higher compression ratios can be utilized to increase the engine thermal efficiently while reducing the NO_x emissions. The location of the spark plug, with respect to the opening of the exhaust valve, affects the NO_x emissions. The closer the spark plug to the exhaust valve opening, the greater the NO_x emissions. This is due to the relatively high temperature in the spark plug region (53).

Aldehyde emission from gasoline-fueled internal combustion engine are relatively insignificant parts of gasoline fuel exhaust. Therefore, they are currently unregulated. In alcohol-gasoline fuel blends, aldehyde emissions are 2 to 4 times greater than those from gasoline fuel (27,50,54). The oxidation process with gasoline occurs through two paths, of which only one involves formation of aldehydes (55,56). On the other hand, with alcohol the intermediate mechanism of the oxydation process is through the formation of formaldehyde (HCHO) in the case of methanol, or acetaldehyde (CH_3CHO) in the case of ethanol (19,54).

The effect of such engine parameters as compression ratio (CR), equivalence ratio (ϕ), and exhaust temperature on aldehyde emissions has been variously studied (19,27,57,58). Aldehyde emissions increased with increasing compression ratio and also with the change from stoichiometric to lean equivalence ratios. Other studies (45,50) showed that an increase in the compression ratio from 9.7 to 14 reduced aldehyde emissions by 50% to levels comparable with those for gasoline. No explanations were offered. Since exhaust temperatures with alcohol were lower than with gasoline fuel, reduced oxidation in the exhaust system may also contribute to the higher aldehyde emission. Control of aldehydes in exhaust emissions can be achieved by suitable alteration of engine operating parameters, and by treatment of the cylinder with additives like aniline and water (54), heating the intake manifold with exhaust gases, and improving fuel-air spray atomizations (50). Aldehyde emissions can also be reduced by using after-treatment devices, like catalytic converters. Compromises should be considered between CR, equivalence ratio, spark timing and exhaust temperatures to obtain the best engine performance.

According to the literature which has been reviewed, alcohols offer promise as a substitute fuel or a blending agent with gasoline in internal combustion engines. Fuel blends show some advantages over pure gasoline and some disadvantages. The major benefits of using alcohol blended with gasoline as a motor fuel are the reduction of HC, CO, and NO_x emissions in exhaust gases and the improvement of the anti-knock quality. Most of the studies indicate that specific fuel consumption is increased more with alcohol or alcohol blends than with gasoline. The power output is generally higher with methanol or ethanol fuel if used as rich mixtures. Some studies reported drivability demerits with alcohol fuel blends, especially for methanol. A significant increase in aldehyde and UBF emissions was noticed with alcohol and alcohol blends.

CHAPTER III

EFFECT OF ALCOHOL ON SI ENGINE COMBUSTION AND EXHAUST EMISSIONS

3.1 Introduction

The combustion process in internal combustion engines is complex. It involves the interaction of chemistry and fluid mechanics. In all combustion processes, chemistry plays a central role even though fluid mechanics may dominate and drive the phenomena. Addition of alcohol, generally, decreases the overall combustion cycle temperature due to its high latent heat of vaporization compared to gasoline.

There are two main types of combustion: controlled combustion initiated by a spark plug, and uncontrolled combustion initiated either by a combustion chamber hot spot or by auto-ignition. (In auto-ignition the fuel/air mixture spontaneously ignites without an ignition source.)

3.2 Types of Combustion

3.2.1 Controlled (Normal) Combustion

The operating principle of spark ignition engines is the Otto cycle. In operation, before the end of the compression stroke, the spark plug is fired and the mixture of fuel and air starts to burn. Combustion spreads to the envelope of the mixture by the flame front at a rate depending primarily on the temperature of the flame front and secondarily on the temperature, density and pressure of the surrounding envelope. The flame front travels across the chamber until the whole mixture is combusted except for a thin "quench" layer near the cool surface. Depending on the degree of turbulence in the cylinder, the flame front may wrinkle and break into eddies. These effects speed up the process. The flame front always moves subsonically relative to the unburned mixtures and there is a rapid but controlled rise in combustion chamber pressure.

3.2.2 Uncontrolled Combustion

3.2.2.1- Abnormal (knock) Combustion. In normal combustion, after the flame is ignited at the spark, the flame front travels in a fairly uniform manner across the chamber compressing the unburned gas before it. The gas ahead of the flame, called the end gas, receives heat due to compression by the hot expanding gases and by radiation from the advancing flame front.

This heat transfer will decrease in the case of an alcohol-gasoline blend under controlled combustion. Under abnormal combustion conditions, however, the end gas spontaneously ignites ahead of the flame front. Shortly after the spontaneous ignition of the end gas a characteristic high-pitch "knocking" sound is heard. Due to the characteristics of the alcohol, high octane number (RON and MON) and high latent heat, the rate of knocking in the SI engines will decrease when using alcohol-gasoline blend at moderate speed. The blend octane number decreases somewhat at high speed, corresponding more nearly to the gasoline octane number (59,60) although it remains higher than pure gasoline.

3.2.2.2 Pre-ignition Combustion. Under severe operating conditions some part of the cylinder surface may be hot enough to ignite the unburned charge. If there is insufficient time for hot spot ignition to take place before the spark ignites the mixture, normal combustion will take place. As the temperature of the hot spot increases, a condition may be reached when the engine will run more or less normally with the ignition switched off. Further increases in the spot temperature would cause the mixture to ignite before the spark ignites. This is equivalent to advancing the ignition, but since the hot spot surface is larger than the spark, the combustion rate would be faster than normal combustion, creating very high cylinder pressures and temperatures. This brings about excessive negative compression work and increased heat loss to the walls, the overall effect being a loss in power.

From experimental work (61), the fuel most susceptible to self-ignition is undoubtedly methanol, which has a strong tendency to decompose under relatively low pressure and temperature conditions. The decomposition occurs spontaneously, igniting the air-fuel-mixture before the ignition timing fires the spark. Ethanol has less tendency to pre-ignition than to methanol.

3.2.2.3 Running-On Combustion. Running-on combustion occurs when the engine is switched off and the throttle closed and the engine continues to run. This is due to the combustion deposits and may occur with sudden power demand upon the engine, causing the deposits to glow and ignite the mixture. Alcohol fuel has a good effect on deposits. As an oxidizer, it reacts with some of these deposits during the combustion process. Thus the number and size of the deposits will tend to decrease with alcohol fuel.

3.3 Combustion Chamber Chemical Reaction Model

From a chemical point of view the combustion chamber is assumed to be divided into two main zones (62). The burned zone is from the spark plug to the flame front and the unburned zone is beyond the flame front (end gas). It is assumed that, in the unburned zone, there are no chemical reactions, while the reactions that take place in the burned zone satisfy chemical and thermodynamic equilibrium, and follow appropriate rate equations (63). For a hydrocarbon fuel (C_nH_m) and alcohol (ethanol and or methanol) mixed with air, the stoichiometric chemical reaction for each individual fuel constituent can be modeled as

$$C_nH_m + [n + \frac{m}{4}]\, O_2 + 3.76\, [n + \frac{m}{4}] N_2 \rightarrow nCO_2 + mH_2O + 3.76 \qquad \text{(Eqn. 1)}$$

$$CH_3OH + 1.5O_2 + 5.64N_2 \rightarrow CO_2 + 2H_2O + 5.64\, N_2 \qquad \text{(Eqn. 2)}$$

$$C_2H_5OH + 3O_2 + 11.28\, N_2 \rightarrow 2CO_2 + 3H_2O + 11.28N_2 \qquad \text{(Eqn. 3)}$$

at the elevated temperature in the burned gas zone.

Carbon dioxide (CO_2) and water vapor (H_2O) will partially dissociate to form carbon monoxide (CO), oxygen (O_2), and hydrogen (H_2). Furthermore, molecular oxygen (O_2), hydrogen (H_2), and nitrogen (N_2), will each partially dissociate to form atomic oxygen (O), hydrogen (H) and nitrogen (N). There will also be concentrations of hydroxyl (OH) and nitrous oxide (NO). Thus in the burned gas zone there are approximately the following species:

CO_2, CO, H_2O, OH, CHO, H_2, O_2, NO, H, O, N, N_2

Concentrations of these various species will depend on the air/fuel ratio, pressure, temperature and time. Numerical values of the concentrations can be computed by published methods (59,63,64).

3.4 Formation of Exhaust Gases

Complete engine combustion processes are exceedingly difficult to model. Even in conventional spark-ignition engines, where, under many operating modes, fuel and air can be treated as premixed, the combustion process is initiated in a three-dimensional, time-varying turbulent flow. The fuel is actually a blend of hundreds of different organic compounds whose combustion chemistry is rather poorly understood. The reactions take place in a combustion chamber whose volume and geometry vary with time, which directly influences the process. Therefore it is little wonder that the process is difficult to describe (65).

3.4.1 Carbon Monoxide

Carbon monoxide (CO) resulting from dissociation is always present in exhaust gases. When using fuel-rich mixture, the concentration of CO during the equilibrium reactions is increased due to the smaller carbon/oxygen ratio, and actual output concentration of CO will be greater than the calculated equilibrium concentrations. This indicates that recombinations were not complete in the expansion or exhaust stroke. Reactions in the expansion stroke must, therefore, be rate-controlled. Figure 3.1 shows that carbon monoxide emissions are controlled by the bulk of burned gas for fuel-rich mixtures, with the quench regions becoming increasingly important as the mixture is made leaner (65). The existence of alcohol in the blend increases the oxygen/carbon ratio which reduces the concentrations of CO in exhaust gases.

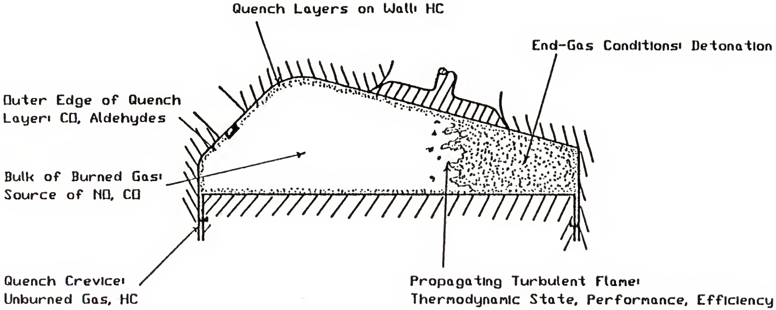


FIG. 3-1 SCHEMATIC OF SPARK-IGNITION ENGINE COMBUSTION PROCESS

3.4.2 Hydrocarbons

The oxidation of hydrocarbons is a chain reaction process with intermediate products that include aldehydes. Hydrocarbons appear in exhaust gases for a number of reasons. Hydrocarbon emission can be directly related to unstable ignition (misfire), a product of poor operation, like excessive lubricating oil in the exhaust (due to blow-by), and from crevices in the combustion chamber which are too narrow for the flame to enter (for instance around valves and between piston rings).

The two main combustion-hydrocarbon generating sources are intermediate products and wall quenching. Photographic measurements taken from combustion processes in engines showed that, as the flame propagates to the wall, there is a thin layer adjacent to the wall where no chemical reaction occurs, with the exception of some fuel breakdown. This thin layer, containing non-reacting hydrocarbons, is called the quench distance (see Fig. 3-1). The proximity to the wall has two effects. First, it inhibits a chain reaction by increasing the surface-to-volume ratio of the reaction vessel (66). Second, it acts as a heat sink, which causes the temperature of the wall layer to drop below the necessary ignition temperature. The quench distance typically varies in thickness from 0.008 to 0.038 cm (65). The unburned hydrocarbons adjacent to the wall are swept upwards by the piston ring during the exhaust stroke. The wall layer rolls up to form a vortex, causing the hydrocarbons to enter the exhaust stream. The quench distance is influenced by mixture temperature, pressure, air-fuel ratio, wall temperature, wall material, and combustion deposits. Concentration of hydrocarbons increases with rich mixtures, decreases to a minimum at approximately the point of maximum temperature close to stoichiometric, then remain almost constant. However, if the mixture is too "lean" due to the alcohol-gasoline blend, the concentration could increase due to misfiring.

3.4.3 Nitric Oxides

Nitric oxides in the products of combustion arise from dissociation of molecular oxygen and nitrogen. Under equilibrium conditions one would expect that the concentrations of NO would fall with pressure and temperature during the expansion stroke to negligible proportions at the exhaust valve opening. All experiments on engines indicate that the NO concentrations in the exhaust gases are well above those predicted by equilibrium conditions, implying that the NO reactions are rate-controlled. Thus, in order to more accurately calculate the expected quantity of NO, it is necessary to establish the chemical mechanism so that the appropriate rate equations can be used. There have been a number of mechanisms suggested. Consider the Zeldovich chain reaction as suggested by Newhall and Starkman (68).

$$O_2 \rightleftharpoons 2O.$$

$$O + N_2 \rightleftharpoons NO + N,$$

$$N + O_2 \rightleftharpoons NO + O.$$

These equations indicate that, at the elevated temperatures in the cylinder, molecular oxygen dissociates to atomic oxygen which reacts with the molecular nitrogen N_2 to form NO and atomic nitrogen N, the latter reacting with O_2, forming NO and atomic oxygen O. There have also been suggestions that this model is not complete, and Lavoie et al. (69) proposed a modified Zeldovich reaction which includes the hydroxyl (OH) radical.

$N + OH \rightleftharpoons NO + H,$

$H + N_2O \rightleftharpoons N_2 + OH,$

$O + N_2O \rightleftharpoons N_2 + O_2,$

$O + N_2O \rightleftharpoons NO + NO.$

Annad (62) has suggested a different group of reactions to be added to the modified Zeldovich reaction.

$N + NO \rightleftharpoons N_2 + O_2,$

$N + O_2 \rightleftharpoons NO + O,$

$N_2O + M \rightleftharpoons N_2 + O + M.$

Where M is a mediator in the reaction process.

The concentration of NO is related to the peak temperature and to the flame speed. The higher the peak temperature the higher the concentration, and the lower the flame speed the longer the time NO takes to dissociate to atomic nitrogen and oxygen. Figure 3.1 shows that nitric oxides form primarily in the bulk burned-gas region, behind the flame.

Experimentally, nitrogen oxides are almost unaffected by the alcohol in the blend. It was expected that alcohol in fuel would reduce NO_x either by effectively leaning the fuel mixture or as a consequence of the additional cooling of the intake charge caused by the high heat of vaporization. However, it was found that nitrogen oxide production was increased only slightly at a cold ambient temperature and decreased only slightly at a high ambient temperature (70). Other experimental work generally agreed with the report that nitrogen oxide increased from 4 to 13 percent with alcohol-gasoline blends (71,72).

3.4.4 Aldehydes

In the case of pure gasoline fuel, aldehydes are produced during chain reactions of hydrocarbons as an intermediate product. Some of these aldehydes (formaldehyde) are stable and pass into the exhaust gas. As would be expected, experimental work shows that alcohol-gasoline blends increase the aldehyde concentration in exhaust gases.

A classic model of methanol oxidation proposed by Westbrook and Dryer (56) and Browning and Pefley (57) postulates two primary paths for the formation of formaldehyde: one through hydroxymethyl radicals, CH_2OH, and the other through the methyl radical, CH_3. The following reactions account for formaldehyde formation and destruction at the temperatures encountered in the combustion chamber and exhaust systems. Formation reactions:

$$CH_2OH + O_2 \rightarrow CH_2O + H_2O$$

$$CH_2OH + M \rightarrow CH_2O + H + M$$

$$CH_3 + O_2 \rightarrow CH_2O + OH$$

$$CH_3 + O \rightarrow CH_2O + H$$

Dominant destruction reactions:

$$CH_2O + OH \rightarrow CHO + H_2O$$

$$CH_2O + H \rightarrow CHO + H_2$$

$$CH_2O + M \rightarrow CO + H_2 + M.$$

In the case of ethanol, the oxidation process studies by Bamford and Tipper (55), at relatively low temperature (270°C - 370°C), have shown that acetaldehyde is an oxidation product that can be detected. Thus, formation of acetaldehyde appears to be a primary step in the mechanism of ethanol oxidation. With hydrocarbon fuels, the same mechanism used in case of methanol is applied with ethanol (55,56).

3.5 Emission Standards and Controls

In the USA, the 1970 Amendments to the Clean Air Act required 90% reductions for each of the three major gaseous emissions (HC, CO, and NO_x) by 1975. This was in addition to the requirements of 30% to 40% reduction of carbon monoxide and unburned hydrocarbons which had been legislated for introduction in 1968. The 1981 Federal emission standards for regulated exhaust gases (73) were as follows:

Hydrocarbons	0.41	g/mi
Carbon monoxide	3.4	g/mi
Nitrogen oxides	1.0	g/mi

The automotive industry considered that any attempt to approach these stringent levels of control would require use of catalytic converters. These in turn would require large supplies of unleaded gasoline to avoid damage to the catalyst. Following the legal requirement for unleaded gasoline, all U.S. manufacturers of vehicles have designed engines to operate with lower Research octane number (91 RON) than the previous leaded grades which had Research octane numbers of 93-94 and 99-100 for regular and premium gasoline, respectively. This has been achieved by reducing average compression ratios from about 9.4:1 to 8.85:1. Alcohol could be used as an octane booster for unleaded gasoline.

Emission control was accompanied by a fundamental problem when using alcohol-gasoline blend due to the differences in stoichiometric air-fuel ratios of the two fuels, gasoline and alcohol (14.6 for gasoline, 9.0 for ethanol, and 6.5 for methanol). The existing metering systems (carburetor and intake manifold) used to adjust air-fuel ratio, were designed to use gasoline as a fuel. When using alcohol-gasoline blend, the exhaust control systems designed for gasoline may be used to control emissions of the regulated gases (CO, HC, and NO_x) after one or more of the following modifications:

1. Adjusting the metering systems
2. Insulated thermal reactor with air pump
3. Oxidation catalyst with or without air pump in addition to exhaust gas recirculation (EGR)
4. Three-way conversion catalyst (TWC) with a closed-loop fuel control system.

The last one is equipped with an oxygen sensor, placed in the exit of exhaust manifold, to activate a vacuum valve which maintains a stoichiometric air-fuel ratio (74-76).

Unregulated exhaust gases, such as aldehydes, can be controlled by placing additives like aniline and water in the cylinder or by treatments external to the cylinder, like inlet air preheating, secondary air injection to the exhaust line, increasing rate of flow of cooling water, or use of catalytic converters (54).

In summary, using an alcohol-gasoline blend enhances the performance of spark ignition engines due to the characteristics of the alcohol. The fuel octane number increases and the occurrence of knocking decreases. However the possibility of pre-ignition increases, especially with methanol. The build-up of hydrocarbon deposits inside the cylinder decreases with increasing alcohol addition to the gasoline. The effect of alchohol on exhaust emissions is significant.

The concentration of carbon monoxide decreases, hydrocarbon emission decreases with lean mixture and increases with rich mixtures, and nitric oxides generally increase as alcohol concentration is increased.

CHAPTER IV

EXPERIMENTAL WORK

4.1 Introduction

This study consists primarily of experimental work performed on an OEM (Original Equipment Manufacturer) 4-cylinder engine. Tests were run using different settings of the four independent variables: equivalence ratio, spark timing, percent of alcohol in the alcohol-gasoline blends, and methanol-to-ethanol ratio in the alcohol of the blend. The dependent variables measured were power (torque), brake specific fuel consumption, and brake specific energy consumption. Tests were run under selected contant speed and constant load conditions.

The engine used was a 1978 Ford 2.3 liter in-line four cylinder with an overhead camshaft, cogged belt drive, 9.0:1 compression ratio and a two-barrel carburetor (Appendix B). All emission controls and recirculation systems were disconnected so that no interference could occur in the carburetion and spark timing. The engine was mounted on a Superflow SF-800 dynamometer (Fig. 4-1) which facilitated measurement of torque, speed, and air and fuel flow rates. These measurements in turn permitted power and brake specific fuel consumption to be computed (Appendix C).

Exhaust samples were taken by 50-cc syringes, with Luer-lock tips, from an auxiliary spiral tube inserted inside the main exhaust pipe, as shown in the schematic of the engine dynamometer (Fig. 4-1). The

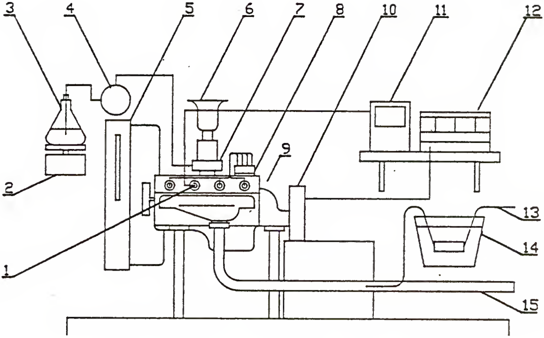


FIG. 4-1 SCHEMATIC OF ENGINE DYNAMOMETER

1 Pressure Transducer
2 Scale
3 Alcohol-Gasoline Blend
4 Fuel Pump
5 Radiator
6 Air Sensor
7 Carburetor
8 Distributor
9 4-Cylinder Engine
10 Absorption Unit
11 Oscilloscope
12 Console
13 Sample
14 Water Jacket
15 Exhaust Pipe

spiral tube was immersed in a water bath to quench the exhaust gases. Samples were injected into and analyzed by a gas chromatograph (Varian 3700) and the results were printed by the synchronized data system (Varian 401). A schematic diagram of the exhaust gas analysis equipment is shown in Fig. 4-2.

4.2 Data Points

There are many independent variables that affect the performance of internal combustion engines. Among those the following were choosen.

4.2.1 - Equivalence Ratio

This ratio, "ϕ" = (Air/Fuel)actual/(Air/Fuel) Stoich.

Three values of "ϕ" were choosen, the normal value "3", lean value "1", and rich value "5". To obtain "1" and "5" the carburetor primary and secondary jets were changed to different diameters as shown below.

Equiv. Ratio ϕ	Primary Jet (mm)	Secondary Jet (mm)	Avg. Jet Area (mm^2)
ϕ_1	1.04	1.02	0.84
ϕ_3	1.22	1.07	1.03
ϕ_5	1.32	1.12	1.16

4.2.2 - Spark Timing "S"

Three values of "S" were selected, the normal value "S_3" and other two values, "S_1" and "S_5".

S_1 (Retard) = 10° BTDC = -10°

S_3 (Normal) = 20° BTDC = 0°

S_5 (Advance) = 30° BTDC = +10°

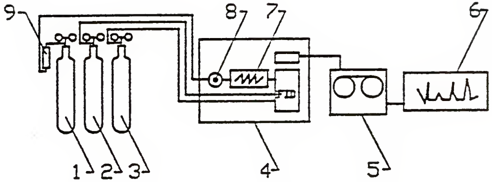


FIG. 4-2 SCHEMATIC OF GAS CHROMATOGRAPH ANALYSIS

1 Nitrogen (carrier)
2 Air
3 Hydrogen
4 Gas Chromatograph
5 Data System
6 Gas Chromatogram
7 Column
8 Injection Port (sample)
9 Filter

Spark timing was measured at idle speed, no load, and disconnected vacuum.

4.2.3. Per Cent of Alcohol (M) in Blend

Anhydrous (200 proof) methyl and ethyl alcohol were used as blending components with gasoline. Five values of the alcohol per cent by volume in the blends were choosen for "M":

M_1 = 0% Alcohol--unleaded gasoline
M_2 = 5% " " "
M_3 = 10% " " "
M_4 = 15% " " "
M_5 = 20% " " "

4.2.4. Ratio of Methanol to Ethanol (A) Blend

Three different methanol to ethanol ratios were used for each of the M_2 to M_5 alcohol-gasoline blends:

A_0 = 0% alcohol (pure gasoline)
A_1 = 100% anhydrous ethanol in the blend
A_2 = 50% each, ethanol and methanol in the blend
A_3 = 100% anhydrous methanol in the blend.

Characteristics of alcohol and alcohol-gasoline blends are illustrated in Appendix A. Table 4.1 shows the calculated specific gravities and heating values (H.V.) of the different mixtures of alcohol-gasoline blends.

The independent variables were related to each other in the factorial design, Fig. 4-3, to determine the conditions at each datum point.

Table 4.1 ALCOHOL-GASOLINE BLENDS: SPECIFIC GRAVITY AND HEATING VALUES.

		Specific gravity	Heating Value BTU/lb
M1	A0	0.735	18700
M2	A1	0.738	18322
	A2	0.738	18242
	A3	0.738	18162
M3	A1	0.741	17942
	A2	0.741	17793
	A3	0.741	17622
M4	A1	0.743	17568
	A2	0.743	17328
	A3	0.743	17089
M5	A1	0.746	17196
	A2	0.746	16879
	A3	0.746	16560

IND.VAR.	LEVELS			EQUIVALENCE RATIO								
				PHI 1			PHI 3			PHI 5		
			I.V.	S.TIME			S.TIME			S.TIME		
			L.	S1	S3	S5	S1	S3	S5	S1	S3	S5
%AGE OF GASOLINE	M1	KIND OF ALCOHOL	A0									
	M2		A1									
			A2									
			A3									
	M3		A1									
			A2									
			A3									
	M4		A1									
			A2									
			A3									
	M5		A1									
			A2									
			A3									

Fig. 4-3 Factorial Design of Independent Variables.

4.3 Test Procedure

4.3.1. Adjustment of Carburetor and Distributor

The carburetor jets were replaced by the specified jets to adjust the values of "ϕ" and the distributor was set to adjust the values of "S" according to the factorial design table, Fig. 4-3.

4.3.2. Fuel Preparation

Blends of gasoline and alcohol (200 proof methanol and ethanol) were prepared by volume measure. Specific gravities of the blends were determined by means of a sensitive blance measurement of the mass of 100 cc of each mixture. The fuel specific gravity calibration of the dynamometer was adjusted to the predetermined value. Three liters of fuel were used for each run.

4.3.3. Air Density

The air density calibration was set to the density of the air entering the air flow sensor (fixed on the top of the carburetor). The readings of the air flow were then indicated in standard cubic feet per minute (SCFM). Air density was determined by means of the perfect gas equation on the basis of measurements of the humidity ratio, temperature and barometric pressure (test pressure). A dry and wet bulb thermometer was used to determined the humidity ratio.

4.3.4. Setting and Starting the Dynamometer

The water flow to the dynamometer adsorption unit was checked at the beginning of each experiment. The engine was started and the load control was gradually adjusted to the predetermined load at 2500 rpm that the dynomometer exerts on the engine. Starting with pure gasoline, as a heating up fuel, the engine was allowed to reach a steady state cooling-water temperature and RPM before recording data. Then a two-way valve was used to switch from the gasoline fuel supply to the specified alcohol-gasoline blend. The engine was allowed to continue to run with the fuel blend until it reached a stable speed and load before data were recorded.

4.3.5. Data Recording

Data were recorded at the predetermined speed, 2500 rpm. The data included torque (T), horsepower (HP), rate of fuel flow (F), rate of air flow (SCFM), air-fuel ratio (A/F) and brake specific fuel consumption (BSFC). Data recording and printouts were repeated from five to ten times under the same condition for each run to insure consistency.

4.4-Data Correction

Corrected is the term commonly used for the calculated values of the of an engine adjusted to standard temperature and pressure (STP). Transforming the data to standard conditions (60°F, dry air, and sea level barometric pressure) was done to permit comparisons to be made with the data accumulated from tests under different environmental conditions.

To determine the values of the torque and power, friction power of the engine at the specified condition was measured. Friction power is that consumed internally by the engine to overcome bearing friction, ring-drag, oil pump drag, cam friction, distributor drag and windage. These factors do not change with barometric pressure or temperature. Friction power is normally measured by driving the engine with an electric motor and measuring the required power. This procedure is not feasible for many engine tests, including the the present ones, since the dynamometer used does not incorporate a primemover. As an alternative the air and fuel flow required to run the engine with no load at 2500 rpm was measured. Then friction power was estimated by means of a calibration table provided by the manufacturer which used engine speed and air flow as the independent variables. The estimated friction power value of the engine was 14 HP. The necessary calculations for this test are presented in Appendix B. Equations B-1, B-2, and B-3 were applied to standardize the actual data. The results are recorded in Tables 4-2 to 4-10.

4.5 Chemical Analysis of Exhaust Gases

Gas chromatography is a complex technique involving precision instrumentation, valving and sample handling. It also requires careful interpretation. The degree of complexity depends upon the type of sample to be analyzed, its reactivity with materials used in the instrument system, concentration levels, and available columns, valves and detectors.

The gas chromatograph used was a Varian Model 3740 G.C. It was used in conjunction with Varian CDS 401 central data station. The detector used was a flame ionization detector (FID), which is sensitive to CO, HC and CHO gases.

The procedures of gas chromatographic analysis are presented in Appendix D. The results are tabulated in Tables 4-11 to 4-13.

TABLE 4-2 EXPERIMENTAL CORRECTED DATA AT: PHI1-S5 & 2500 RPM

COND.	T LB FT	W HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	76	36	23	61	12.1	0.68	12700
M2-A1	76	36	24	66	12.4	0.70	12700
M3-A1	76	36	24	69	13.4	0.69	12400
M4-A1	NA	NA	NA	NA	NA	NA	NA
M5-A1	NA	NA	NA	NA	NA	NA	NA
M1-A0	76	36	23	61	12.1	0.68	12700
M2-A2	74	36	23	66	13.0	0.69	12600
M3-A2	77	37	26	65	11.6	0.71	12700
M4-A2	NA	NA	NA	NA	NA	NA	NA
M5-A2	NA	NA	NA	NA	NA	NA	NA
M1-A0	76	36	23	66	12.1	0.68	12700
M2-A3	76	36	23	66	12.8	0.69	12500
M3-A3	77	36	23	70	13.2	0.71	11900
M4-A3	NA	NA	NA	NA	NA	NA	NA
M5-A3	NA	NA	NA	NA	NA	NA	NA

NA: THE ENGINE WOULD NOT RUN AT 2500 RPM AT WOT WHEN THE ALCOHOL EXCEEDED 10% IN ALCOHOL-GASOLINE BLEND .i.e THE MAXIMUM HORSE-POWER WAS SOMEWHAT LESS THAN THE PREDETERMINED VALUE.

TABLE 4-3 EXPERIMENTAL CORRECTED DATA AT: PHI1-S3 & 2500 RPM

COND.	T LB FT	W HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	77	37	26	69	12.43	0.73	13700
M2-A1	77	37	25	61	11.02	0.73	13300
M3-A1	76	36	24	71	13.34	0.71	12800
M4-A1	75	36	22	74	15.68	0.70	12200
M5-A1	NA	NA	NA	NA	NA	NA	NA
M1-A0	77	37	26	69	12.43	0.73	13700
M2-A2	73	36	22	66	14.82	0.73	13300
M3-A2	74	36	21	70	12.87	0.73	13100
M4-A2	75	36	22	74	13.45	0.73	12600
M5-A2	NA	NA	NA	NA	NA	NA	NA
M1-A0	77	37	26	69	12.43	0.73	13700
M2-A3	73	35	24	66	12.80	0.71	12800
M3-A3	74	36	24	70	13.25	0.71	12600
M4-A3	73	35	24	70	13.25	0.73	12500
M5-A3	NA	NA	NA	NA	NA	NA	NA

NA: THE ENGINE WOULD NOT RUN AT 2500 RPM AT WOT WHEN THE ALCOHOL EXCEEDED 15% IN ALCOHOL-GASOLINE BLEND .i.e THE MAXIMUM HORSE-POWER WAS SOMEWHAT LESS THAN THE PREDETERMINED VALUE.

TABLE 4-4 EXPERIMENTAL CORRECTED DATA AT: PHI1-S1 & 2500 RPM

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	76	34	52	65	6.3	1.52	28400
M2-A1	76	34	24	71	14.1	0.69	12700
M3-A1	NA	NA	NA	NA	NA	NA	NA
M4-A1	NA	NA	NA	NA	NA	NA	NA
M5-A1	NA	NA	NA	NA	NA	NA	NA
M1-A0	76	34	52	65	6.3	1.52	28400
M2-A2	74	34	21	72	15.9	0.63	11500
M3-A2	NA	NA	NA	NA	NA	NA	NA
M4-A2	NA	NA	NA	NA	NA	NA	NA
M5-A2	NA	NA	NA	NA	NA	NA	NA
M1-A0	76	34	52	65	6.3	1.52	28400
M2-A3	74	34	21	71	16.6	0.55	10000
M3-A3	NA	NA	NA	NA	NA	NA	NA
M4-A3	NA	NA	NA	NA	NA	NA	NA
M5-A3	NA	NA	NA	NA	NA	NA	NA

NA: THE ENGINE WOULD NOT RUN AT 2500 RPM AT WOT WHEN THE ALCOHOL EXCEEDED 5% IN ALCOHOL-GASOLINE BLEND .i.e THE MAXIMUM POWER WAS SOMEWHAT LESS THAN THE PREDETERMINED VALUE.

FIG. 4-5 EXPERIMENTAL CORRECTED DATA AT PHI3, S5, and 2500 rpm.

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	75	36	25	56	10.3	0.73	13700
M2-A1	74	36	25	66	11.9	0.74	13500
M3-A1	75	36	24	66	12.3	0.72	12900
M4-A1	74	36	25	66	12	0.73	12800
M5-A1	74	36	25	66	11.8	0.74	12700
M1-A0	75	36	25	56	10.3	0.73	13700
M2-A2	73	36	27	66	11.2	0.79	14500
M3-A2	74	36	24	66	11.4	0.79	14000
M4-A2	74	36	26	66	11.6	0.76	13100
M5-A2	74	36	31	66	10.7	0.83	14000
M1-A0	75	36	25	56	10.3	0.73	13700
M2-A3	75	36	24	66	14.4	0.71	12900
M3-A3	73	36	26	66	11.4	0.78	13800
M4-A3	74	36	28	66	10.9	0.82	14000
M5-A3	75	37	28	66	10.9	0.82	13700

FIG. 4-6 EXPERIMENTAL CORRECTED DATA AT PHI3, S3, and 2500 rpm.

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	78	38	25	61	11.5	0.69	13000
M2-A1	74	36	24	61	11.1	0.70	12900
M3-A1	75	36	25	61	11.1	0.72	12900
M4-A1	76	36	24	61	10.8	0.72	12600
M5-A1	77	37	26	61	10.5	0.73	12600
M1-A0	78	38	25	61	11.5	0.69	13000
M2-A2	76	38	24	61	11.5	0.70	12800
M3-A2	75	36	25	61	11.4	0.72	13100
M4-A2	76	36	25	61	11.2	0.73	12600
M5-A2	76	36	25	61	11.6	0.73	12400
M1-A0	78	38	25	61	11.5	0.69	13000
M2-A3	75	36	24	61	10.0	0.70	12700
M3-A3	77	37	26	61	10.9	0.73	12900
M4-A3	75	36	24	61	11.8	0.72	12200
M5-A3	76	36	25	61	11.7	0.74	11800

FIG. 4-7 EXPERIMENTAL CORRECTED DATA AT PHI3, S1, and 2500 rpm.

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	78	36	28	57	9.3	0.78	14600
M2-A1	75	36	29	63	10.0	0.83	15200
M3-A1	74	36	27	61	10.4	0.79	14200
M4-A1	75	36	27	64	10.9	0.79	13900
M5-A1	74	36	27	64	10.8	0.80	13800
M1-A0	78	36	28	57	9.3	0.78	14600
M2-A2	76	36	27	61	10.5	0.78	14200
M3-A2	75	36	28	63	10.5	0.82	14500
M4-A2	76	37	28	65	10.5	0.81	14100
M5-A2	74	36	28	65	10.8	0.82	13800
M1-A0	78	36	28	57	9.3	0.78	14600
M2-A3	73	36	27	61	10.5	0.80	14500
M3-A3	74	36	29	62	10.4	0.82	14500
M4-A3	75	36	28	63	9.1	0.81	13800
M5-A3	75	36	28	65	10.6	0.83	13800

FIG. 4-8 EXPERIMENTAL CORRECTED DATA AT PHI5, S5, and 2500 rpm.

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	77	36	25	61	11.0	0.74	13800
M2-A1	76	36	26	66	11.7	0.75	13800
M3-A1	79	38	28	66	11.0	0.76	13600
M4-A1	77	36	27	66	11.3	0.78	13700
M5-A1	79	37	28	66	10.6	0.78	13400
M1-A0	77	36	25	61	11.0	0.74	13800
M2-A2	75	36	26	66	11.4	0.76	13900
M3-A2	81	38	27	66	11.1	0.75	13300
M4-A2	78	37	27	66	11.1	0.78	13500
M5-A2	80	38	29	63	10.1	0.77	12900
M1-A0	77	36	25	61	11.0	0.74	13800
M2-A3	78	37	27	66	11.1	0.77	13900
M3-A3	77	37	27	66	11.2	0.77	13600
M4-A3	78	37	28	65	10.6	0.8	13900
M5-A3	81	39	30	64	9.9	0.77	12700

FIG. 4-9 EXPERIMENTAL CORRECTED DATA AT PHI5, S3, and 2500 rpm.

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	80	38	25	56	10.3	0.70	13200
M2-A1	76	36	24	61	10.9	0.71	13100
M3-A1	77	36	24	61	11.4	0.72	12800
M4-A1	74	36	25	61	10.1	0.73	12800
M5-A1	76	37	27	61	10.7	0.75	12900
M1-A0	80	38	25	56	10.3	0.70	13200
M2-A2	77	37	26	61	11.0	0.72	13100
M3-A2	76	36	26	61	10.9	0.75	13300
M4-A2	77	37	27	61	10.6	0.76	13000
M5-A2	77	37	27	61	10.4	0.76	12900
M1-A0	80	38	25	56	10.3	0.70	13200
M2-A3	77	37	25	61	11.0	0.73	13300
M3-A3	76	36	25	61	11.0	0.74	13000
M4-A3	75	36	25	61	11.4	0.74	12600
M5-A3	76	36	26	61	10.9	0.75	12400

FIG. 4-10 EXPERIMENTAL CORRECTED DATA AT PHI5, S1, and 2500 rpm.

COND.	T LB FT	P HP	$\dot{m}_f$ LB/HR	$\dot{m}_a$ SCFM	A/F	BSFC LB/HP-HR	BSEC BTU/HP-HR
M1-A0	78	38	24	57	11.0	0.71	13300
M2-A1	78	37	24	60	10.5	0.72	13200
M3-A1	77	36	23	61	11.1	0.74	13300
M4-A1	77	36	26	61	10.7	0.76	13300
M5-A1	77	36	27	62	10.6	0.76	13000
M1-A0	78	38	24	57	11.0	0.71	13300
M2-A2	79	39	24	61	12.3	0.71	12900
M3-A2	77	36	26	61	11.0	0.75	13300
M4-A2	77	36	23	61	11.9	0.73	12600
M5-A2	75	36	27	61	11.0	0.76	12900
M1-A0	78	38	24	57	11.0	0.71	13300
M2-A3	75	38	25	61	11.2	0.73	13300
M3-A3	76	36	22	61	12.9	0.73	12900
M4-A3	77	36	22	61	12.6	0.75	12700
M5-A3	74	36	22	61	12.4	0.77	12700

TABLE 4-11 CARBONMONOXIDE IN PPM IN EXHAUST GASES-2500 RPM

	P1-S1	P3-S1	P5-S1	P1-S3	P3-S3	P5-S3	P1-S5	P3-S5	P5-S5
M1-A0	3480	3610	3870	3510	3640	4020	3650	3720	4210
M2-A1	2140	2470	2540	2280	2430	2680	2330	2440	2610
M3-A1	NA	2050	2180	2000	2250	2420	2260	2370	2430
M4-A1	NA	1590	1770	1670	1830	1940	NA	2190	2060
M5-A1	NA	1380	1500	NA	1510	1490	NA	1630	1700
M1-A0	3480	3610	3870	3510	3640	4020	3650	3720	4210
M2-A2	1980	2260	2390	2160	2360	2490	2200	2370	2530
M3-A2	NA	2030	2140	1970	2200	2350	2000	2110	2350
M4-A2	NA	1790	1860	1720	1850	1950	NA	1780	1940
M5-A2	NA	1450	1500	NA	1500	1610	NA	1450	1520
M1-A0	3480	3610	3870	3510	3640	4020	3650	3720	4210
M2-A3	1860	2300	2110	2200	2300	2400	2160	2370	2500
M3-A3	NA	1900	2340	1810	1900	2030	1870	2000	2350
M4-A3	NA	1500	1640	1410	1500	1650	NA	1690	1720
M5-A3	NA	1420	1390	NA	1420	1500	NA	1330	1490

NA: DATA WERE NOT AVAILABLE UNDER THE FOLLOWING CONDITIONS:

1- AT PHI1-S1 WHEN THE ALCOHOL EXCEEDS 5% IN THE FUEL.
2- AT PHI1-S3 WHEN THE ALCOHOL EXCEEDS 15% IN THE FUEL.
3- AT PHI1-S5 WHEN THE ALCOHOL EXCEEDS 10% IN THE FUEL.

TABLE 4-12 HYDROCARBON (PROPANE) IN PPM IN EXHAUST GASES - 2500 RRM

	P1-S1	P3-S1	P5-S1	P1-S3	P3-S3	P5-S3	P1-S5	P3-S5	P5-S5
M1-A0	1490	1470	1750	733	810	863	853	940	1030
M2-A1	1340	1413	1730	880	870	593	689	960	1100
M3-A1	NA	1440	1520	859	920	857	885	902	930
M4-A1	NA	1310	1380	642	940	842	NA	921	960
M5-A1	NA	1340	1420	NA	830	1200	NA	715	1010
M1-A0	1490	1470	1750	733	810	863	893	940	1030
M2-A2	1270	1314	1490	770	870	763	720	900	990
M3-A2	NA	1290	1550	837	882	917	692	941	1060
M4-A2	NA	1340	1460	1116	910	894	NA	1056	1100
M5-A2	NA	1430	1540	NA	980	986	NA	966	920
M1-A0	1490	1470	1750	733	810	863	893	940	1030
M2-A3	1200	1410	1460	589	930	846	860	885	1070
M3-A3	NA	1330	1510	866	931	896	723	974	1030
M4-A3	NA	1410	1590	886	1040	1210	NA	1120	1090
M5-A3	NA	1300	1430	NA	960	1084	NA	1060	1130

NA: DATA WERE NOT AVAILABLE UNDER THE FOLLOWING CONDITIONS:
1- AT PHI1-S1 WHEN THE ALCOHOL EXCEEDS 5% IN THE FUEL.
2- AT PHI1-S3 WHEN THE ALCOHOL EXCEEDS 15% IN THE FUEL.
3- AT PHI1-S5 WHEN THE ALCOHOL EXCEEDS 10% IN THE FUEL.

TABLE 4-13 ALDEHYDE IN PPM IN EXHAUST GASES - 2500 RPM

	P1-S1	P3-S1	P5-S1	P1-S3	P3-S3	P5-S3	P1-S5	P3-S5	P5-S5
M1-A0	280	260	250	320	280	250	370	330	280
M2-A1	500	440	410	530	460	440	560	520	490
M3-A1	NA	630	610	670	650	620	690	670	630
M4-A1	NA	740	720	810	770	740	NA	800	760
M5-A1	NA	890	870	NA	950	920	NA	980	950
M1-A0	280	260	250	320	280	250	370	330	280
M2-A2	480	440	420	520	460	430	550	480	470
M3-A2	NA	640	630	690	670	640	710	690	660
M4-A2	NA	750	710	800	770	740	NA	810	760
M5-A2	NA	910	900	NA	960	940	NA	980	960
M1-A0	280	260	250	320	280	250	370	330	280
M2-A3	520	460	400	540	460	410	580	510	540
M3-A3	NA	610	562	670	630	610	700	670	630
M4-A3	NA	740	690	780	750	740	NA	780	750
M5-A3	NA	800	780	NA	830	810	NA	870	860

NA: DATA WERE NOT AVAILABLE UNDER THE FOLLOWING CONDITIONS:
1- AT PHI1-S1 WHEN THE ALCOHOL EXCEEDS 5% IN THE FUEL.
2- AT PHI1-S3 WHEN THE ALCOHOL EXCEEDS 15% IN THE FUEL.
3- AT PHI1-S5 WHEN THE ALCOHOL EXCEEDS 10% IN THE FUEL.

CHAPTER V

DATA ANALYSIS

5.1 Introduction

The methods of statistical analysis were used to study the relationships between different variables.

Regression analysis is one of the principal types of analysis. Specific applications of this technique include linear regression (linear model) and multiple linear regression (general linear model). Choosing one or the other depends on the type and quantity of the data, type of variables, and the experimental system. The principles of experimental design have been employed in this work in an effort to provide the most information with the available resources.

Treatment selection involves the choice of the independent variables: equivalence ratio (ϕ), spark timing (S), percent of alcohol in the blend (M), and ratio of ethanol to methanol (A). In making this choice the levels that these variables experience experimentally has to be considered. Changes in the response variables (torque, BSFC, and BSEC) due to changes in the treatment level are called effects of the factor. Experiments containing all possible combinations of levels of factors are called factorial experiments.

5.2 Statistical Methods

According to the factorial design table (Fig. 4-3) the data were grouped into nine files with 614 observations and twelve variables (some of which are controlled): ϕ, S, M, A, fuel and air flow rate, A/F, power, torque, BSFC, H.V. and BSEC. The independent variables are torque, BSFC, and BSEC. The computing facilities of the Northeast Regional Data Center (NERDC) and the Statistical Analysis System (SAS) software were used to analyze the data.

5.2.1 General Linear Model (GLM) Procedure

The program in Appendix E was used to study the effect of the independent variables on the dependent variables. The program was applied on the nine files of the data.

The Classes = ϕ, S, M, A

The Model = Torque, BSFC, BSEC

Each model was tested among the different classes of the independent variables. From the GLM printout performed on the independent variables the following analysis was obtained:

Dependent Variable Torque, Table 5-1

1- The significance probability value (PR>F)=0.0001 is highly significant, i.e. the values of the independent variables (ϕ, S, M, & A), contribute most to the model. At PR>F = 0.0001 the risk for nonsignificance of the data is very small.

2- The ratio of regression sum square, (R-SQUARE) = 0.586, is very reasonable. In this case the data were obtained according to a discrete factorial design rather than as quasi-continuous, viz. with very small intervals. This permitted the effect of the independent

Table 5-1 Statistical Analysis of Torque.

```
                                      SAS    23:18 THURSDAY, MAY 2, 1985 2
                              GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: TORQUE

SOURCE                DF     SUM OF SQUARES          MEAN SQUARE    F VALUE

MODEL                 98     1372. 13389690          14.00136629       7.45

ERROR                515      967. 45079365           1.87854523     PR > F

CORRECTED TOTAL      613     2339. 58469055                         0. 0001

R-SQUARE             C.V.        ROOT MSE            TORQUE MEAN

0. 586486         1.9119       1. 37060032           71.68892508

SOURCE                DF          TYPE I SS    F VALUE     PR > F

PHI                    2      247. 11301184     65. 77    0. 0001
S                      2       65. 73575442     17. 50    0. 0001
PHI*S                  4      110. 72205687     14. 74    0. 0001
M                      4       56. 99399826      7. 58    0. 0001
PHI*M                  7       89. 93573710      6. 84    0. 0001
S*M                    8      222. 64598330     14. 82    0. 0001
PHI*S*M               11      115. 76883005      5. 60    0. 0001
A                      2       13. 08149469      3. 48    0. 0315
PHI*A                  4       67. 97012126      9. 05    0. 0001
S*A                    4       73. 19297747      9. 74    0. 0001
PHI*S*A                8       45. 64501809      3. 04    0. 0024
M*A                    6       23. 17604370      2. 06    0. 0568
PHI*M*A               10       54. 42190231      2. 90    0. 0016
S*M*A                 12      133. 13314689      5. 91    0. 0001
PHI*S*M*A             14       52. 59782065      2. 00    0. 0162

SOURCE                DF       TYPE III SS     F VALUE     PR > F

PHI                    2      158. 86531787     42. 28    0. 0001
S                      2       45. 59126701     12. 13    0. 0001
PHI*S                  4      103. 57183199     13. 78    0. 0001
M                      3        8. 38693983      1. 49    0. 2153
PHI*M                  5       19. 66544817      2. 09    0. 0641
S*M                    6      145. 36520550     12. 90    0. 0001
PHI*S*M                7      103. 60467197      7. 88    0. 0001
A                      2        9. 82395338      2. 61    0. 0742
PHI*A                  4       33. 58011116      4. 47    0. 0015
S*A                    4       53. 66766655      7. 14    0. 0001
PHI*S*A                8       68. 93940546      4. 59    0. 0001
M*A                    6       24. 00548319      2. 13    0. 0486
PHI*M*A               10       48. 81826594      2. 60    0. 0044
S*M*A                 12      128. 01270747      5. 68    0. 0001
PHI*S*M*A             14       52. 59782065      2. 00    0. 0162
```

variables on the dependent variables, torque, BSFC & BSEC to be investigated. The value of R-SQUARE indicates that torque is adequately represented as a linear function of the independent variables (ϕ, S, M & A).

3- The coefficient of variation, CV=1.912, measures the ratio of variation of the standard deviation of the mean value of torque expressed as a percentage. It indicates that the residual variation, 1.912, is within the accepted statistical range of less than 5%. In most published statistical work, statisticians regard the confidence interval of the coefficient of variation as up to 5%.

Dependent Variable BSFC, Table 5-2

1- The significance probability value, (PR>F)=0.001, is very significant.

2- Ratio of regression sum square, (R-SQUARE)=0.672, indicates that the value of BSFC is linear with the independent variables (ϕ, S, M & A).

3- Standard Deviation, $\sigma=0.0596$, has a slightly higher value, than normal because the rate of fuel consumption was irregular, especially when the percent of alcohol in the blend exceeded 10%. This was due to the design of the metering system (carburetor and intake manifold) of the engine. Some of the data were not available at specific conditions (as shown in tables 4-3 to 4-5), since the engine was not running at 2500 rpm and WOT.

4- Coefficient of variation, CV=7.942, is higher than the normal value (± 5% of the sample value) for the same reasons mentioned in item 3.

Table 5-2 Statistical Analysis of BSFC.

```
                              SAS    23:18 THURSDAY, MAY 2, 1985 3
                      GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: BSFC

SOURCE              DF     SUM OF SQUARES        MEAN SQUARE   F VALUE

MODEL               98         3. 75632834        0. 03832988    10. 78

ERROR              515         1. 83196563        0. 00355721    PR > F

CORRECTED TOTAL    613         5. 58829397                      0. 0001

R-SQUARE          C.V.          ROOT MSE            BSFC MEAN

0. 672178       7.9418      0. 05964239          0. 75099349

SOURCE              DF          TYPE I SS    F VALUE    PR > F

PHI                  2      0. 13524137      19. 01    0. 0001
S                    2      0. 13468453      18. 93    0. 0001
PHI*S                4      0. 27195993      19. 11    0. 0001
M                    4      0. 31077922      21. 84    0. 0001
PHI*M                7      0. 48245456      19. 38    0. 0001
S*M                  8      0. 54407930      19. 12    0. 0001
PHI*S*M             11      1. 64010441      41. 91    0. 0001
A                    2      0. 00804537       1. 13    0. 3236
PHI*A                4      0. 04290293       3. 24    0. 0123
S*A                  4      0. 04603695       3. 02    0. 0178
PHI*S*A              8      0. 07011489       2. 46    0. 0126
M*A                  6      0. 01188903       0. 56    0. 7646
PHI*M*A             10      0. 01670001       0. 47    0. 9097
S*M*A               12      0. 02306795       0. 54    0. 8884
PHI*S*M*A           14      0. 01826789       0. 37    0. 9833

SOURCE              DF      TYPE III SS    F VALUE    PR > F

PHI                  2      0. 04093429       5. 75    0. 0034
S                    2      0. 51342756      72. 17    0. 0001
PHI*S                4      0. 76520731      53. 78    0. 0001
M                    3      0. 04590154       4. 30    0. 0054
PHI*M                5      0. 00496147       0. 28    0. 9239
S*M                  6      0. 00289323       0. 14    0. 9916
PHI*S*M              7      0. 01330827       0. 53    0. 8099
A                    2      0. 00632518       0. 89    0. 4117
PHI*A                4      0. 01578774       1. 11    0. 3512
S*A                  4      0. 03912375       2. 75    0. 0277
PHI*S*A              8      0. 04838215       1. 70    0. 0957
M*A                  6      0. 01439564       0. 67    0. 6704
PHI*M*A             10      0. 01928081       0. 54    0. 8604
S*M*A               12      0. 02438350       0. 57    0. 8657
PHI*S*M*A           14      0. 01826789       0. 37    0. 9833
```

Dependent Variable BSEC, Table 5-3

1- The significance probability value, (PR>F)=0.0001, is significant at the same level as that of torque.

2- Ratio of regression sum square, (R-SQUARE) = 0.0705, indicates that the value of BSEC is linear with the independent variables ϕ, S, M & A.

3- Standard Deviation, σ=1055.665, has a slightly higher value than the normal as was indicated in the case of BSFC.

4- Coefficient of Variation, CV=7.933%, is higher than the normal value (5% of the sample value) for the same reason as in item 3 in the case of BSFC.

5.2.2 Higher Order Interaction

A program was designed to study the higher order interaction between the dependent variables and the independent variables. The results are shown in Tables 5-1, 5-2, and 5-3.

Dependent Variable, Torque

From Table 5-1, two types of sum of squares were used, type I (sequential sum of squares) and type III (partial sum of squares). The significance probability value, PR>F, in both types indicates that the higher order interactions (ϕ x S x M x A) are very significant except for the interaction between torque and M x A, in type I, and the interaction between torque and M, in type III. In these two cases the values of PR>F exceeded the confidence ratio [(PR>F)<0.05], i.e., not significant at 95% confidence level. The reason for the insignificant interaction in these two cases may be the lack of data (the engine was not running at 2500 rpm at ϕ_1-S_1 conditions when the percent of

Table 5-3 Statistical Analysis of BSEC.

```
                                      SAS    23:18 THURSDAY, MAY 2, 1985 4
                              GENERAL LINEAR MODELS PROCEDURE
DEPENDENT VARIABLE: BSEC

SOURCE                 DF        SUM OF SQUARES          MEAN SQUARE    F VALUE

MODEL                  98 1368968643. 9299938   13969067. 7952040      12. 53

ERROR                 515  573931242. 0635059    1114429. 5962398      PR > F

CORRECTED TOTAL       613 1942899885. 9934997                          0. 0001

R-SQUARE             C.V.            ROOT MSE              BSEC MEAN

0. 704601          7.9332        1055. 6654755        13307. 00325733

SOURCE                 DF             TYPE I SS    F VALUE     PR > F

PHI                     2    12613020. 5424411       5. 66     0. 0037
S                       2    49486597. 7749037      22. 20     0. 0001
PHI*S                   4   101144727. 3672698      22. 69     0. 0001
M                       4   181223425. 6740374      40. 65     0. 0001
PHI*M                   7   173898192. 7913066      22. 29     0. 0001
S*M                     8   177247551. 3871388      19. 88     0. 0001
PHI*S*M                11   596866455. 5489928      48. 69     0. 0001
A                       2     6893165. 7058181       3. 09     0. 0462
PHI*A                   4    13058564. 2352860       2. 93     0. 0205
S*A                     4    13300828. 4205064       2. 98     0. 0187
PHI*S*A                 8    20648047. 8495670       2. 32     0. 0190
M*A                     6     3235758. 2423945       0. 48     0. 8205
PHI*M*A                10     5197550. 4439856       0. 47     0. 9116
S*M*A                  12     7574810. 2418926       0. 57     0. 8694
PHI*S*M*A              14     6579947. 7044537       0. 42     0. 9680

SOURCE                 DF           TYPE III SS    F VALUE     PR > F

PHI                     2    15278344. 9950861       6. 85     0. 0012
S                       2   173855281. 5596987      78. 00     0. 0001
PHI*S                   4   283561548. 6743358      63. 61     0. 0001
M                       3    19850918. 0721632       5. 94     0. 0006
PHI*M                   5     1981227. 3159542       0. 36     0. 8792
S*M                     6     1312076. 3814885       0. 20     0. 9778
PHI*S*M                 7     5243046. 8441083       0. 67     0. 6976
A                       2     7171996. 1674738       3. 22     0. 0408
PHI*A                   4     6663312. 8000060       1. 49     0. 2024
S*A                     4    11887855. 2141109       2. 67     0. 0317
PHI*S*A                 8    14000145. 4158741       1. 57     0. 1309
M*A                     6     3563760. 2150913       0. 53     0. 7833
PHI*M*A                10     5857436. 6958662       0. 52     0. 8731
S*M*A                  12     7884318. 7314951       0. 59     0. 8513
PHI*S*M*A              14     6579947. 7044537       0. 42     0. 9680
```

alcohol was more than 10% in the blend) and also may be due to the large number of independent variables (ϕ,S,M,&A) in the study.

Dependent Variables BSFC & BSEC

From tables 5-2, 5-3 the significance probability values, PR>F, in both types of sum of squares show that the interactions of each of the individual independent variables are very significant. The high order of interaction is not significant, probably because of the lack of M data, the large number of independent variables, and the effect of A. The interaction of A as an individual parameter is strong, but when compared to the other independent variables it shows the least interaction, i.e., changing the kind of alcohol, does not so greatly affect the dependent variables.

5.3 Analysis of Exhaust Gas Data

The experimental study was designed to show the change in chemical composition of exhaust emissions at all tested conditions. Sampling, analysis, interpretation techniques, and the equipment used were explained in Chapter IV.

5.3.1 Interpretation of Carbon Monoxide (CO) in Exhaust Gases

Figures 5-1, 5-2, and 5-3 (retard, normal, and advance spark timing, respectively) show that carbon monoxide emissions were primarily a function of the equivalence ratio (ϕ) where carbon monoxide production increases on the rich side. The presence of methanol and ethanol reduced carbon monoxide production, probably because those molecules are rich in oxygen (Appendix A). Such reduction was not dramatic for all alcohol-gasoline blends (ethanol, methanol or 50% of each). It was found that as the mixture was leaned out either with methanol or ethanol, very low levels of carbon monoxide could be reached (Figs. 5-4,5-5, and 5-6). However, it was not possible to go leaner with

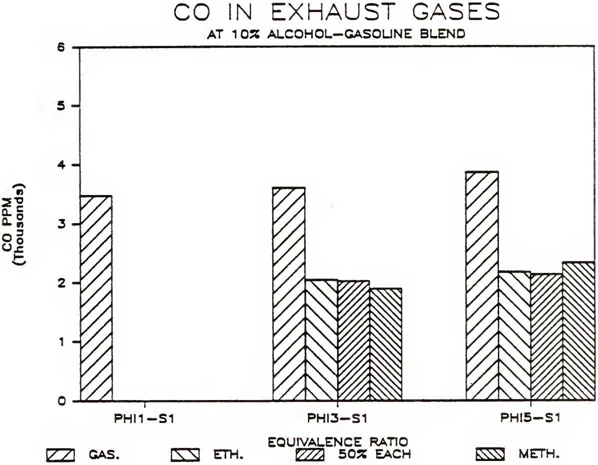


FIG. 5-1 PRODUCTION OF CO AT DIFFERENT EQUIVALENCE RATIOS AND RETARD SPARK TIMING

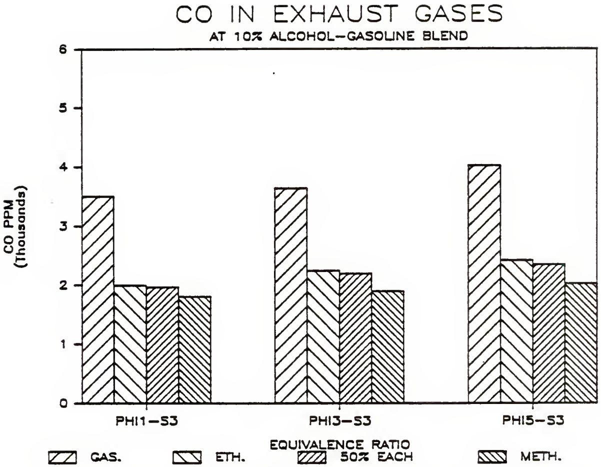


FIG. 5-2 PRODUCTION OF CO AT DIFFERENT EQUIVALENCE RATIOS AND NORMAL SPARK TIMING

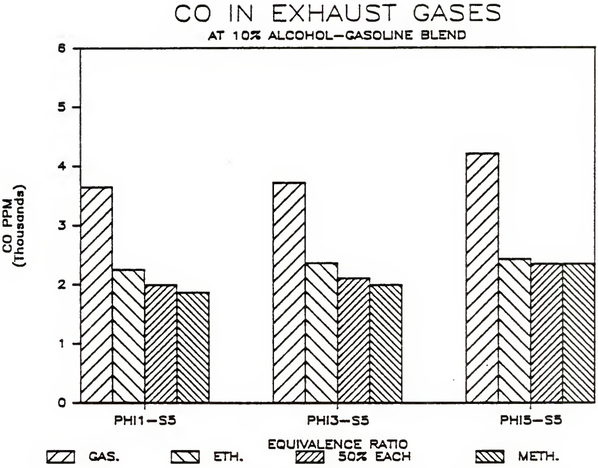


FIG. 5-3 PRODUCTION OF CO AT DIFFERENT EQUIVALENCE RATIOS AND ADVANCE SPARK TIMING

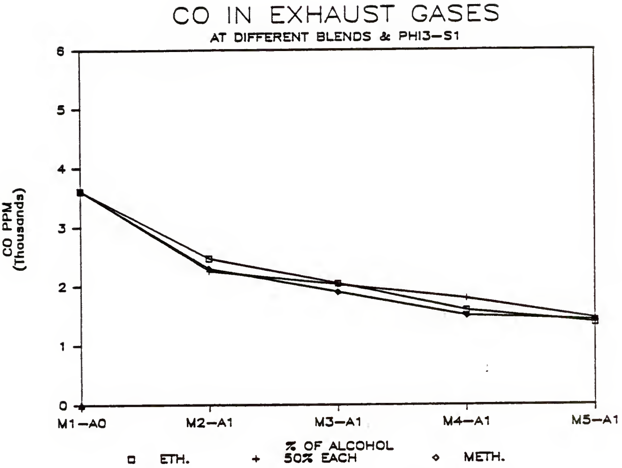


FIG. 5-4 PRODUCTION OF CO WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT RETARD SPARK TIMING

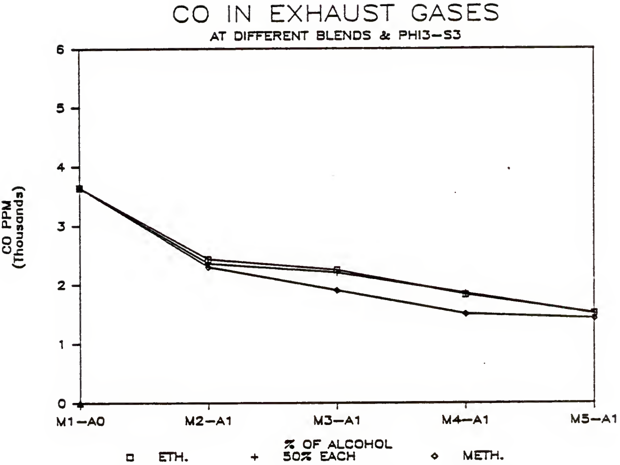


FIG. 5-5 PRODUCTION OF CO WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT NORMAL SPARK TIMING

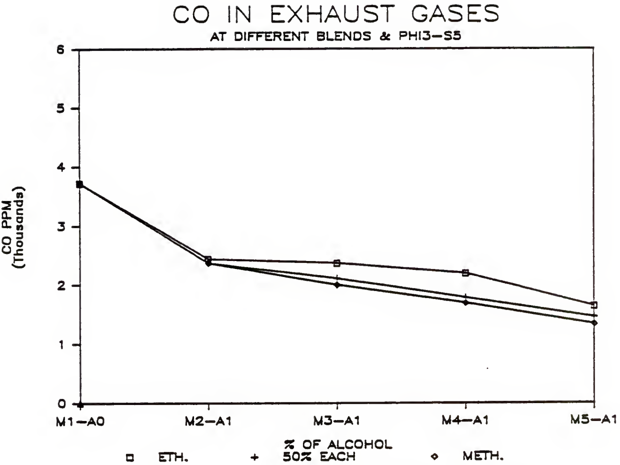


FIG. 5-6 PRODUCTION OF CO WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT ADVANCE SPARK TIMING

alcohol without a drivability (engine running) problem. The results are consistent with the literature (1,16,17).

5.3.2 Interpretation of Hydrocarbon (HC) in Exhaust Gases

From Figs. 5-7, 5-8, 5-9, it is seen that hydrocarbon production increased as the air-fuel ratios changed from lean to rich. The presence of alcohol in the blend did not cause a large change in the production of HC. In the case of retarded spark timing (Fig. 5-8), the production of HC in the exhaust gases was less with alcohol-gasoline blends than with gasoline fuel due to the leaning effect of the blend. In the case of normal and rich air-fuel ratios (Figs. 5-8 and 5-9), there was an increase in HC production as compared to gasoline. This increase may be due to the leaning effect of alcohol and/or of the alcohol's role in increasing pressure of vapor of the fuel which is being ingested into the engine and increases the HC production. This observation is in agreement with the results reported elsewhere (1,16,17,28,70).

The production of HC was slightly decreased with the increase of alcohol in the blend at retarded spark settings (Fig. 5-10). HC was slightly increased with the increase of the alcohol percent in the blend at standard and advance spark timing (Fig. 5-11, 5-12). There is no reasonable explanation for this result. The literature suggests that HC production depends primarily on the metering systems and engine configuration.

5.3.3 Interpretation of Aldehyde (CHO) in Exhaust Gases

Aldehyde emissions were markedly higher with the alcohol-gasoline blends than with gasoline (Figs. 5-13, 5-14, 5-15). This result is in agreement with other findings (1,2,6,12,16,17,28,36,77). It is probably due to the alcohol's high latent heat of vaporization which

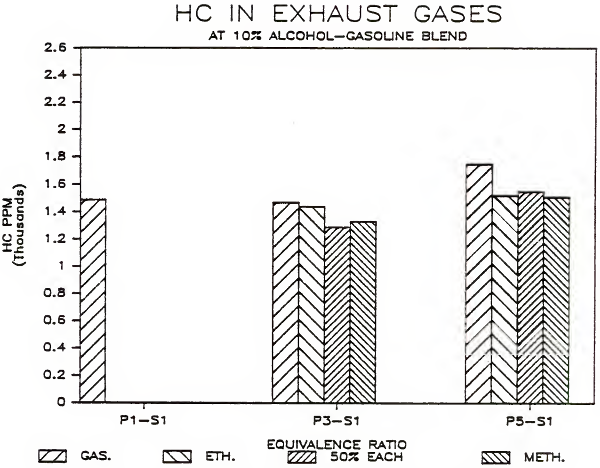


FIG. 5-7 PRODUCTION OF HC AT DIFFERENT EQUIVALENCE RATIOS AND RETARD SPARK TIMING

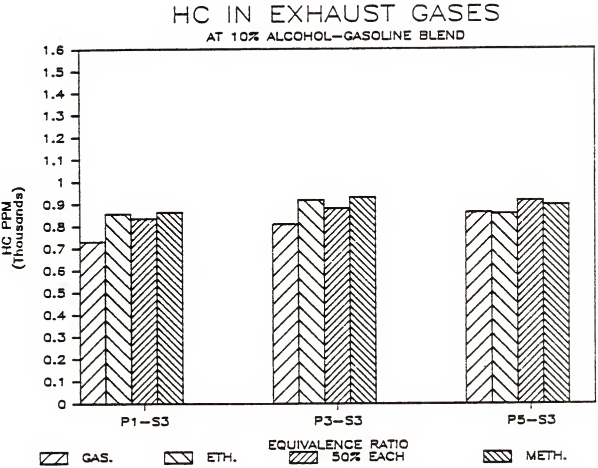


FIG. 5-8 PRODUCTION OF HC AT DIFFERENT EQUIVALENCE RATIOS AND NORMAL SPARK TIMING

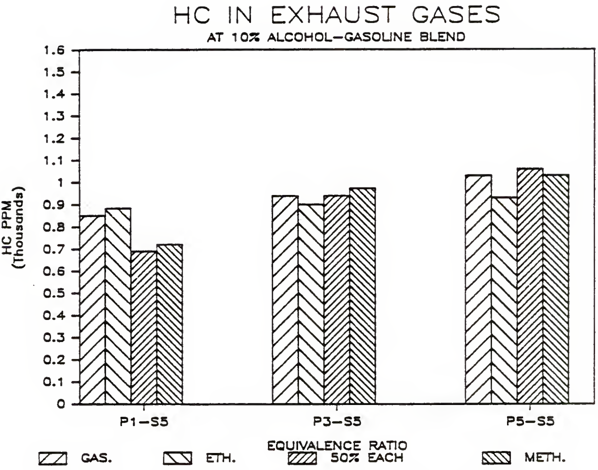


FIG. 5-9 PRODUCTION OF HC AT DIFFERENT EQUIVALENCE RATIOS AND ADVANCE SPARK TIMING

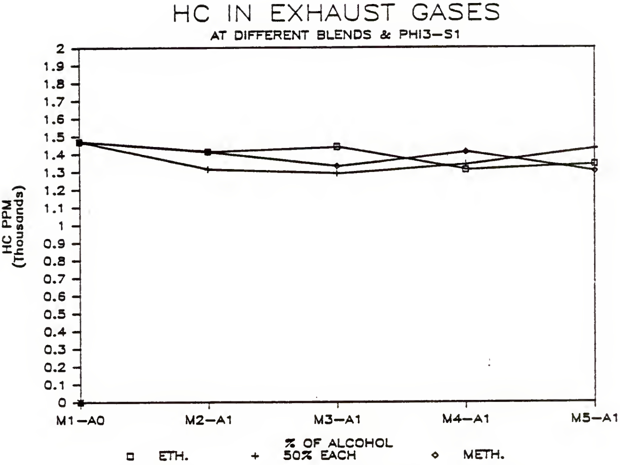


FIG. 5-10 PRODUCTION OF HC WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT RETARD SPARK TIMING

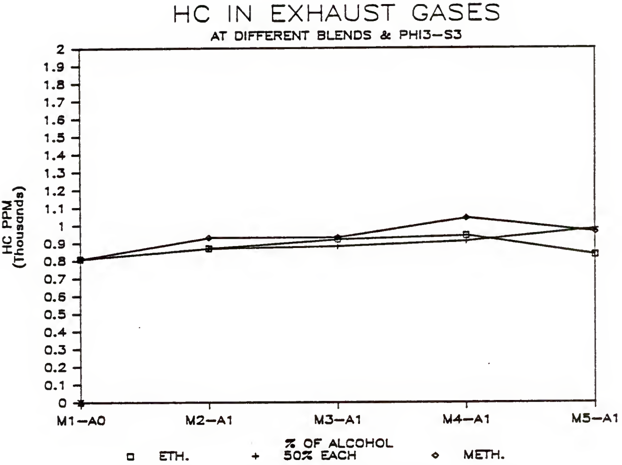


FIG. 5-11 PRODUCTION OF HC WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT NORMAL SPARK TIMING.

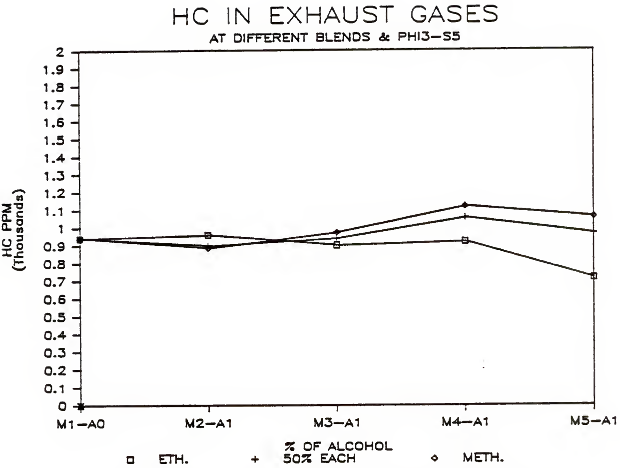


FIG. 5-12 PRODUCTION OF HC WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT ADVANCE SPARK TIMING

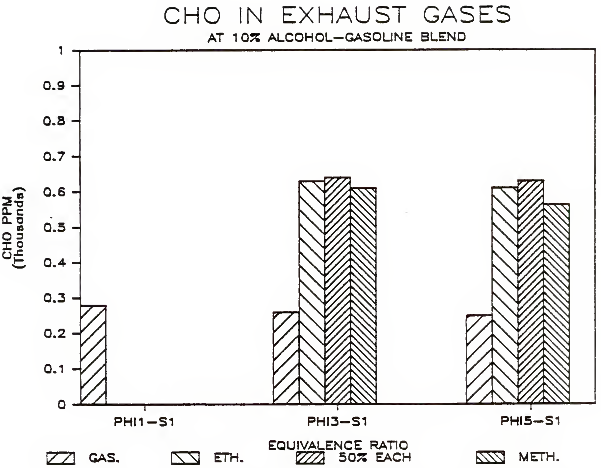


FIG. 5-13 PRODUCTION OF CHO AT DIFFERENT EQUIVALENCE RATIOS AND RETARD SPARK TIMING.

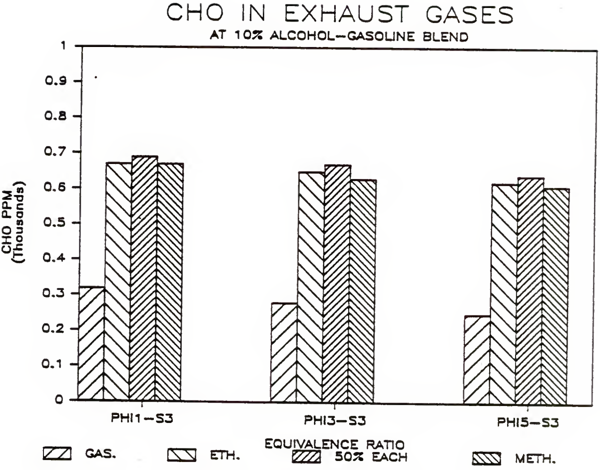


FIG. 5-14 PRODUCTION OF CHO AT DIFFERENT EQUIVALENCE RATIOS AND NORMAL SPARK TIMING.

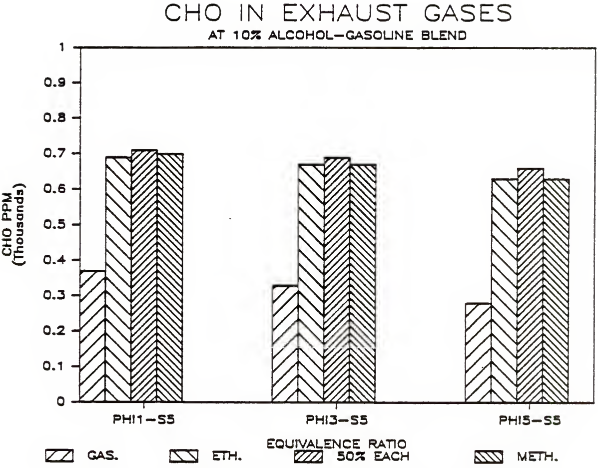


FIG. 5-15 PRODUCTION OF CHO AT DIFFERENT ALCOHOL-RATIOS AND ADVANCE SPARK TIMING.

reduces the maximum combustion temperature. Accordingly, the quench layer increases where the aldehydes are being formed. Another reason for this is that alcohol is oxidized through aldehyde formation (Appendix A). The aldehyde production decreases with the rich mixture (54,55,56) due to the increase of of combustion temperature and consequently to the decrease of the quench layer on the internal surface of the combustion chamber. Aldehyde production is also increased with increased ratio of alcohol in the alcohol-gasoline blend and with increased spark advance (Figs. 5-16, 5-17, 5-18).

5.4 Experimental Error Analysis

All measurements inevitably involve experimental uncertainity. In this section the uncertainity of each independent variable is discussed as well as computations relating each to the net uncertainty of the dependent variables.

Accuracy of results may be affected by two different type of errors:

Systematic error

Random error

The systematic error was very small due to the frequent and precise calibrations always done on the equipment according to the manufacturers suggestions. The equipment was designed to simplify the periodic check-out and calibration. The errors which occurred in the results were assumed to be mostly of a random nature. For instance, the load applied to the engine and the speed were constant, but some results read differently. This was due to random error. Random error may have been introduced as a result of characteristics or malfunctioning of equipment and instruments.

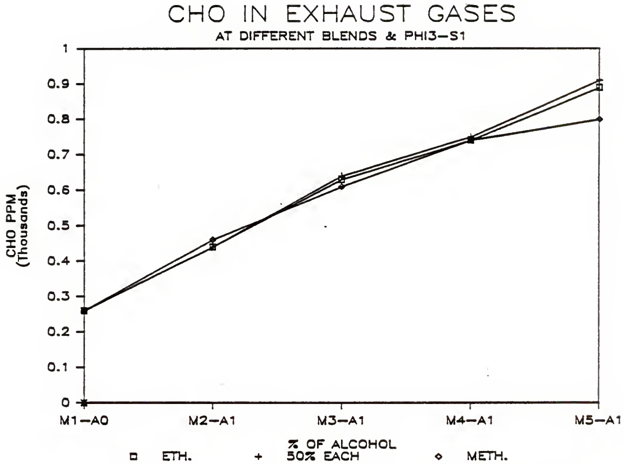


FIG. 5-16 PRODUCTION OF CHO WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT RETARD SPARK TIMING

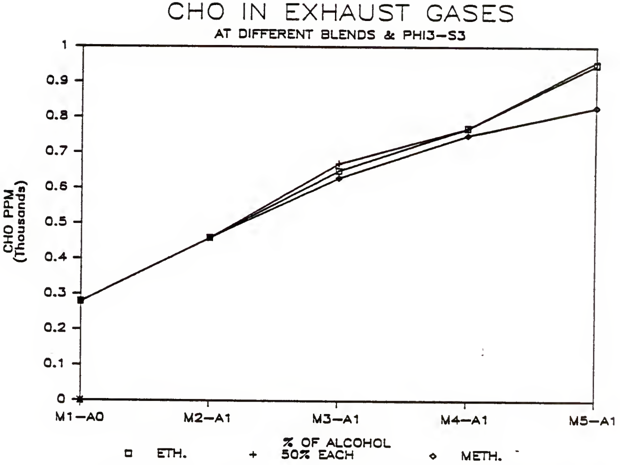


FIG. 5-17 PRODUCTION OF CHO WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT NORMAL SPARK TIMING.

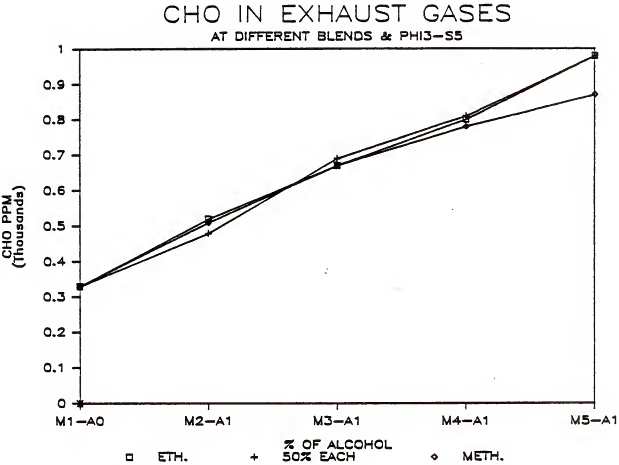


FIG. 5-18 PRODUCTION OF CHO WITH DIFFERENT ALCOHOL-GASOLINE BLENDS AT ADVANCE SPARK TIMING

The principal random error arose from the characteristics of fuel (alcohol-gasoline blend) flow. The excess vapor pressure associated with alcohol in the fuel blends caused the fuel pump to partially malfunction which affected the speed of the engine (fluctuation around the 2500 rpm set point) due to the fuel flow fluctuation.

The engine was run for a relatively long time to reach as stable a speed as possible before beginning to record data. This change in the flow rate fluctuation, nevertheless, probably caused the greatest error in the results, up to 6%.

Samples of exhaust gases were taken and kept from 6 to 8 hours in syringes before the chemical analysis was done. This delay time may affect the life time of molecular species. The gas chromatograph condition also could have introduced error in the values of the species due to malfunctioning of the column or other accessories. Errors which may have been introduced for these reasons were minimized by regular checks of the equipment. It has been assumed that excess random error in chemical analysis is 7% besides the other uncertainities while measuring the peak heights from the charts, concentration of the standard gases, and the volume injected in the column of the standard gas and the sample.

Calculations of the uncertainity of the dependent variable results are presented in Appendix E and the values of uncertainty are tabulated in Tables 5-4 to 5-11 and graphed in Figs. 5-20 to 5-42.

TABLE 5-4 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phil, S3, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	77	4.2	0.73	0.14	13700	2400
M2-A1	77	5.5	0.73	0.2	13300	2500
M3-A1	76	3.7	0.71	0.04	12800	800
M4-A1	75	2.8	0.7	0.04	12200	1000
M5-A1	NA	NA	NA	NA	NA	NA
M2-A2	73	2.6	0.73	0.18	13300	2100
M3-A2	74	2.3	0.73	0.1	13100	1600
M4-A2	75	2.8	0.73	0.08	12600	1300
M5-A2	NA	NA	NA	NA	NA	NA
M2-A3	73	2.8	0.71	0.04	12800	900
M3-A3	74	1.5	0.71	0.01	12600	800
M4-A3	73	2.8	0.73	0.04	12500	200
M5-A3	NA	NA	NA	NA	NA	NA

NA: THE ENGINE WOULD NOT RUN AT 2500 RPM AT WOT WHEN THE ALCOHOL EXCEEDED 15% IN ALCOHOL-GASOLINE BLEND .i.e THE MAXIMUM POWER WAS SOMEWHAT LESS THAN THE PREDETERMINED VALUE.

TABLE 5-5 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phil, S5, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	76	3.2	0.68	0.06	12700	1100
M2-A1	76	2.7	0.7	0.06	12700	1300
M3-A1	76	2.8	0.69	0.01	12400	200
M4-A1	NA	NA	NA	NA	NA	NA
M5-A1	NA	NA	NA	NA	NA	NA
M2-A2	74	7.5	0.69	0.1	12600	2000
M3-A2	77	2.2	0.71	0.04	12700	700
M4-A2	NA	NA	NA	NA	NA	NA
M5-A2	NA	NA	NA	NA	NA	NA
M2-A3	76	2.5	0.69	0.01	12500	200
M3-A3	77	2.3	0.71	0.18	11900	1700
M4-A3	NA	NA	NA	NA	NA	NA
M5-A3	NA	NA	NA	NA	NA	NA

NA: THE ENGINE WOULD NOT RUN AT 2500 RPM AT WOT WHEN THE ALCOHOL EXCEEDED 10% IN ALCOHOL-GASOLINE BLEND .i.e THE MAXIMUM POWER WAS SOMEWHAT LESS THAN THE PREDETERMINED VALUE.

TABLE 5-6 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phi3, S5, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	75	1.47	0.73	0.01	13700	200
M2-A1	74	2.5	0.74	0.06	13500	1100
M3-A1	75	2.3	0.72	0.06	12900	1100
M4-A1	74	2.6	0.73	0.06	12800	900
M5-A1	74	2.5	0.74	0.09	12700	1500
M2-A2	73	2.9	0.79	0.09	14500	1500
M3-A2	74	2.6	0.79	0.12	14000	2000
M4-A2	74	2.6	0.76	0.14	13100	2100
M5-A2	74	2.5	0.83	0.12	14000	2300
M2-A3	75	2.5	0.71	4.04	12900	900
M3-A3	73	2.3	0.78	0.14	13800	2000
M4-A3	74	2.6	0.82	0.15	14000	2100
M5-A3	75	2.2	0.82	0.15	13700	2300

TABLE 5-7 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phi3, S3, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	78	3.3	0.69	0.1	13000	1700
M2-A1	74	2.1	0.7	0.04	12900	800
M3-A1	75	2.8	0.72	0.04	12900	700
M4-A1	76	2.6	0.72	0.04	12600	700
M5-A1	77	2.6	0.73	0.04	12600	800
M2-A2	76	2.2	0.7	0.04	12800	700
M3-A2	75	2.6	0.72	0.1	13100	1100
M4-A2	76	1.9	0.73	0.1	12600	1400
M5-A2	76	1.5	0.73	0.1	12400	1500
M2-A3	75	2.8	0.7	0.04	12700	700
M3-A3	77	2.5	0.73	0.08	12900	1300
M4-A3	75	1.5	0.72	0.08	12200	1500
M5-A3	76	1.5	0.74	0.14	11800	1600

TABLE 5-8 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phi3, S1, AND 2500 RPM

COND.	T LB FT	Tunc LB FT	BSFC LB/HP-HR	BSFCunc LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	78	1.5	0.78	0.01	14600	200
M2-A1	75	3.8	0.83	0.08	15200	1500
M3-A1	74	1.5	0.79	0.14	14200	1400
M4-A1	75	2.5	0.79	0.14	13900	1600
M5-A1	74	2.2	0.8	0.14	13800	1500
M2-A2	76	1.5	0.78	0.12	14200	1300
M3-A2	75	3	0.82	0.16	14500	1800
M4-A2	76	3.8	0.81	0.1	14100	1600
M5-A2	74	3.2	0.82	0.12	13800	1200
M2-A3	73	2.5	0.8	0.1	14500	1800
M3-A3	74	2.2	0.82	0.2	14500	1400
M4-A3	75	3.7	0.81	0.18	13800	1900
M5-A3	75	3.8	0.83	0.2	13800	2200

TABLE 5-9 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phi5, S5, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	77	1.5	0.74	0.06	13800	110
M2-A1	76	2.5	0.75	0.1	13800	1400
M3-A1	79	1.5	0.76	0.06	13600	1000
M4-A1	77	1.5	0.78	0.01	13700	200
M5-A1	79	2.5	0.78	0.1	13400	1200
M2-A2	75	2.5	0.76	0.1	13900	1600
M3-A2	81	2.5	0.75	0.06	13300	900
M4-A2	78	2.5	0.78	0.08	13500	1100
M5-A2	80	2.5	0.77	0.12	12900	1400
M2-A3	78	3.5	0.77	0.12	13900	1400
M3-A3	77	3.6	0.77	0.12	13600	1600
M4-A3	78	2.5	0.8	0.14	13900	1500
M5-A3	81	3.6	0.77	0.14	12700	1600

TABLE 5-10 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phi5, S3, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	80	3.3	0.7	0.1	13200	1400
M2-A1	76	2.3	0.71	0.04	13100	1900
M3-A1	77	3.5	0.72	0.1	12800	1500
M4-A1	74	1.5	0.73	0.06	12800	1000
M5-A1	76	3.5	0.75	0.06	12900	800
M2-A2	77	2.5	0.72	0.06	13100	1200
M3-A2	76	1.5	0.75	0.08	13300	1200
M4-A2	77	3.2	0.76	0.1	13000	1300
M5-A2	77	2.6	0.76	0.1	12900	1500
M2-A3	77	3.3	0.73	0.1	13300	1500
M3-A3	76	2.2	0.74	0.08	13000	1100
M4-A3	75	3.2	0.74	0.12	12600	1600
M5-A3	76	2.3	0.75	0.06	12400	900

TABLE 5-11 UNCERTAINTY OF INDEPENDENT VARIABLES AT Phi5, S1, AND 2500 RPM

COND.	T LB FT	T_{unc} LB FT	BSFC LB/HP-HR	$BSFC_{unc}$ LB/HP-HR	BSEC BTU/HP-HR	$BSEC_{unc}$ BTU/HP-HR
M1-A0	78	2.3	0.71	0.04	13300	1400
M2-A1	78	3.2	0.72	0.08	13200	1400
M3-A1	77	2.3	0.74	0.04	13300	800
M4-A1	77	1.5	0.76	0.06	13300	900
M5-A1	77	3.5	0.76	0.06	13000	900
M2-A2	79	2.2	0.71	0.1	12900	1200
M3-A2	77	1.5	0.75	0.06	13300	900
M4-A2	77	1.5	0.73	0.01	12600	200
M5-A2	75	1.5	0.76	0.08	12900	1400
M2-A3	75	1.5	0.73	0.01	13300	200
M3-A3	76	2.6	0.73	0.06	12900	900
M4-A3	77	2.2	0.75	0.02	12700	400
M5-A3	74	2.6	0.77	0.15	12700	2100

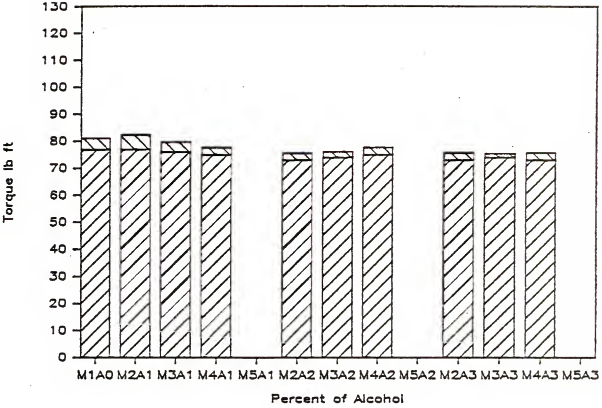


FIG. 5-19 UNCERTAINTY IN TORQUE VALUES AT PHI1, S3, AND 2500 RPM.

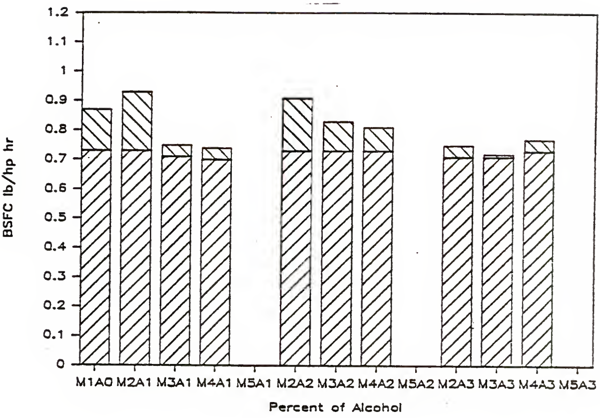


FIG. 5-20 UNCERTAINTY IN BSFC VALUES AT PHI1, S3, AND 2500 RPM.

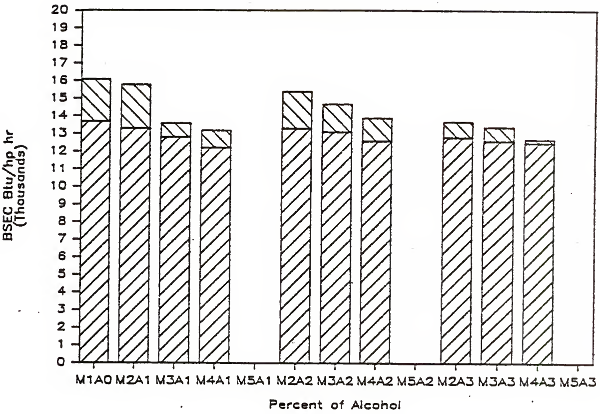


FIG. 5-21 UNCERTAINTY IN BSEC VALUES AT PHI1, S3, AND 2500 RPM.

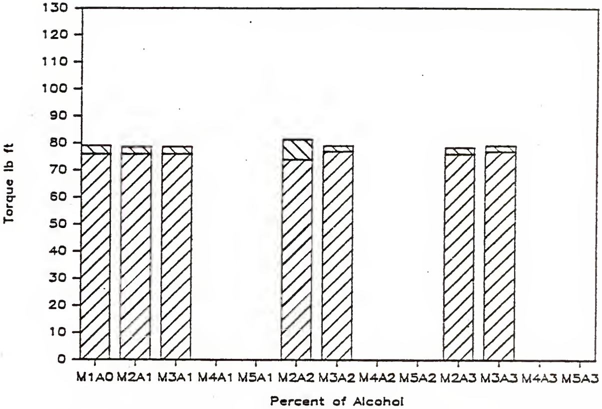


FIG. 5-22 UNCERTAINTY IN TORQUE VALUES AT PHI1, S5, AND 2500 RPM.

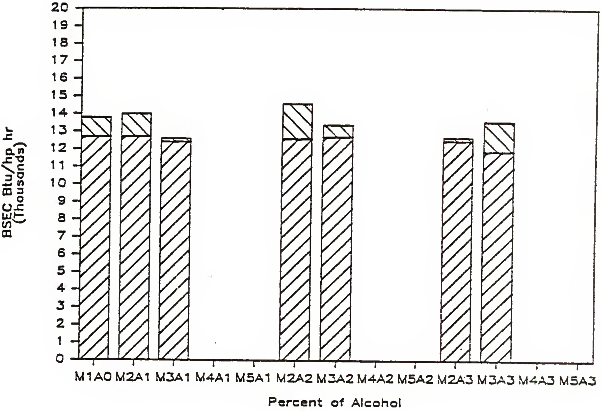


FIG. 5-23 UNCERTAINTY IN BSEC VALUES AT PHI1, S5, AND 2500 RPM.

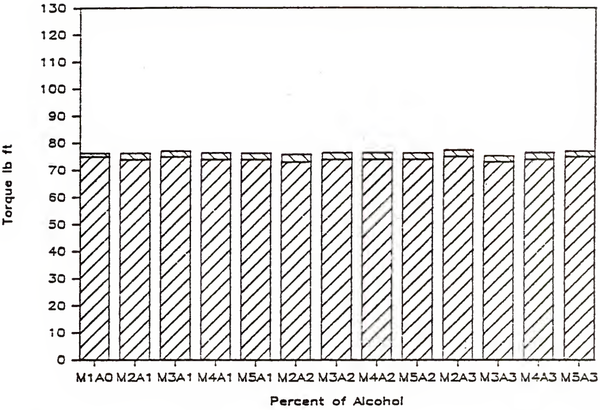


FIG. 5-24 UNCERTAINTY IN TORQUE VALUES AT PHI3, S5, AND 2500 RPM.

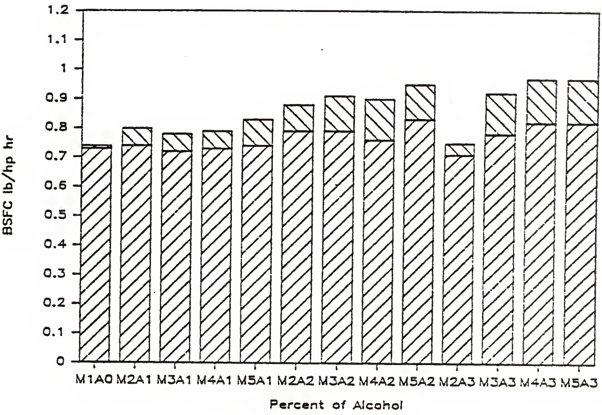


FIG. 5-25 UNCERTAINTY IN BSFC VALUES AT PHI3, S5, AND 2500 RPM.

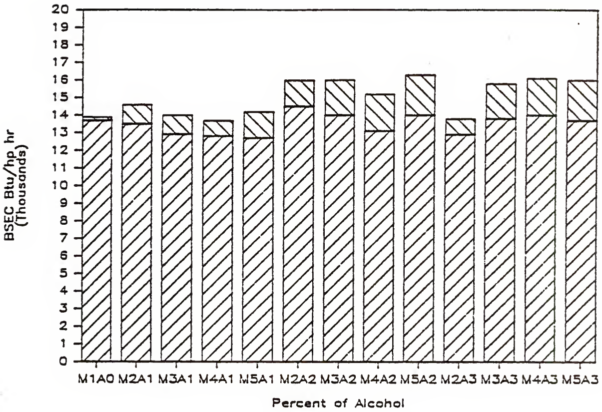


FIG. 5-26 UNCERTAINTY IN BSEC VALUES AT PHI3, S5, and 2500 RPM.

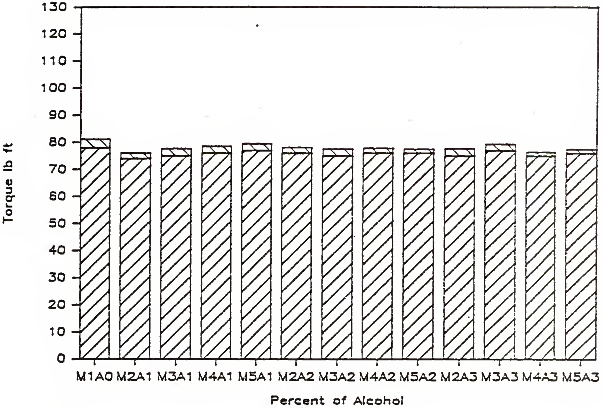


FIG. 5-27 UNCERTAINTY IN TORQUE VALUES AT PHI3, S3, AND 2500 RPM.

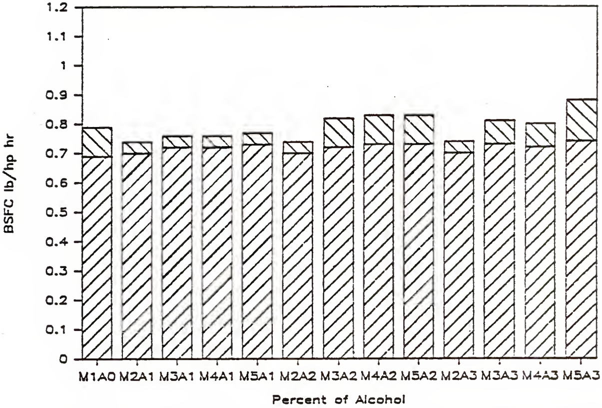


FIG. 5-28 UNCERTAINTY IN BSFC VALUES AT PHI3, S3, AND 2500 RPM.

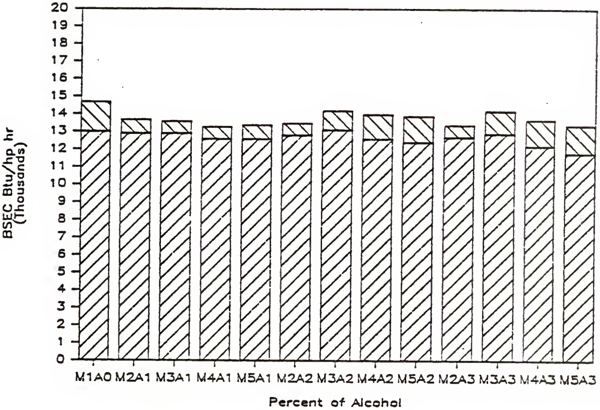


FIG. 5-29 UNCERTAINTY IN BSEC VALUES AT PHI3, S3, AND 2500 RPM.

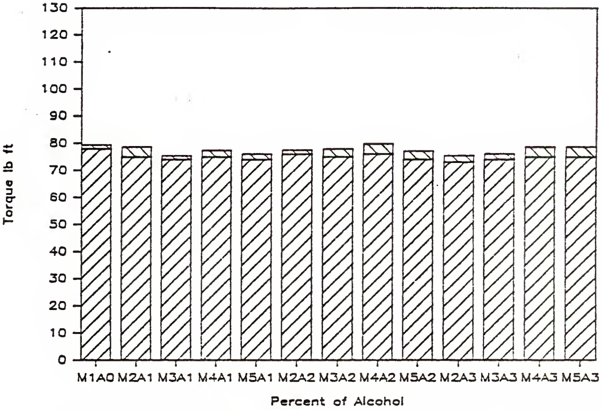


FIG. 5-30 UNCERTAINTY IN TORQUE VALUES AT PHI3, S1, AND 2500 RPM.

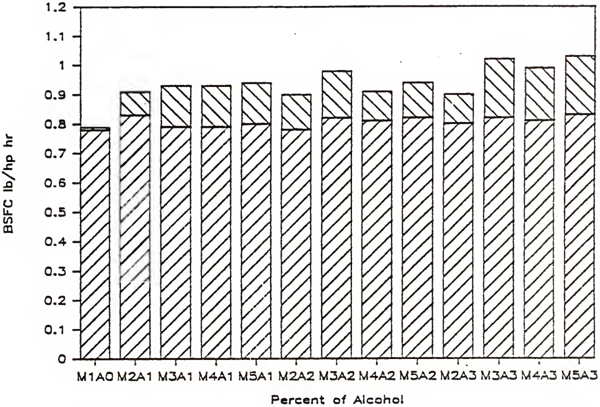


FIG. 5-31 UNCERTAINTY IN BSFC VALUES AT PHI3, S1, AND 2500 RPM.

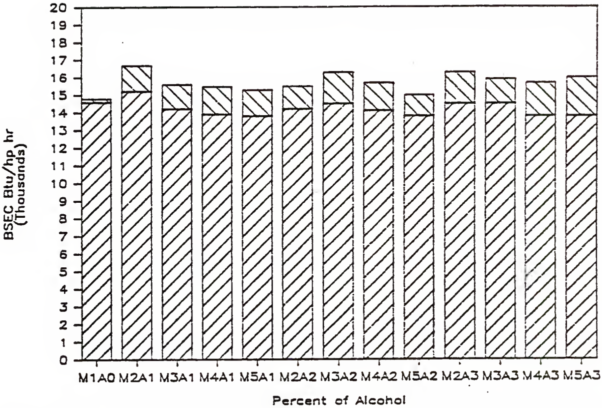


FIG. 5-32 UNCERTAINTY IN BSEC VALUES AT PHI3, S1, AND 2500 RPM.

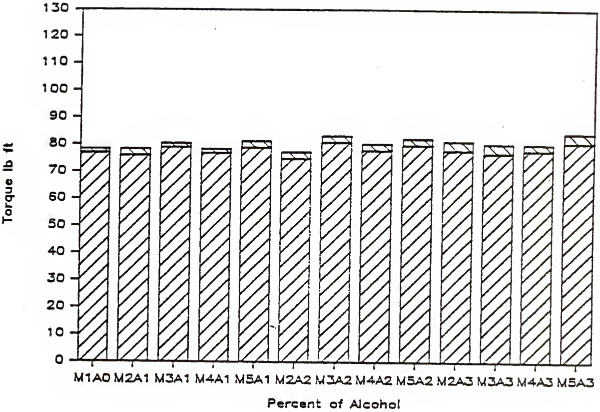


FIG. 5-33 UNCERTAINTY IN TORQUE VALUES AT PHI5, S5, AND 2500 RPM.

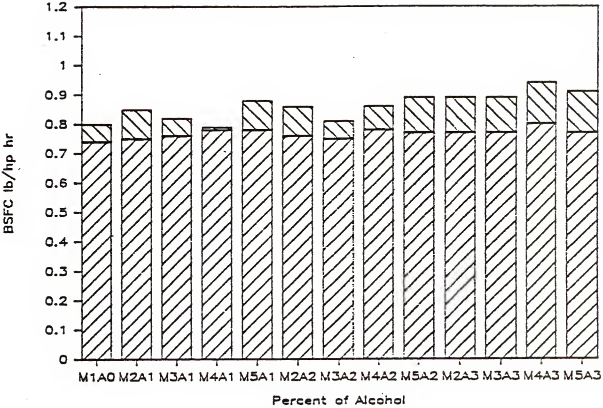


FIG. 5-34 UNCERTAINTY IN BSFC VALUES AT PHI5, S5, AND 2500 RPM.

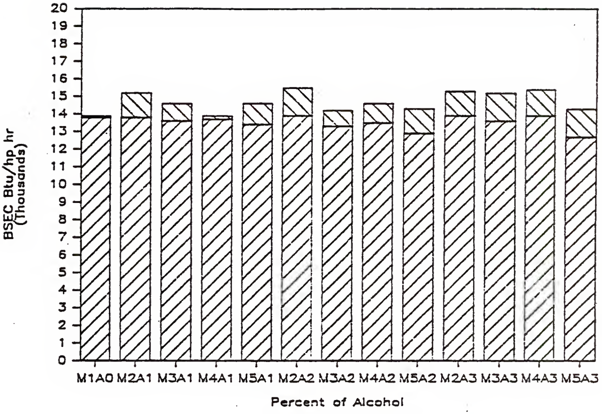


FIG. 5-35 UNCERTAINTY IN BSEC VALUES AT PHI5, S5, AND 2500 RPM.

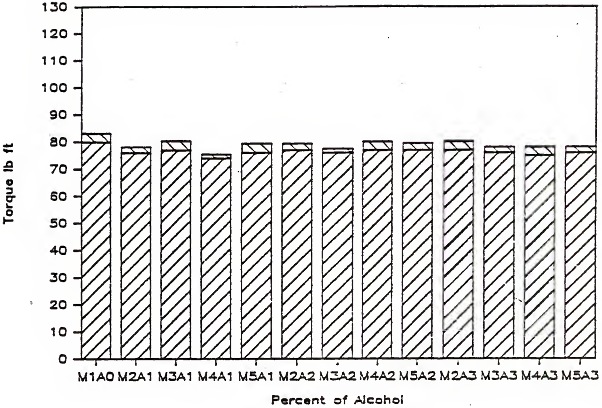


FIG. 5-36 UNCERTAINTY IN TORQUE VALUES AT PHI5, S3, AND 2500 RPM.

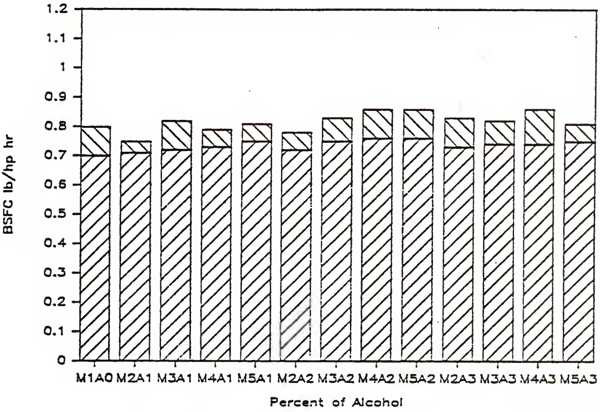


FIG. 5-38 UNCERTAINTY IN BSFC VALUES AT PHI5, S3, AND 2500 RPM.

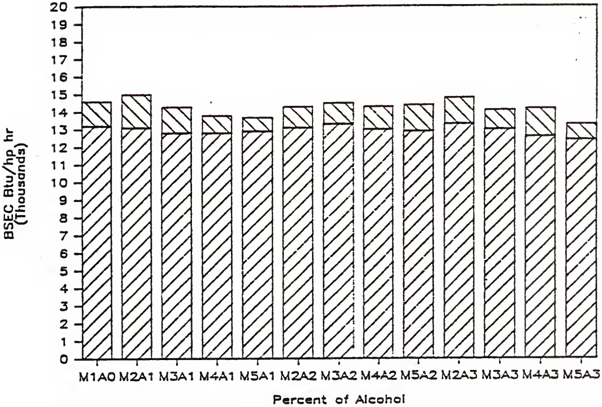


FIG. 5-38 UNCERTAINTY IN BSEC VALUES AT PHI5, S3, AND 2500 RPM.

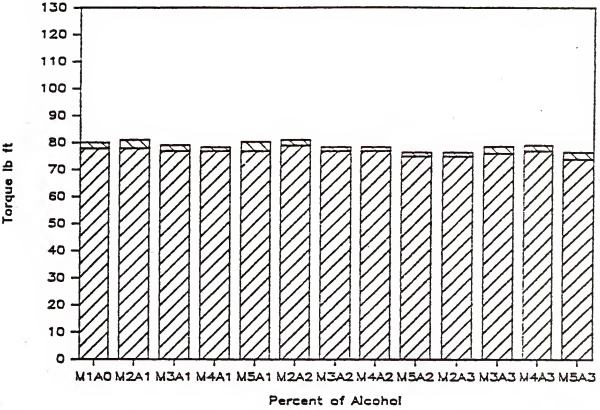


FIG. 5-39 UNCERTAINTY IN TORQUE VALUES AT PHI5, S1, AND 2500 RPM.

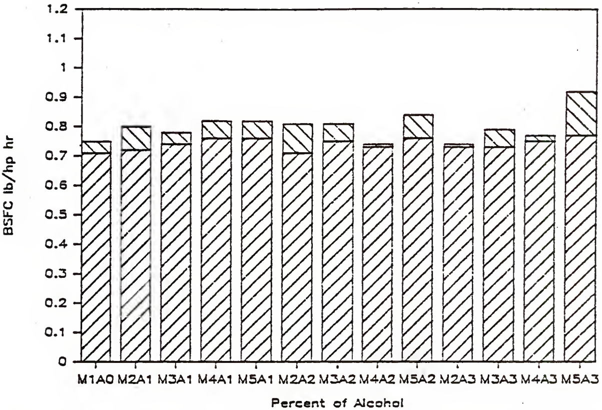


FIG. 5-40 UNCERTAINTY IN BSFC VALUES AT PHI5, S1, AND 2500 RPM.

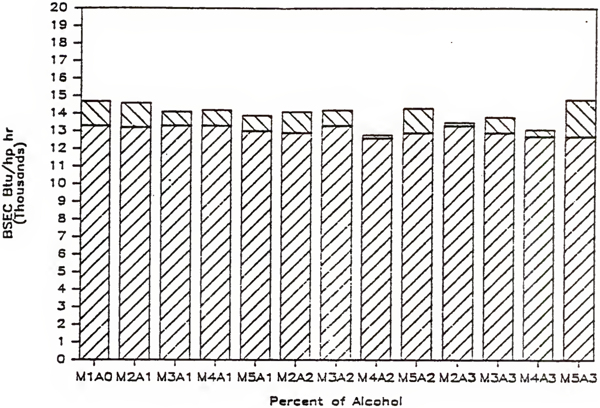


FIG. 5-41 UNCERTAINTY IN BSEC VALUES AT PHI5, S1, AND 2500 RPM.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Results obtained in this work were from engine tests at specific operating conditions. Data were analyzed statistically to determine the significance of the independent variables defining the operating conditions. The effects of these independent variables (ϕ,S,M, and A) on dependent variables (torque, BSFC, and BSEC) were studied. In addition, chemical analyses were conducted on the exhaust gases to find the effects of alcohol on exhaust emissions.

The statistical analyses applied on the data show the influence of the independent variables on the dependent variables to be significant. Even in higher order interactions between dependent and independent variables the relationships generally were significant. However, some of the higher order interactions were not significant due to the distribution of data points over large increments (lack of data) and the large number of independent variables.

The results of this study showed an increase in fuel consumption as the percentage of alcohol increased above 5% in the ethanol-gasoline blend, and even more for half ethanol and methanol-gasoline blends and for methanol-gasoline blends. Fuel consumption also increased 2 to 5% with retarded spark timing (10°BTDC). The influence of alcohol in the blend was noticable in brake specific energy consumption. This decreased by up to 8% with the increase of alcohol up to 15% in the blend. The study showed that the minimum specific energy consumption was at normal (standard) spark time setting (20°BTDC) and equivalence ratio on the lean side, close to stoichiometric. No significant differences were noticed among the three types of alcohol blends (ethanol, 50% each of ethanol and methanol, and methanol) in their effects on the spark time settings for minimum specific energy consumption. At lean conditions ($\phi < 0.8$) and retarded settings (10° BTDC), the engine would not run at 2500 rpm at WOT when the alcohol exceeded5% in alcohol-gasoline blends .i.e. the maximum power was somewhat less than predetermined value. This was due to the extra lean effect of alcohol which caused misfire.

The effect of alcohol in the blend on exhaust emissions was clear. Carbon monoxide production decreased as the percentage of alcohol increased up to 40 to 50%, compared with pure gasoline. Minimum carbon monoxide emissions were observed at the lean equivalence ratio (ϕ_1) and increased as the equivalence ratio increased from lean to rich due to the overall decrease of oxygen-carbon ratio. Production of carbon monoxide was lower in the case of methanol-gasoline blend than with the other blends, but each blend gave less CO than pure gasoline.

Concentrations of hydrocarbons in exhaust emissions were also minimum when the equivalence ratio was on the lean side of the stoichiometric ratio. However, hydrocarbon concentrations could increase on the lean side if it was lean enough to cause misfire. Hydrocarbon concentrations also decreased with the increase of the alcohol percentage in the blend. Retarded timing increased hydrocarbon emissions by up to 60% due to incomplete combustion.

Aldehyde emissions were markedly higher (90%-150%) when using the alcohol blends, as compared to pure gasoline, and increased as the percentage of alcohol increased. The concentrations of aldehydes were also increased as the spark timing was advanced.

Results obtained in this work are from experimental data at specific conditions and using relatively large increments in the variables. Even with these limited settings the minimum number of tests required was 614. These included 5% to 20% for alcohol-gasoline blends, ± 10° deviation of spark timing from the standard, equivalence ratio at rich and lean sides of the normal, and one exhaust sample analyzed by gas chromatograph at each datum point. It is recommended that in future work with multicylinder engines, data points be taken at 1% increments in volume of alcohol in alcohol-gasoline blends and at using increments of ± 2° from the standard spark timing, up to ± 10°. More accurate correlation between dependent and independent variables could be obtained, experimentally and analytically, by using statistical techniques. Chromatograph analyses accurately showed the distribution of exhaust gases, but some data were not available due to incremental sizes of carburetor jets, and more jets, including larger sizes, are recommended to cover all desired operating conditions.

The effect of other independent variables that represent potential problem areas associated with the use of alcohol-gasoline blends in multicylinder engines on torque, BSFC, and BSEC are worthy of investigation. Among these variables are:

1- Volatility, leading to cold and hot starting difficulties.

2- Mixture distribution within the engine.

3- Load rating on the engine and idle speed.

4- Water-pick up and component separation.

5- Corrosion and chemical attack on fuel system and engine components.

6- Lubricant and engine life.

7- Emissions control systems.

The results obtained in this study show the possible advantages of mixing ethanol with methanol in the alcohol-gasoline blends. Ethanol has some superiority over methanol, such as a higher heating value and motor octane number, less corrosive properties to engine parts, and lower vapor pressure. Combining ethanol and methanol, in gasoline blends, although showing insignificant differences from blends that have either methanol or ethanol, is expected to improve the general properties of the fuel blend. Alcohol as an octane booster may be of great importance in advance spark timing which consequently increases engine thermal efficiency.

The net result of using alcohol as an alternate or blending fuel with gasoline would make us less dependent on petroleum-derived fuels and capable of utilizing domestically-produced coal-based or renewable resource-based fuels. The fractions of these fuels could be increased or decreased seasonally as fuel source availability fluctuates-all of this without adversely affecting auto exhaust emissions. Accordingly, attention should be focused on alcohol-gasoline blends.

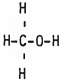
APPENDIX A

METHANOL AND ETHANOL

Structure and General Properities

Alcohols are derivatives of hydrocarbons where one or more hydrogen atoms of the molecule are replaced with hydroxyl (-OH) groups. The simplest alcohols are derived from the alkanes (saturated hydrocarbons) and contain only one hydroxyl group per molecule. The first two members of this group are:

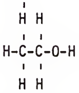
methanol



$$\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-O-H}$$

(CH_3OH)

and ethanol



$$\mathrm{H-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-O-H}$$

(C_2H_5OH)

Since all the hydrogen atoms in molecules of methane or in molecules of ethane (parent hydrocarbons that methanol and ethanol are derived from, respectively) are equivalent, there are no isomeric methanols or ethanols.

The OH group causes polarity in alcohol molecules, so that they tend to associate with one another through hydrogen bonding, which is the attraction of one hydrogen atom of one molecule for some of the electrons of an oxygen atom of another molecule. Hydrogen bonding is believed to give alcohol molecules their higher boiling temperatures compared to their parent hydrocarbons.

Boiling points of methane and methanol are -161° and 65°C, respectively. Unlike the parent hydrocarbons, alcohols with low molecular weights are very soluble in water. This too, is accounted by hydrogen bonding between the hydroxyl group of the alcohol and the water molecules.

In constrast to the alkane hydrocarbons, the alcohols are quite active chemically, because they enter into a number of reactions that involve the OH group. That group, therefore, is the functional group that characterizes physical and chemical properties of alcohols.

Octane Number

Both methy and ethyl alcohols have higher octane numbers than gasoline (Table A-1). The influence of alcohol additions on four base stocks (straight run, catalytically cracked, thermally cracked, and polymer gasoline) is shown in Fig. A-1(1). The greatest improvement in octane number from alcohol addition was obtained by gasoline stocks of the lowest octane number (straight run). Research and Motor octane ratings of regular and premium commercial leaded gasolines, blended with 5,10, and 25% by volume of anhydrous ethyl alcohol, were reported in (2). The addition of alcohol to regular gasoline improved the research and motor octane numbers in a near linear manner (Fig. A-2). For the premium fuel (Fig. A-3) the Research octane number shows less increase, but the Motor octane number is reduced by addition of ethanol. The results indicate that if the octane number of gasoline continues to rise, ethyl alcohol will lose more of its advantage as an octane improver.

Table A-1 Gasoline, Methanol and Ethanol Properties (1).

Chemistry	Gasoline C_8H_{18}	Methanol CH_3OH	Ethanol C_2H_5OH
Approximate specific gravity at 60°F	0.72 - 0.75	0.79	0.79
Boiling point			
°F	85 - 437	149	173
°C	30 - 225	65	78.3
Net heating value (mass)			
BTU/lb	18,700	8,600	11,600
MJ/kg	43.5	20.1	27
Net heating value (volume)			
BTU/gal	117,000	57,000	76,000
MJ/l	32	15.9	21.3
Heat of vaporization			
BTU/gal	170	500	390
KJ/kg	400	1,110	900
Vapor pressure at 100°F			
psi	9 - 13	4.6	2.5
kPa	62 - 90	32	17
Octane number			
Research	91 - 100	112	111
Motor	82 - 92	91	92
Stoichiometric A/F ratio	14.6	6.4	9
Vapor flamability limits, % by volume	0.6 - 8	5.5 - 26	3.5 - 15
Viscosity at 4 °F (40°C)			
Centipoise		0.46	.83
Centistokes		0.58	1.1
Appearance	Colorless to light amber	Colorless	Colorless
Vapor Toxicity	Moderate irritant, extreme concentrations cause narcosis	Irritant, comulative toxicant, causes narcosis	Irritant, toxic only in large doses

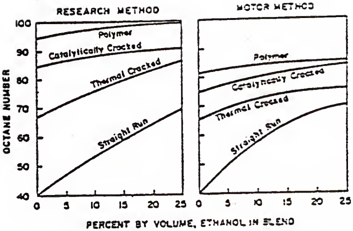


Fig A-1 Increase of octane ratings of several gasoline stocks with alcohol addition (2).

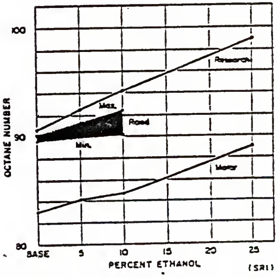
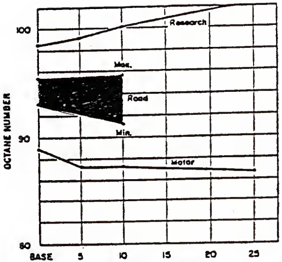
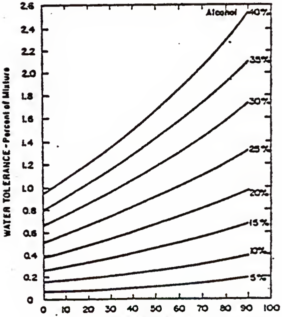


Fig.A-2 Octane ratings of regular gasoline-alcohol blends (2).



(SRI)

Fig.A-3 Octane ratings of premium gasoline-alcohol blends (2).



(Egloff)

Fig.A-4 Water tolerance of alcohol-gasoline blends (2).

Water Tolerance

Gasoline and anhydrous alcohols are miscible in all proportions over a wide range of temperatures. The addition of even small amounts of water to this blended one phase fuel will cause separation. This would cause an engine to stall because it could not run on the denser alcohol-water phase if it were adjusted for gasoline or a low alcohol-gasoline blend. Fig. A-4, taken from (81) shows that the ability of the blend to carry moisture without separation increases when more alcohol is present, and with increase in temperature. The water that can be tolerated by a 25% alcohol blend at room temperature is about 1%. If twice this amount is added to this blend, most of the alcohol will separate from the gasoline in a few seconds and settle to the bottom of the containers. Other blending agents can be added to the mixture which will increase the water tolerance. Among these are benzene, acetone, and butyl alcohol (13,78).

Volatility

Volatility of gasoline differs widely from that of methyl and ethyl alcohols. As Table A-1 shows, gasoline is composed of a mixture of hydrocarbons having boiling temperatures ranging from 30° to 225°C. Alcohols are composed of only one kind of molecule with single boiling temperatures (methanol = 65°C, ethanol = 78.3°C). The distillation curves of straight gasoline, methyl alcohol, and ethyl alcohol are shown in Fig. A-5 (5) and the distillation curves of alcohol-gasoline blends are shown in Fig. A-6. Figure A-5 demonstrates that distillation curves of alcohols lack the light ends with boiling points

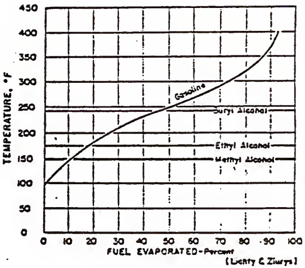


Fig.A-5 ASTM distillation curves for gasoline and alcohol (8).

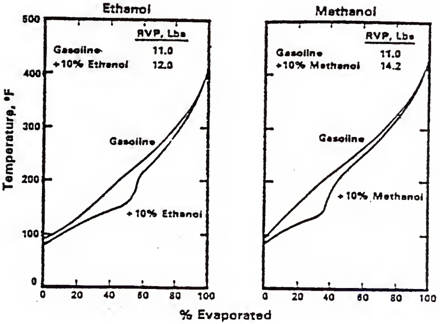


Fig.A-6 Effects of alcohols on vapor pressure and distillation (79).

near 100°F (37.8°) which are essential for severe cold starting of spark-ignited engines. Figure A-6 shows that alcohol markedly changes the shape of the gasoline distillation curve. Most of the alcohol vaporizes at its boiling temperature, giving the so-called "alcohol flat" in the distillation curve.

Figure A-7 demonstrates that methanol has unusual effects on volatility when mixed with gasoline. It causes the blend to distill much more rapidly at temperatures below methanol's boiling point. Methanol shows a positive deviation from Raoult's law for molar vapor pressure additivity when added to gasoline. The vapor pressure of the blend is higher than that of either component.

Dissociation

Methanol dissociates into carbon monoxide and hydrogen as the temperature is raised. The equilibrium fraction of dissociation is shown in Fig. A-8 as a function of pressure. For instance, at equilibrium over 80% of the methanol is dissociated at 200°C and 10 atm. For this reason the combustion properties of methanol are to a large extent similar to a mixture of carbon monoxide and hydrogen.

Combustion

The complete combustion with stoichiometric amounts of air is as follows;

for methanol:

$$CH_3OH + 1.5\ O_2 + 5.65\ N_2 \rightarrow CO_2 + 2H_2O + 5.65\ N_2$$

for ethanol:

$$C_2H_5OH + 3O_2 + 11.28\ N_2 \rightarrow 2CO_2 + 3H_2O + 11.28N_2$$

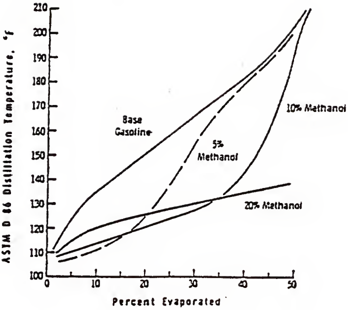


Fig.A-7 Effect of Methanol on Front-end Volatility (80).

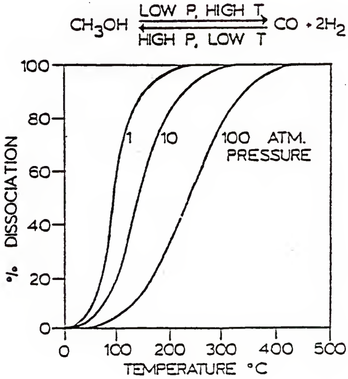


Fig.A-8 The equilibrium Fraction of Dissociation (39).

and for iso-octane (2,2,4 trimethylpentane) used as the standard hydrocarbon to compare fuel properties):

$$C_8H_{18} + 12.5\ O_2 + 47.0\ N_2 \rightarrow 8CO_2 + 9H_2O + 47.0\ N_2$$

Production of Methanol (2)

Commercial production of methanol from natural gas is based on the catalytic synthesis of methanol from carbon monoxide and hydrogen. The two gases are produced by a modified water gas reaction in which methane, the major component of natural gas, is reacted with steam. Carbon dioxide is also introduced into the reaction mixture to produce the proper stoichiometric ratio of two volumes of hydrogen to one volume of carbon monoxide:

$$3\ CH_4 + CO_2 + 2H_2O \rightarrow 4CO + 8\ H_2$$

$$4\ CO + 8\ H_2 \rightarrow 4CH_3OH$$

Both reactions proceed over catalysts at high temperatures ranging from 350° to 800°C. The methanol synthesis requires also high pressure ranging between 5 and 35 MPa.

Using coal, wood, and other forms of biomass for methanol production involves one more reaction that is the partial oxidation of the feedstock in a gasifier. This produces a crude gas which is purified and correctly proportioned for the carbon monoxide and hydrogen.

The technology developed by Mobil (81) for efficiently and economically converting methanol to gasoline by means of a catalyst adds interest to the production of methanol.

Production of Ethanol (2)

Producing ethanol by fermentation does not require an extreme temperature or pressure. Simply stated the starch in grain is converted to sugar by means of enzymes and the sugar is then fermented with yeast to produce a dilute alcohol solution. Distillation is used to seperate and purify the alcohol to a maximum of about 190 proof. The "proof" of an alcohol is equal to twice the per cent by volume of alcohol in the water mixure. If 200 proof is required then distillation with benzene is usually needed.

A less known process for the production of ethanol involves the hydrolysis of cellulose to yield fermentable sugar. This process is not yet in commercial use since the cost of a plant is almost double that of a fermentation plant.

Ethanol is also produced by catalytic hydration of ethylene. An ethylene-to-ethanol plant costs almost as much as a fermentation plant.

APPENDIX B

FORD PINTO ENGINE SPECIFICATIONS

B.1 Discription

This was a 4-cylinder overhead cam engine. Technical specifications are given in Table B-1. See also Fig. 4-1, Chapter IV. The engine had a cross-flow cylinder head with all valves in the head, intake on one side and exhaust on the other. The cylinder block was iron and held the crankshaft on five main bearings and the camshaft on four bearings. The main, connecting rod, camshaft and auxiliary shaft bearings were all replaceable. The valve lash was hydraulically adjusted which automatically regulates the rocker arm pivot height to maintain zero valve lash. The intake manifold was die-cast aluminum, with a two-barrel carburetor. The camshaft was driven from the crankshaft by a cogged, fully enclosed belt, which also operated the auxiliary shaft. The auxiliary shaft operated the oil pump, fuel pump and the distributor. The water pump and fan were separately driven from the crankshaft pulley by the conventional V-belt which also drove the alternator.

Table B-1 Engine Specifications

Number of Cylinders	4
Displacement cu in.(cc)	140 (2300)
HP@ 4800 rpm	88
Torque @ 2800 rpm, lb ft	118
Bore and Stroke in	3.781 x 3.126
Compression Ratio	9.0:1
Oil pressure @ 2500 rpm lb/in^2.	50

B.2 Engine Friction Power

To measure the friction power the dynamometer absorption unit was disconnected from the engine. The engine was then started and an auxiliary photoelectric tachometer was used to measure the engine speed (2500 rpm). To obtain the estimated friction power, the friction HP calibration curve supplied by the manufacturer of the dynamometer was used. The rate of air flow (SCFM) measured by the air sensor at no load was divided by the given factor (as per the dynamometer manufacturer) to get the estimated value of the friction power. The following values were recorded:

Td = 88°F

Tw = 79°F

Patm. = 30.07 in Hg

From wet and dry bulb thermometer:

Humidity Ratio (HR) = 0.0197

Horsepower Correction factor (HPCF) =

$$(P_S/P_t(1-HR)] \times [(Td + 460^\circ)520^\circ] \qquad \text{(Egn. B-1)}$$

where P_S and P_t are the standard and the test pressures successively in lb/in^2 and Td in °F.

HPCF = [(29.92/30.07 (1--0.0197)] x [(88+460)/520] = 1.042

Air flow at 2500 rpm = 17 SCFM

Estimated Friction HP (FHP) = 17/1.2 = 14 HP

HP at Standard Condition = (Reading HP + FHP) x HPCF-FHP (Eqn. B-2)

Friction Torque (T_F) = FHP/W

T_C = (14 x 550 x 60)/2 x 2500

= 29.41 lb ft.

T at std Cond = (Reading T + T_F) x HPCF-T_F (Eqn. B-3)

Equations B-1, B-2, and B-3 were used to standardize the actual data. The results are presented in Tables 4-2 to 4-10, chapter IV.

APPENDIX C

SUPERFLOW-SF-800

This device (Fig. C-1) consists of a steel frame test stand equipped with a hydraulically-actuated power absorption unit. The test stand was equipped with various electronic sensors connected to a reading and registering unit (console) by cables, so that the console could be held outside the experimental chamber. The console used the microprocessor technology in its circuit design (Fig. 4-2, Ch. IV, experimental). The Superflow-SF-800 automatically measured and recorded RPM, torque, horsepower, fuel flow, air flow, air-fuel ratio, brake specific fuel consumption, and exhaust gas temperature, all in less than 1/1000 of a second. Tests were performed while the engine was running at a constant speed. The data were simultaneously exhibited on 8" panel meters and digital displays, and were recorded by the SF-800 memory and printed. The readings were

1- Horsepower. The readouts could be displayed on any of the panel meter's three scale ranges of 0-80, 0-500, and 0-800 HP. During tests, one could observe that the needle reacts to minor or very rapid changes in power.

2- Torque. A second scale on the horsepower panel meter showed the torque the engine was producing, on any of the three scale ranges available for horsepower.

3- Speed. Engine RPM was displayed on both the panel meter and the digtal tachometer. On the panel meter scale ranges of 0-6,000 rpm and

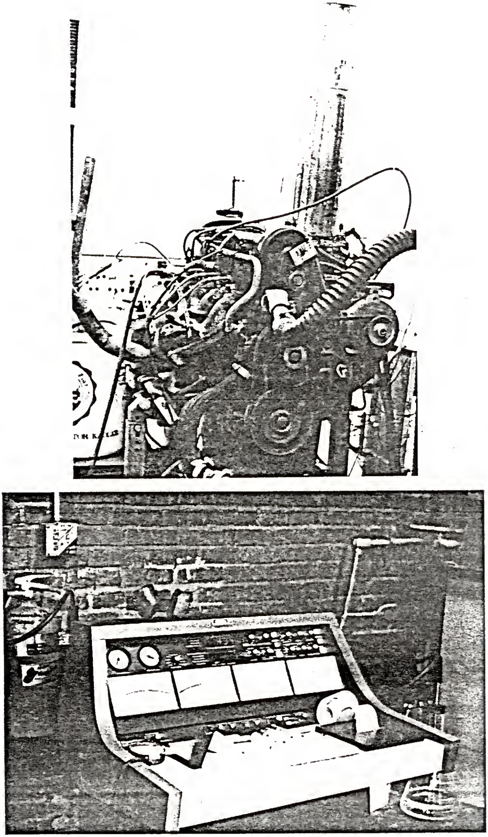


FIG. C-1 ENGINE TEST STAND, SUPERFLOW-SF-800.

4,000-10,000 rpm ± 10 rpm were available with updates every 1/3 second. The panel meter permitted observing rapid rpm changes while the digital tachometer displayed more precise readings at constant engine speeds.

4- Fuel Flow. Two channels for flow measurements were available on the SF-800 so that the flow could be checked through two carburetors, two halves of a four-barrel carburetor (fuel injection system) with by-pass pumps. Readings were displayed on the panel meter and digitally from 1-400 lb/hr for specific gravities from 0.66 to 0.84.

5- Air-Flow. Three sizes of air-flow sensors, 4", 6", and 9", were used to measure air flow from 5-1200 SCFM. Two channels of air-flow were available for measurements with dual carburetors. Air flow could be read out digitally or on the 8" panel meter at air densities from 0.65-1.10 lb/ft^3.

6- Air-Fuel Ratio. Displayed digitally by combining air and fuel flow data.

7- Brake Specific Fuel Consumption (BSFC). SF-800 computed BSFC at each test point and printed it out.

8- Engine Water Temperature (in and out) was measured and displayed on the panel meter.

9- Oil presssure and engine vacuum were measured by built-in gauges.

APPENDIX D

VARIAN MODEL 3740 GAS CHROMATOGRAPH AND VISTA 401

D.1 Introduction

The gas chromatograph used for the quantitative analysis of exhaust gas mixtures consists of the following parts:

1- Oven with necessary temperature controls.

2- Flow controller and pressure regulators.

3- Injection ports (sample inlet) with temperature control.

4- Detectors (TCD, FID, ECD).

5- Recorder or integrator.

6- Cylinders of gases (inert carrier gas, air, hydrogen)

7- Columns.

The varian Model 3740 was a modular unit equipped with an electro-sensor panel (ESP) which continuously checked injectors, column oven, detectors, flames and flows. Its bright, self- diagnostic LED display continuously showed whether the parameters were at their right settings. It has digital controls with positive pushbuttons and thumbwheel switches to set up all chromatographic conditions, flows, temperatures, detector sensitivities, rates and times. Settings were completely reproducible without resettability error. It was also equipped with automatic linear temperature programming and a platinum temperature sensor with feedback circuitry providing accurate temperature control.

The Model 3740 used a flame ionization detector (FID). The ionization of organic compounds when burned is the basis for the FID, which permits analysis on the order of parts per billion at maximum sensitivity. The detector was highly sensitive to organic compounds but was insensitive to inert gases, inorganic compounds and water. It consisted of a hydrogen flame burning in an electrostatic field, established by high voltage electrodes placed close to the flame. When organic compounds, injected into the carrier gas stream, are burned, positive ions and negative electrons are formed. Positive ions will be attracted to a negative electrode, while the negative electrons will be attracted to a positive electrode. Neither the hydrogen for the flame nor the carrier gas will ionize, so no current flows due to these gases. The FID output current is based on the number of carbon molecules per unit time that enter the detector. The greater the number of molecules ionized in a given time, the greater the signal current. Because of this response, a higher flow rate of carrier gas will give greater sensitivity and detect smaller sample components.

D.2 Columns Used In Gas Analysis

Gas-solid chromatography (GSC), a separation technique most commonly used in gas analysis, was employed in the present study. The columns are packed with active solids such as Molecular Sieves or porous polymers which, in combination, provide enough separating capability for almost any mixture of gases. Solid adsorbents such as silica gel, alumina and various forms of activated carbon are also used for some specific applications. Gas-liquid chromatography (GLC), in the column packing consists of an active partition liquid supported on an inert solid, is sometimes used for samples containing the vapors of low-boiling liquids, such as natural gas.

A knowledge of the capabilities and limitations of the various column packings is required in order to develop a method for the separation of a particular mixture of gases. The retention characteristics of the active solids depend upon the physical structure of the particles and the way in which gas molecules are affected by this structure.

The crystal structure of Molecular Sieves contains fine pores, ranging from 3 to 10 Å in diameter. These form a series of interconnecting "tunnels" throughout the particle. Small molecules entering these pores pass through easily; larger ones pass through with more difficulty and therefore more slowly. Thus, separation is due to a sieving effect and elution is usually on the order of increasing molecular size. There are some exceptions to this rule. Large molecules, such as n-butane, with a straight-chain structure, may enter the pores easily because of the small cross-section of the chain. Once inside, however, the length of the chain restricts their movement through the passages and elution is slow. On the other hand, an irregular molecule, such as isobutane, may be prevented from entering the pores completely because of the larger cross-section, due to the side-chain, and may proceed through the column in a series of in-and-out movements over the particles, resulting in much faster elution than would be expected on the basis of its molecular weight and carbon number. Very large, symmetrical molecules may be excluded from the pores entirely and, as a result, may be eluted without retention.

Silica gel and alumina separate gases by adsorption, a surface effect. The activity of these adsorbents in GSC is lower than that of the Molecular Sieves. They do not separate O_2, N_2 and CO under normal conditions, but will elute larger inorganic molecules and light hydrocarbons in a reasonable time.

The mechanism of retention of porous polymers is not yet fully understood. It may be due to adsorption or to surface gas-solid solution, or may be to a combination of several mechanisms. Regardless of the processes involved, the result is a solid material capable of separating and eluting gases and liquids which would be retained excessively on adsorption columns.

The three types of active solids, molecular sieves, adsorbents and porous polymers, provide a series of overlapping retention characteristics which permits separation of the whole range of gases, from hydrogen and helium up to propellants and low-boiling liquids. Although the mechanism is not always adsorption, columns prepared with these and other active solids are commonly referred to as adsorption columns.

There is no single column that will separate all gases at ambient or elevated temperatures. Therefore, a more complex cryogenic system would be required. The choice of a column for a particular analysis lies solely with the researcher, since columns are tailored to a specific need.

The column Porapak-Q 80/100 (ethylvinylbenzene copolymer) which is designed for the analysis of low-molecular weight compounds, was used for the analysis of the exhaust gases. The specifications are as follows:

Length(ft)	OD(in)	ID(mm)	Mesh	Max. Temp.(°C)
6	1/4	2	80/100	250

D.3 Routine Column Conditioning (Activation)

Reconditioning the column, at intervals, was usually necessary because of its slow deactivation, due to traces of moisture in the carrier gas or in the injected gas samples. The column was reactivated by baking for long periods (overnight) at a temperature at least 20°C below the maximum degree specified by the manufacturer. During the baking time the carrier gas was circulated through the column at a flow rate of approximately 10-30 ml/min. Before the conditioning process, the column exit end was disconnected from the detector (FID). During the first period of conditioning the column oven temperature was programmed to raise slowly (3-5°C/min) from the selected minimum to the maximum conditioning temperature to allow volatiles to leave slowly without blistering the surface film. Often during conditioning the volatile liquid phase bleeds off of the support (material inside the column) to the extent that minor support rearrangement occurs. This is evidenced by the appearance of small (1 or 2 mm) voids or cracks in the bed continuity, visible in the glass column. As long as these separations appear as clean perpendicular breaks, no greater than 3 or 4 mm in width and no more than 2 or 3 in number, no significant decrease in column performance will result.

D.4 Column Efficiency

In gas chromatography, the key to a good separation is the selection of a proper column, which depends primarily upon two factors:

1- Column efficiency, expressed as number of theoretical plates per foot, or more often the height equivalent to theoretical plates (HETP) which could be evaluated as follows:

$N = 16\ (t_r/W)^2$

Where N is the number of plates, t_r is the distance between injection point and the concerned peak, and w is the peak width at base.

HETP = L/N

Where L is the length of the column.

It can be seen from these equations that the lower the HETP the higher is the column efficiency and the narrower are the peaks. Column efficiencies vary with carrier gas flow rates, sample size, column temperature and the physical characteristics of the column packing material.

2- Partition coefficients which depend on solute-solvent phases and can be related to the polarity and structure of the sample compounds.

Chromatograms with narrow peaks offer the best resolutions. It is a measure of the relative separation of two sample components. The equation for resolution (R) is a function of the retention time and width at the base of the two peak.

$R = 2(\ t_r)/(W_1 + W_2)$

$\quad = \ t_r/W_2$

where t_r is the distance between two successive peaks.

D.5 Procedures of Gas Chromatographic Analysis

1- The glass column was fixed in the gas chromatograph with extra care to prevent breakage of this fragile instrument. It was very important to fix the column in the proper orientation. The column leg with the 2-in. "void" portion was always the inlet of the column and was inserted in the injector. This empty region was provided to prevent the needle from penetrating the column packing, and to allow sample vaporization expansion for on-column injectors. Frequent needle penetration of the column packing causes fragmentation of packing particles, which can in turn lead to an accumulation of particles that can cause increased column pressure, tailing peaks or abnormal retention times.

2- The flow rates of gases through the column were adjusted so that the flame in the FID could be detected. Injector and detector column fittings were checked for leaks by snoop fluid detector.

The rates of flow selected after many trials to achieve near optimum sensitivity from the column were as follows:

Carrier gas, Nitrogen	25-30	ml/min
FID, Hydrogen	25-30	ml/min
FID, Air	300	ml/min
Sample injected	40-200	l depending on the gas.

3- The FID dual flames were lit and checked by the condensation of moisture on the surface of the mirror checker.

4- The injector (inlet), oven column, and detector temperatures were adjusted. The injector and the FID were adjusted to 175°C, 25°C higher than the maximum oven programmed temperature. Temperature controls of the system were tested to be sure they were functioning normally.

5- The oven temperature program was set so that the starting temperature was 50°C, the final temperature 150°C, and the increment 8°C/min. These settings were selected after many trials to get high resolution output peaks from the exhaust gas species.

6- The system was allowed at least 30 min to stablize before the start of recording of the base line with the programmed temperature.

7- The standard gas for each component (CO, HC, and CHO) was injected separately with a known concentration (ppm) to determine the standard retention time for each particular gas.

8- The detector base line was run with the results recorded from the standard gases to combine the base line of the detector with the standard gas retention time.

9- A sample from the exhaust gases in the 50 ml syringe was taken by a 100 syringe and injected into the injection port for analysis.

10- The recorded results were correlated with the base line, derived in step f, to check for compatability. Fig. D-1 is a sample of a gasoline chromatogram.

11- The peak of each component was defined on the recorded chart by comparing with the retention time obtained for the standard calibration gases. From the analysis of the standard calibration gas charts, the retention time of each gas was found to be

Gas	Retention Time (min.)	Concentration (PPM)
CO	0.7	100
HC (propane)	6.7	1000
CHO (Formaldhyde)	10.6	1000

The peak of each component was determined at the specified retention time. The height of each peak was measured from the base line to determine the y-sample. The concentration of CO in each sample was calculated from the following equation:

$$\text{Concentration of CO} = \frac{Y_s}{Y_{std}} \times C \times \frac{V_s}{V_{std}}$$

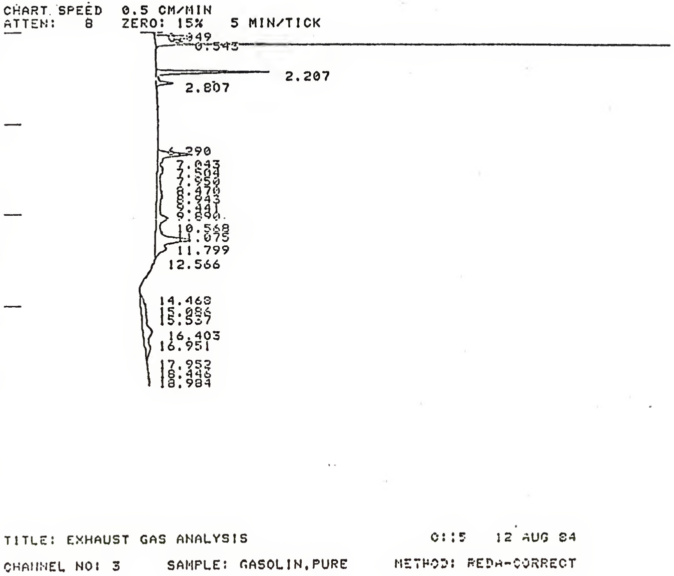


FIG. D-1 SAMPLE OF GASOLINE CHROMATOGRAPH CHART.

where Y is the height of the peak from the base line, C is the concentration of the standard gas, and V is the volume of the injected sample. Consider Fig. D-1 as an example to calculate the following concentrations.

CO=(142mm)/(19mm) x 100ppm x (200 /40) =3720 ppm

Concentrations of HC and CHO were calculated by the same way and they are:

HC = 940 ppm

CHO = 330 ppm

APPENDIX E

CALCULATION OF UNCERTAINTY

For a given variable, to estimate the uncertainty in the calculated results on the basis of uncertainties in the primary variables, the following method was applied.

$y = f(x_1, x_2, x_3, \ldots x_n)$ (Eqn. E-1)

Let W_1, W_2, W_3, $\ldots, W_n$ be the uncertainties of the primary variables. The uncertainty in the results of the variable y will be

$$W_y = \left[\left(\frac{\partial y}{\partial x_1} W_1\right)^2 + \left(\frac{\partial y}{\partial x_2} W_2\right)^2 + \ldots . \left(\frac{\partial y}{\partial x_n} W_n\right)^2\right]^{\frac{1}{2}} \quad \text{(Eqn. E-1)}$$

E.1 Friction Horsepower Uncertainity

The engine dynamometer, Super Flow-800, is capable of measuring the friction horsepower by applying an empirical formula:

$\text{FHP} = K \times (\text{SCFM})$ (Eqn. E-3)

$= 0.833 \times \text{SCFM}$

To calculate the uncertainty in the FHP result, the uncertainty in SCFM and K should be known. SCFM is a function of the air density as was mentioned in the calculation of air density.

$$\text{Air density (Ratio)} = [P_{test}(1\text{-HR})/P_{std.}] \times T_{std.}\ °\text{F}/T_{test}\ °\text{F}$$

$$A = [P_{test}(1\text{-HR})/29.92 \text{ in}] \times 520\ °\text{F}/T_d\ °\text{F}$$

Apply eqn. E-2 to calculate the uncertainty in air density.

Consider the readings taken before to calculate FHP.

$T_d = 88°F$

$T_w = 79°F$

Pat. = 30.07 in. mercury

H.R. = 0.0197

$$W_A = [(\frac{\partial A}{\partial P} W_p)^2 + (\frac{\partial A}{\partial HR} W_{HR})^2 + (\frac{\partial A}{\partial T_d} W_{T_d})^2]^{\frac{1}{2}}$$

$$\frac{\partial A}{\partial P} = \frac{1-HR}{29.92in} \times \frac{520° F}{T_d} = 0.031$$

$$\frac{\partial A}{\partial HR} = \frac{-P_t}{29.92in} \times \frac{520° F}{T_d} = -0.954$$

$$\frac{\partial A}{\partial T_d} = \frac{-P_t(1-HR)}{29.92} \times \frac{520° F}{(548)^2} = 0.002$$

The least counts for barometric pressure gage, psychrometric chart and thermometer are as follows:

W_p = 0.01 in Hg

W_{HR} = 0.0002 lb of water/lb of air

W_{Td} = 1°F

$$W_A = [(0.031 x 0.01)^2 + (-0.954 \times 0.002)^2 + (0.002 \times 1)^2]$$

$$= 0.002 \text{ SCFM}$$

From equ. E-2, the uncertainty in FHP result is

$$W_{FHP} = [(\frac{\partial FHP}{\partial A} W_A)^2 + (\frac{\partial FHP}{\partial K} W_K)^2]^{\frac{1}{2}}$$

The uncertainty in the value of the constant of eqn. E-3 could be ± 5%, otherwise the company that manufactured the dynamometer would never state eqn. E-3 in their catalog, and this represents the accepted range of confidence.

W_k = 0.833 x 5% = 0.042

$W_{FHP} = [(0.833 \times 0.002)^2 + (17 \times 0.042)^2]^{\frac{1}{2}}$

$= 0.714$ HP

FHP $= 14 \pm 0.7$ 14 HP

E.2 Uncertainty in Horsepower Correction Factor

To calculate the uncertainty in brake horsepower results, the uncertainty in the horsepower correction factor should be considered. Consider HP correction formula,

$$\text{HP correction factor} = [\frac{P_{std}}{P_{test}(1-HR)}] \times (\frac{T_d}{T_{std}})^{\frac{1}{2}}$$

$$\text{Uncertainty in HPCF} = [(\frac{\partial HPCF}{\partial P_{test}} W_P)^2 + (\frac{\partial HPCF}{\partial HR} W_{HR})^2 + (\frac{\partial HPCF}{\partial T_d} W_{T_d})^2]^{\frac{1}{2}}$$

$W_{HPCF} = 0.001$

HPCF $= 1.042 \pm 0.001$

$= 1.043$

E.3 Uncertainity in BHP results

BHP $= T \times W$

Torque and rpm were measured automatically by the dynamometer. Minimum reading values recorded during the experiments are

Torque = 69 lb ft.

BHP = 32 HP

Least counts are:

W_T = 1 lb ft.

W_{rpm} = 25 rpm (2.62 rad/sec)

W_{BHP} = ± 0.6 HP

W_{BHP} = 32

= 32 ± 0.6 HP

Consider the standard deviation values (σ's) from Table E-1

Uncertainty in BHP results = $[(0.6\ HP)^2 + (2\sigma)^2]$

E.4 Uncertainty in Torque results

$T = BHP/\omega$

Consider the torque minimum reading values of Torque and BHP mentioned before.

Least count of BHP = 1 HP

$$W_T = [(\frac{\partial T}{\partial BHP} W_{BHP})^2 + (\frac{\partial T}{\partial \omega} W_\omega)^2]^{\frac{1}{2}}$$

$$= \pm 1.47 \text{ lb ft}$$

Consider the standard deviation values (σ's) of torque from Table E-1.

Uncertainty in Torque results = $[(1.47\text{lb ft})^2 + (2\ )^2]$

E.5 Uncertainty in BSFC results

BSFC = Fuel Rate lb/(hr-hp)

$W_{BSFC} = [(\frac{\partial BSFC}{\partial F} W_F)^2 + (\frac{\partial BSFC}{\partial HP} W_{HP})^2]^{\frac{1}{2}}$

Minimum BSFC = 0.55 lb/hp hr

Minimum Fuel flow rate = 16 lb/hr

Minimum H.P. = 32 HP

Least count

W_{HP} = 0.6 HP

W_{Fuel} = 0.01 lb/hr

$W_{BSFC} = 0.55\ [(\frac{0.01}{16})^2 + (\frac{0.6}{32})^2]^{\frac{1}{2}}$

= 0.01 lb/HP hr

E.6 Uncertainity in BSEC results

BSEC = BSFC in lb/hp-hr x Heating Value in Btu/lb

$W_{BSEC} = [(\frac{\partial BSEC}{\partial BSFC} W_{BSFC})^2 + (\frac{\partial BSEC}{\partial HV} W_{HV})^2]^{\frac{1}{2}}$

Minimum BSEC = 9988 Btu/hp hr

Minimum H.V. = 16561 Btu/lb

Minimum BSFC = 0.55 lb/hp hr

Least Count

W_{BSFC} = 0.01 lb/hp hr

$W_{H.V.}$ = 100 Btu/lb

$W_{BSEC} = 9988\ [(\frac{0.01}{0.55})^2 + (\frac{100}{16561})^2]^{\frac{1}{2}}$

= 182 Btu/hp-hr

Uncertainty in BSEC results = $[(2\sigma)^2$ + (182 Btu/(hp-hr)$^2]$

E.7 Uncertainty in Chemical Analysis Results

E.7.1 Carbon Monoxide (CO)

Concentration of CO = $\frac{Y_s}{Y_{std}}$ x 100 ppm x $\frac{200\mu\ell}{40\mu\ell}$

Consider uncertainty of 10% from the value of the standard calibration gas (100 ppm) and uncertainty of 7% of the gas chromatograph

$$W_{CO} = [(\frac{\partial CO}{\partial y_s} W_S)^2 + (\frac{\partial CO}{\partial y_{std}} W_{std})^2 + (\frac{\partial CO}{\partial Concent} W_{Concent})^2 + (\frac{\partial CO}{\partial inj.std} W_{injstd})^2 + (\frac{\partial CO}{\partial injS.} W_{injs.})^2 + (0.07)^2]^{\frac{1}{2}}$$

Minimum values are

CO = 1330 ppm

y_{sample} = 51 mm

$y_{std.gas}$ = 16 mm

Least counts are

W_{sample} = 0.5 mm

$W_{std.gas}$ = 0.5 mm

$W_{concent.}$ = 10 ppm

$W_{inj.std.gas}$ = 1 $\mu\ell$

$W_{inj.samp}$ = 1 $\mu\ell$

$$W_{CO} = 1330\left[\left(\frac{0.5}{51}\right)^2 + \left(\frac{0.5}{16}\right)^2 + \left(\frac{10}{100}\right)^2 + \left(\frac{1}{200}\right)^2 + \left(\frac{1}{40}\right)^2 + (0.7)^2\right]^{\frac{1}{2}}$$

$$= 180 \text{ ppm}$$

CO concentration = Reading from table (4-13) ± 180 ppm.

E.7.2 Hydrocarbon (HC)

$$\text{Concentration of HC} = \frac{y_s}{y_{std}} \times 1000 \text{ ppm}$$

$$W_{HC} = \left[\left(\frac{HC}{y_s} W_s\right)^2 + \left(\frac{HC}{y_{std}} W_{std}\right)^2 + \left(\frac{HC}{conc.} W_{conc.}\right)^2 + (0.07)^2\right]^{\frac{1}{2}}$$

Minimum Values are

$HC = 593$ ppm

$y_{sample} = 5$ mm

$y_{std.gas} = 6$ mm

Least counts are

$W_{sample} = 0.5$ mm

$W_{std.gas} = 0.5$ mm

$W_{concent.} = 100$ ppm

$$W_{HC} = 593\left[\left(\frac{0.5}{5}\right)^2 + \left(\frac{0.5}{6}\right)^2 + \left(\frac{100}{1000}\right)^2 + (0.07)^2\right]^{\frac{1}{2}}$$

$$= 106 \text{ ppm}$$

HC concentration = Reading from Table (4-13) ± 106 ppm

E.7.3 Aldehyde (CHO)

$$\text{Concentration of CHO} = \frac{y_s}{y_{std}} \times 1000 \text{ ppm}$$

$$W_{CHO} = \left[\left(\frac{CHO}{y_s} W_s\right)^2 + \left(\frac{CHO}{y_{std}} W_{std}\right)^2 + \left(\frac{CHO}{conc.} W_{conc.}\right)^2 + (0.07)^2\right]^{\frac{1}{2}}$$

Minimum values are

$CHO = 250$ ppm

y_{sample} = 1.5 mm

y_{std} = 4 mm

Least counts are

W_{sample} = 0.5 mm

W_{std} = 0.5 mm

$W_{concent.}$ = 100 ppm

$$W_{CHO} = 250\left[\left(\frac{0.5}{1.5}\right)^2 + \left(\frac{0.5}{4}\right)^2 + \left(\frac{100}{1000}\right)^2 + (0.07)^2\right]^{\frac{1}{2}}$$

$$= 94 \quad \text{ppm}$$

CHO concentration = Reading from table (4-14) ± 94 ppm

In the chemical analysis work, one exhaust sample was taken but there was no statistical work done to calculate the standard deviation in each individual result.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a Dissertation for the degree of Doctor of Philosophy.

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