THE GENERATION AND USE OF PRODUCER GAS
IN STATIONARY C.I. ENGINES

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ABSTRACT

The Generation and Use of Producer Gas in Stationary C.I. Engines

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A fixed bed downdraft gasifier capable of using charcoal and woodchip as the feedstock was designed and fabricated.

Using air as the gasifying agent and with charcoal as the feedstock, the optimum operating point of the gasifier was established. At this setting a gas with a calorific value of about 4.7 MJ/Nm³ with a CO concentration of 32% a H_2 concentration of 7.6% and a CH_4 concentration below 1% was generated.

Using a mixture of air and steam and a mixture of air, steam and CO_2 as the gasifying agents, gases with comparable heating values to that generated when using air alone, was obtained at the lower prevailing reaction temperatures. Operating at these lower reaction temperatures, reduced the occurence of slagging, that was present when air alone was used.

Exhaust emissions from a C.I. engine was reused as the gasifying medium to determine whether any savings in carbon could be achieved. It was found that a 10%

concentration of the exhaust emission in the air stream gave maximum benefit and a 4.5% saving in fuel.

With the gas mixture generated at the operating point of the gasifier using air as the gasifying agent, the producer gas was used as the primary fuel along with quantities of diesel injection for ignition purpose, to dual fuel a C.I. engine rated at 9 KW at 1800 RPM. The ratio of diesel fuel injection under normal diesel operation when compared to the quantity injected for dual fuel operation was as high as 10:1 in instances and with producer gas operation, the torque range available was greater than that obtainable under normal diesel operation. The proportion of energy supplied by the gas to the engine decreased as the speed increased and as high as 90% of fuel energy replacement between low and intermediate torque levels could be supplied by producer gas. Producer gas use in the engine resulted in higher pollutant levels at low engine torque than with diesel fuel alone but as the torque increased, the pollutant levels became comparable with those of normal diesel operation.

For the cost of shaft power under producer gas operation to be significantly lower than the diesel operation, a fuel energy replacement of over 50% by the gas is required.

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DEDICATION

Affectionately dedicated to my wife, Lena A. Ingram and two sons, Andrew D. Ingram and Brian R. Ingram.

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CHAPTER 1

INTRODUCTION, LITERATURE SURVEY, RESEARCH OBJECTIVES AND LINES OF APPROACH

1.1 INTRODUCTION

Most of the countries in the Caribbean, with the exception of Trinidad and Tobago, which is a major oil producing country, rely to a very large extent, on imported fuel which in most instances, provide well over 90 percent of commercial energy requirements (1).

This has severe economic consequences on foreign exchange earnings and has had adverse effects on the economic development of the countries. It is becoming increasingly important therefore, for them to identify and develop indigenous alternative energy resources.

One of the alternative energy sources available in reasonably abundant quantities in the region, is biomass which could include wood, crop residue, animal manure, food processing waste etc. (2). If this biomass could be harnessed, it could provide a significant amount of useful energy.

Biomass may be used directly or converted for use through gasification. This means of conversion offers an attractive supplement or replacement to fossil fuel and under suitable condition, can result in a significant reduction in energy cost. The product of the gasification of biomass namely Producer Gas, has been used extensively in Compression Ignition (C.I.) engines and Spark Ignition (S.I.) engines. Its application in small stationary Internal Combustion (I.C.) engines for shaft power generation, is quite attractive since in most developing countries, about 95 percent of shaft power requirements are in systems below 10kw (3).

In general, producer gas is made when a thin stream of air passes through a bed of glowing coal. This coal may originate though, from quite a varied number of feed stocks which may include wood and crop residue.

Most of the carbon dioxide and steam initially formed by the burning of solid fuel, are reduced to carbon monoxide and hydrogen on the incandescent carbon surface of the glowing coal which are combustible (4).

Producer gas by itself under conditions existing in the C.I. engine, will not undergo spontaneous ignition. However by admitting a small amount of diesel fuel into the cylinder for ignition purposes, the engine will operate satisfactory.

Generally, no significant modifications are necessary for converting a C.I. engine to operate with producer gas. Whatever modifications are required are simple and can be effected quite simply (5). Such modifications can infact be undertaken while the engine is in operation and hence, a minimum of downtime for conversion is incurred.

Furthermore since the primary reactions occurring in the gasifier are the conversion of carbon dioxide to carbon monoxide and steam to hydrogen, it would appear that the carbon dioxide and steam in the exhaust of the engine, may usefully be converted to carbon monoxide and hydrogen by recycling through the gasifier. The above regeneration process seems also to be practical for the products of combustion from direct combustion systems which provide process heat.

The cost of producer gas generation, can vary from location to location. However, provided the feed stocks are available within close proximity and the processing cost are low, the gas production cost can be much less than that of the fossil fuel. It cannot be over-emphasised that existing high cost of fossil fuel and the high capital cost required for electricity generation and distribution to rural areas make it often uneconomical for local farmers to use power from the local grid. Here again it should be noted, that within the Caribbean, the majority of farmers operate at a subsistence level and would welcome an inexpensive energy source.

By applying this technology, it may be possible to achieve much more economic development, since small farmers can then mechanize. The saving in fuel cost would then represent a significant increase in disposable income.

1.2 CASE FOR STUDY

The use of producer gas systems can find extensive applications in the West Indies. However, experience in the design, fabrication and use of such systems, are virtually unknown in the region, though a few units are known to have been used in Guyana. A study of the design, fabrication and operation of producer gas systems may therefore be considered an essential starting point for the wider utilization of such systems in the West Indies and which could lead to reduction in reliance on imported fossil fuel with beneficial consequences flowing therefore.

1.3 LITERATURE SURVEY

1.3.1 Historical Background

The history of gasification can be traced back to the 17th century when Shirley and Clayton obtained coal gas from pyrolytic experiments (21).

Towards the end of the 18th century, Gardner generated gas from coal and used it extensively for lighting purposes and for the firing of furnaces in the iron working industries. The first commercially used gas producer can be attributed to Bishof, Simons and Duncan in the mid 1800's (6).

These were the first systems that were used successfully on stationary engine and could be described as being the starting point of modern gas producer engine systems.

By the beginning of the 20th century, gas producers were used to power pumping systems of about 1000Hp in capacity.

The outbreak of the First World War in 1914, resulted in an increase in demand for automotive fuel. Since the availability of liquid fuel was limited in Europe, attention was focused on portable gas producer systems (3). The systems in use then were of the updraft type and were not highly successful in their adaptation to engine operations.

By the early 1920's, several other types of systems were manufactured. One of the more popular design was the "Imbert" downdraft gasifier. This new system proved to be the most successful to date and was widely used on I.C. engines.

At the start of the Second World War, the production of gasifier systems was said to be limited only by the shortage of metal and tyres (4) (50). Gasifiers came into widespread use in all European countries and were largely used on automobiles, trucks, tractors, river barges and large river boats. Following the war, the use of the gas as a fuel for transport and stationary engine was largely discontinued with the easy availability of liquid fuel. Within recent time however, in response to the instability in petroleum prices and further threat of shortages, several agencies and engineers have begun re-investigating the uses of gas producers and their modern potentials.

Presently, gas producer systems have found application in the supplying of shaft power to stationary I.C. engine for electricity generation, water pumping and for process heat generation. This technology has however, wider applications in rural areas where there is a scarcity of cheap power supply and an abundance of agricultural residues.

1.3.2 Producer Gas Generation

Gasification is in essence, the conversion of solid carbonaceous material to gaseous and liquid products, leaving the mineral constituent of the fuel as a residue. The gasification of solid fuel usually takes place in an air sealed, closed chamber (called the gasifier) sometimes under slight pressure relative to ambient pressure. The fuel column is ignited and exposed to a controlled air blast and the gas is then drawn off.

The main products of gasification are CO, H_2, CO_2, CH_4 and N_2 with several trace gases. Four main types of gasifiers may be identified as (3) (7) (8) (9) (10) (11) (12) (13):-

(1) Updraft gasifier
(2) Downdraft gasifier
(3) Cross draft gasifier
(4) Fluidized bed gasifier.

The main properties of the fuel that identify their suitability or otherwise in the various type of gasifiers are:-

(1) Percentage moisture content
(2) Percentage ash content
(3) Bulk density (kg/m^3)
(4) Physical size (length and cross-sectional area)
(5) Volatile matter.

Fuel with high moisture content can cause a lowering of reaction temperatures as a result of quenching. This can result in poor gas quality (14) (15) (16).

Fuels possessing high ash content, can pose problems of slagging (3) (6). This is as a result of the melting of the oxide of silicon and its fusing together at high reaction temperatures. This can obstruct gas flow and result in poor gas quality production.

With regards to bulk density, feed stocks with low bulk density can create flow problems and can cause excessive pressure build up in the system. This type of fuel can also create space problem as a result of the large volume occupied by a small mass. The fluidised bed system tries to overcome some of these problems. However, if the fuel is required for use in the other systems mentioned, they would have to be densified (17).

Large particle size can cause bridging which can allow the air blast and gas produced to be forced through an uneven fuel bed. The net result could be slagging, caused by hot spots and low residence time of the gas generated. These both can result in poor quality gas (3).

The presence of large quantities of volatiles in the feed stock can be undesirable if the system is not designed to crack the tar generated after the fuel is pyrolyzed. The extent to which the gas is cleaned depends to a large extent on its final use. However, if the system is not capable of doing this, additional tar removal equipment has to be incorporated (18).

As far as fuel feed for the gasifier is concerned, there are two modes of operations available. The fuel can be gasified directly or pyrolyzed before gasification to give a char (14). Separate pyrolysis before gasification means that at least 50 percent of the energy is lost (6). However the design is much simplier since tar removal equipment is less elaborate.

Some of the more common feed stocks used are charcoal, woodchip, peat, coconut shell, corncob, rice husk, rice straw and saw dust (3) (11) (15) (19) (20).

Pitakarnnop (12) and Kaup (21) used a fluidized bed gasifier to produce low Btu gas from rice husk. Both investigators indicated that, there was a substantial quantity of tarry liquid present after pyrolysis. Pitakarnnop produced charcoal briquets with the char leaving the system and also collected the tar oil produced. This tar oil was blended with normal furnace oil for steam generation in an oil fired boiler.

Locke et al (17) have done work in establishing an Integrated Rural Energy Centre (IREC) in Sri Lanka. The centre primarly was used to dry coir and form it into briquets. The briquets were then gasified in a fixed bed gasifier, where the producer gas generated was used to fuel a Diesel engine which was coupled to a 140KVA generator. The power generated was distributed to local consumers and was used also to operate the briqueting system.

It has been reported (14) (22) (23) that the injection of steam into a generator can greatly improve the quality of gas obtained and in addition, can largely reduce the effect of slagging of the ash formed after combustion (16).

Steam injection is practiced on dry, high carbons fuel such as charcoal, anthracite, coke etc. which burns with high heat and are less easily quenched (6) (50).

This method however, is not appropriate for most agricultural residue since their moisture content are already sufficiently high.

White, Fox, Fleer and Weiss (24) (25) (26) did extensive studies on catalytic reaction of carbon with steam-oxygen mixture using coke. The catalysts used were sodium and potassium carbonate. The effect of the catalysts were to assist in the dissociation of steam so that the hydrogen content and hence the energy content of the gas could be raised. One of the observation was that after conversion started, the reaction rate was doubled for each 75°C rise in temperature in the gasifier and at 1000°C, practically complete decomposition of steam was obtained, with a contact time of about 5 seconds.

Reaction temperatures in the gasifiers can be in the region of 1000-1500°C. Such high temperatures are required in order to approach equilibrium conditions for the two main gasification reactions of carbon, namely the Boudouard reaction and the water gas reaction which are temperature dependent (12) (15) (16) (24) (25) (26).

The channeling of exhaust emissions from I.C. engines through gasifiers has been explored (20) (50). The kalle gasifier (50) allowed about 25 percent of automotive exhaust emission through it. It's primary purpose was to maintain low levels of reaction temperatures.
Williams et al (20) indicated its practicality by interconnecting the exhaust of a stationary

C.I. engine to a gasifier. Result of his findings were not available.

1.3.3 Engine Operation With Producer Gas

The use of producer gas in I.C. engines can be seen from the Swedish Experience 1939-1945 (50) as one of the possible alternative to fossil fuel, if its limitations are understood and accepted. Before its use in the engine however, the gas has to be cooled and cleaned. Cooling increases the engines volumetric efficiency and cleaning prevents any moisture, acid vapour, tar and ash from reaching the engine (5) (6) (7) (9) (27) (28) (29) (30) (31) (32) (51).

Kaup and Goss (6) found that the wear of parts in the engine cylinder during producer gas operation was largely as a result of corrosion and to a lesser extent abrasion.

The reason given was that, the wall temperature of the engine, was lower during producer gas operation, than in normal diesel operation, in view of the lower adiabatic flame temperatures in the cylinder. The corrosion was attributed mainly to the presence of acetic acid, ammonia and sulphur compounds. The acid vapours changed the pH of the lubricating oil slightly.

In the conversion of diesel engine to producer gas operation, the options available were to run on the gas totally using a spark ignition system or using the gas as the main fuel with the injection of diesel fuel for ignition purpose (5) (6).

For running on producer gas using a spark ignition system, gasoline cannot be used with compression ratios above 9.5 unless a high proportion of alcohol or tetraethyl lead is added to the gasoline to increase the octane number (50).

On the other hand dual fuel operation would involve only slight modifications and possibly could be done while the engine was actually in operation (5). For best diesel fuel economy however, it may be necessary to adjust the fuel pump since it was observed that the required quantity of diesel injection in most cases, were lower than the amount injected (20).

Williams et al (20) working with a 4 stroke, six cylinder, direct injection diesel engine, dual fueled with producer gas, found that alterations has to be done to the engine control in order to obtain and maintain minimum diesel injection. For most of the test the pilot injection quantity was kept constant. The quantity was just the amount needed for no load idling at 1800 rpm. It was discovered that at torque levels greater than 60 percent of maximum torque, the engine would not operate without knocking occuring and at below 60 percent torque levels, they were able to achieve a gas-diesel fuel energy ratio of about 4.5:1.

Karim, Klat and Moore (33) noted that the knock limited power output of a dual-fuel engine, depends largely on the nature of the primary gaseous fuel being used, the temperature and to a lesser extent, on the nature of the pilot liquid fuel employed, to initiate combustion of the charge. The effect of the charge temperature on the knock-limited output, was found by them to be predicted well by the following relationship.

$$\log \text{(knock-limited BMEP)} = A + \frac{B}{T_o}$$

where A & B are constants depending on the fuels and T_o is the absolute intake temperature. From tests done on a single cylinder direct injection C.I. engine using methane, it was found that as pilot quantity increased, the ignition delay decreased. This was attributed to the change in overall mixture strength.

Broeze (34) described the dual fuel engine as one with a high degree of technical and economical flexibility. They are modified diesel engines in whose design, special attention was paid to the injection of very small amounts of fuel normally 5 percent at full load and approximately 15 percent for normal no load conditions.

Annand and Abayazid (35) did work on the self-ignition of natural gas using a supercharged C.I. engine.
The gas inlet temperature, inlet pressures and engine speed were varied. With varying mixture strength between the air and the gas the occurence of self-ignition of the mixture produced a pop. The observation showed that the firing frequency depended on the inlet mixture pressure and temperature. At the highest frequencies, self ignition occured near Top Dead Centre (TDC) and the lowest frequency occured near the end of the expansion stroke.

Several investigators did work on the effect of addition of fuel to intake air itself on a C.I. engine (36) (37) (38) (39) (40) (41) (42) (43) (44) (52).

Karim and Weizba (40) found that the introduction of a small amount of gaseous fuel with air when using pilot injection in C.I. engines does produce a significant increase in the ignition delay period of the pilot. This they said can cause a significant reduction in power output at light load, combined with a significatn increase in the specific energy consumption of the engine.

Karim (41) also found that the knock phenomenon observed in dual fuel C.I. engines is of the auto ignition nature and was as a result of the gaseous mixture around the ignition centre. He also observed that the levels of oxides of nitrogen in the exhaust emission was significantly reduced under dual fuel operation. This suggested that this was as a result of the reduced levels of liquid fuel being used.

Lyon, Howland and Lom (42) working with a C.I. engine found that the performance of a indirect injection system dual fueled with LPg was unsatisfactory when compared to the direct injection system under the same conditions. In the indirect injection system there was a persistent knocking. Attempts at eliminating it met with little success. They also observed that the levels of aldehydes, hydrocarbon and CO in the exhaust under light loading condition was high.

Giffen et al (43) found that high power output with a C.I. engine was possible when the engine was running at injection pump setting giving visible though not excessive smoke. However the setting normally used was in the interest of fuel economy and to avoid exhaust smoke. They further stated that changing injection timing did not significantly affect the power output. Mechanical interconnection of the gas and air throttles were found to be critical and that independent controls were better for good performance.

Negretti (44) did extensive work on producer gas operated C.I. vehicle using a turbocharger. From the investigation it was showed that it is possible to increase the output power by 60 percent compared to normally aspirated engines. Several other investigators (20) (45) confirmed Negretti's findings. However, excessive shaft wear of the turbocharger may result due to the presence in the exhaust gas of water vapour and dust particles.

In looking at the development of C.I. engine under dual fuel conditions, it was thought useful to look at work done by some investigators on spark ignition (31) engine systems. Both systems can have similarities in their operation and information drawn from their findings could prove useful in gaining a better understanding of the gas operation in C.I. engine.

The octane number of producer gas can be as high as 120 when compared to that of gasoline of 90-106 (4) (6).

The high octane number makes it possible to run the engine at much higher compression ratios in S.I. engines and hence, high combustion efficiencies can be achieved.

From investigations done on the S.I. engine using producer gas (46) (47) (48) (49), it was the general conclusion that, a loss of power can be expected with an unmodified gasoline engine and that like the C.I. engine the ignition timing may have to be advanced beyond the setting for normal operation. Advancing the ignition, facilitates the flame to cross the combustion zone before the piston reaches Top Dead Centre (TDC).

The greater the hydrogen content in the gas, the less the engine timing needs to be advanced. As is the case with C.I. engines, an increase in liquid fuel supply, supercharging and turbo-charging were each found to result in an improvement of engine performance.

1.4 RESEARCH OBJECTIVES AND LINES OF APPROACH

From the foregoing review, it is clear that extensive investigative work has been carried out in the design and development of the gasifier and its use in I.C. engines.

In the West Indies however, experience in the design and use of gasifiers and their uses with I.C. engines is limited or non-existent.

The main purpose of the present investigation may therefore be summarized as follows:-

(a) To design, construct and operate a gasifier system using locally available charcoal as the fuel input.

(b) To study the effect of the primary parameters such as:-

  (i) Air
  (ii) Mixture of air and steam
  (iii) Mixture of air, steam and CO_2

on the performance of the system in term of:-

  (i) The composition of the gas
  (ii) The energy content of the gas
  (iii) The conversion efficiency.

(c) To study the performance of a C.I. engine designed for normal diesel fuel operation, when operating off the gas from the gasifier with diesel fuel, used mainly as a mean for the ignition source.

A relative economic analysis will also be carried out to determine the condition under which a gas producer supplied C.I. engine system will be economical.

CHAPTER 2

APPARATUS AND PROCEDURE FOR THE GASIFICATION OF CHARCOAL

2.1 INTRODUCTION

2.1.1 Types Of Gasifiers

The main types of gasifiers in general were identified in section 1.3 as:-

(i) Updraft gasifier

(ii) Downdraft gasifier

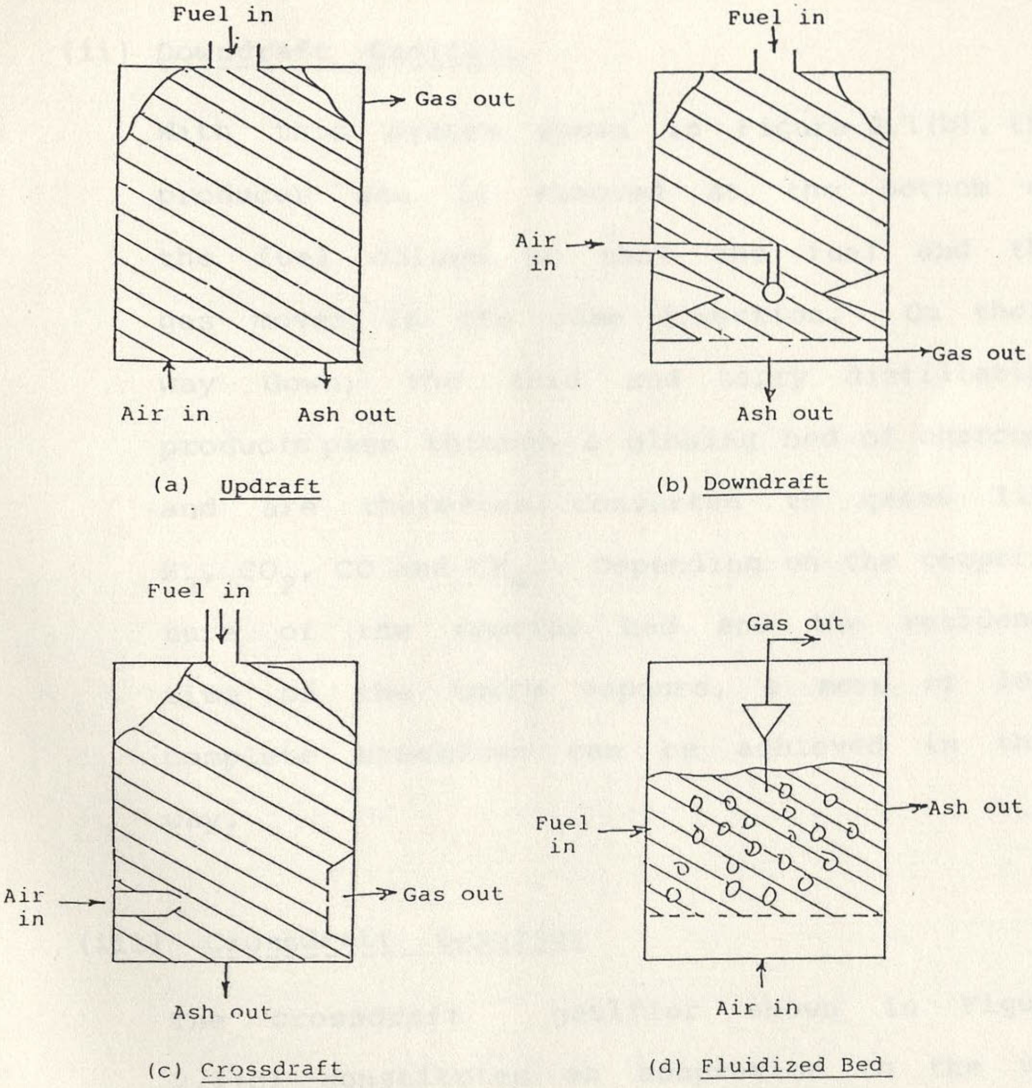
(iii) Cross draft gasifier

(iv) Fluidized bed gasifiers.

Each particular type has its different mode of operation and consequently the gas generated would be of varying quality (See Figure 2.1).

(i) Updraft Gasifier

This type of gasifier is shown schematically in Figure 2.1(a) and may be the oldest and simplest type of gasifier. The air enters at the bottom of the fuel bed and the gas leaves at the top. Combustion occurs at the bottom of the system and from the heat transferred throughout the fuel bed, devolatilization of the fuel at the top of the reactor occurs thereby allowing volatiles and acid vapours to be entrained in the gas stream produced.



(a) Updraft

(b) Downdraft

(c) Crossdraft

(d) Fluidized Bed

FIGURE (2.1)

Types of Gasifier

(ii) Downdraft Gasifier

With this system shown in Figure 2.1(b), the producer gas is removed at the bottom of the fuel column so that the fuel and the gas moves in the same direction. On their way down, the acid and tarry distillation products pass through a glowing bed of charcoal and are therefore converted to gases like H_2, CO_2, CO and CH_4. Depending on the temperature of the reactor bed and the residence time of the tarry vapours, a more or less complete breakdown can be achieved in this way.

(iii) Crossdraft Gasifier

The crossdraft gasifier shown in Figure 2.1(c) constitutes an adaptation to the use of high carbon fuel. This system suffers from the disadvantage of minimal tar converting capabilities and the associated need for high quality (low volatile content) fuel.

A concentrated combustion zone is achieved by one single nozzle and result in high gas exit temperatures, relatively poor CO_2 reduction and high gas velocity with extremely short gas residence time.

The nozzle in most cases are water cooled because of the high local temperature that develops.

(iv) Fluidized Bed Gasifier

The other three systems mentioned before are limited by the morphological, physical and chemical properties of the fuel. Problems commonly encountered by them are lack of bunker flow, slagging and high pressure drop across the gasifier. The fluidized bed gasifier aims to alleviate these problems.

The solid particles are kept in a state of suspension by the introduction of a high velocity air blast. This system however suffers from the disadvantage of high tar content in the producer gas generated.

From the description of the systems operating characteristic, it is seen that the downdraft system has the best overall tar cracking capabilities. This allows for a wider variation in volatile content in the fuel used and at the same time produces a gas that has a very low tar content.

For use in C.I. engines, it is necessary that the gas produced be free of tarry distillates. Clearly the downdraft gasifier is the one that could meet this requirement.

2.2 DESIGN CONSIDERATIONS

Since the gas produced would ultimately be used to fuel a C.I. engine, the downdraft system was chosen. This was because of its ability to produce gas with a low tar and acid content.

The minimum capacity of the gasifier required was based on the amount of gas required by the engine. With this in mind, the system was designed giving main considerations to the following aspects:-

(a) Diameter of reactor zone

(b) Diameter of the constriction (throat)

(c) Position of the air inlet

(d) Diameter of air inlet (nozzles) and velocity of air entering

(e) Depth of reactor bed.

In order to have an even air distribution within the combustion zone, the air was supplied by a ring of nozzles which were placed at equidistance at the top of the zone (See Figure 2.2). With a knowledge of the gas quantity needed, the required air flow rate could be determined.

The throat concept was used in order to maintain an even temperature distribution in the reactor and also to allow the reactor temperature to build up to sufficiently high values for distribution. This was accomplished through a throat which is a reduction in the reactor cross sectional area (See Figure 2.2).

The position of the grate determines the height of the reactor bed. This is of major importance since the residence time of the gas and hence its quality is highly dependent on this. The cracking of tars usually takes place in regions close to the grate.

The reactor was designed to supply about 0.6 Nm³/min (21.2 SCFM) of gas. The position of the grate along with the nozzle size and reactor size, were calculated based partly on theoretical considerations (i.e. quantity of gas required, quantity of charcoal consumed in the process) and partly on an evaluation of the dimensions of successful gasifier designs done by Venselaar, Schlapper and Tobler (8) who presented several plots relating throat sizes to height of nozzle above throat, diameter of air inlet, air inlet velocities and depth of reduction zone.

Although the primary fuel to be used in the system was charcoal, the gasifier was capable

(1) Fuel Shaker
(2) Vent
(3) Thermocouple Position
(4) Lighting Port
(5) Gas Burner
(6) Clean Out Port
(7) Grate Wiper
(8) Grate
(9) Reduction Zone
(10) Throat
(11) Air Inlet Pipe
(12) Preheater
(13) Nozzle
(14) Combustion Zone

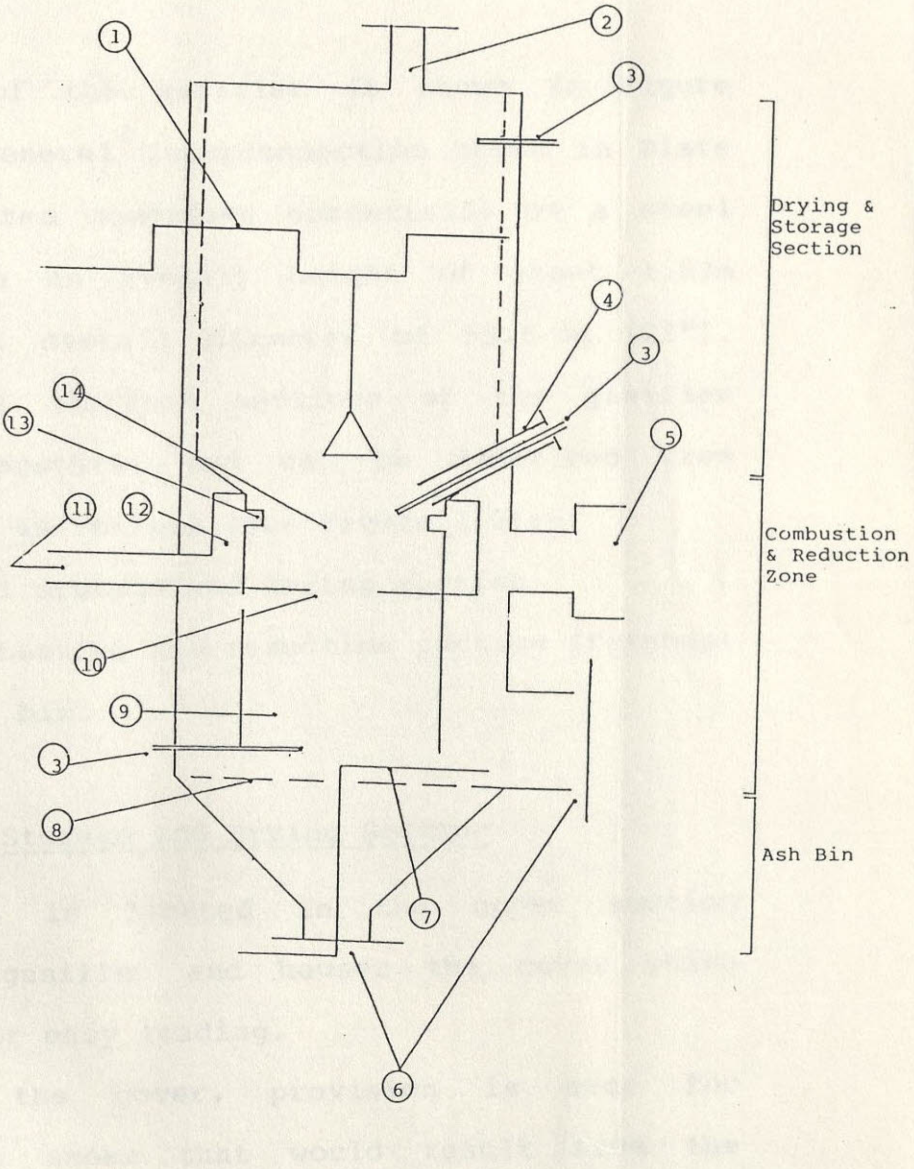


FIGURE 2.2

Fixed Bed Downdraft Gasifier

of handling a much wider range of raw material eg. woodchip and corn cob.

2.3 APPARATUS

2.3.1 The Gasifier

Details of the gasifier is shown in Figure 2.2 and its general interconnection shown in Plate 2-1. The system comprises essentially of a steel container with an overall height of about 1.82m (6'0") and an overall diameter of 55.8 cm (22").

The three distinct sections of the gasifier are bolted together, and can be described from top to bottom, as follows (See Figure 2.2):-

(i) The fuel storage and drying section
(ii) The combustion and reduction section (firebox)
(iii) The ash bin.

(i)a The Fuel Storage And Drying Section

This is located in the upper section of the gasifier and houses the cover which allows for easy loading.

On the cover, provision is made for releasing smoke that would result from the initial lighting up process.

A pressure relief valve which is spring loaded is also located on the cover. This

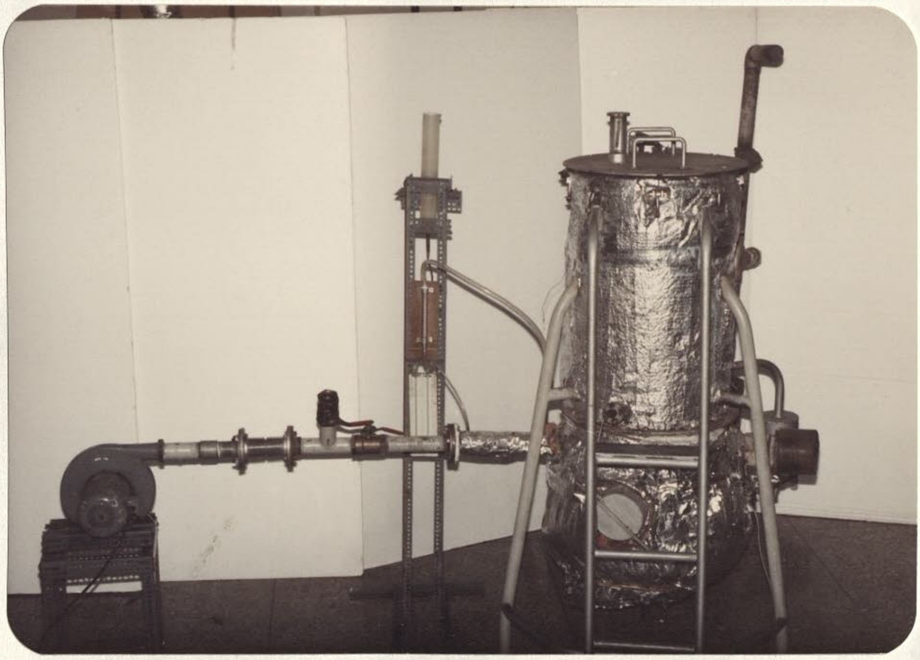


PLATE 2-1

LAYOUT FOR AIR AND AIR-STEAM GASIFICATION OF CHARCOAL performs the function of pressure relieving in the event the pressure in the gasifier builds up to unasceptable levels, as can occur when the fuel bed is tightly packed and the gas produced is confined to the system.

For sealing the cover after closure, asbestos gaskets were used. In fact this type of gasket was used at all the bolted connections on the system.

The fuel storage and drying section along with the other sections is fabricated from mild steel. It has a volume of about 0.06m³ (2.2 cu ft) and can store approximately 2½ bags of charcoal (1 bag is approximately 27 lb/12·3 kg). The section has a perforated lining, the specific function of which was to allow any water vapour driven off from the fuel, to pass through and then be collected in a condensate tank. A drain tap was incooperated to drain the condensate periodically.

The fuel normally feeds from the storage section through the reaction zone under the influence of gravity. A crank mechanism is incooperated in the system to enable the fuel feed to be agitated if for any reason, blockages occur in the system.

This mechanism essentially consists of a crank handle which is located on the outside and a crank with a push rod. The rotating of the crank handle results in a reciprocating movement by the push rod which agitates and forces down the charcoal.

(i)b The Ignition Port

An ignition port was provided just towards the bottom of the storage and drying section and comprises of a pipe of diameter 5.1 cm (2") to channel the igniting flame and fuel towards the combustion zone (See No. 4 Figure 2.2).

A wick attached to a handle was used for lighting the gasifier.

(ii) Combustion And Reduction Section

The combustion and reduction section is situated in the lowest section of the assembly i.e. just below the storage and drying section. The primary reactions take place in the fire box (See Nos. 9 and 14 Figure 2.2) which is 30.5 cm (12") in diameter and is enclosed by the outer casing of the system.

Towards the bottom of the fire box is a supporting grate (See No. 8 Figure 2.2). In addition to supporting the fuel bed, the grate allows for the seperation of the ash from the fuel bed. The grate which is slotted, is incooperated with a wiper which rests on top of it. A shaft extending outside from the wiper is connected to a handle which is used for rotating the wiper. The rotating action of the wiper, forces the ash through the slotted grate into the ash bin (See No. 7 Figure 2.2).

The gasifying agent normally is supplied radially inwards to the fixed fuel bed through six nozzles which are fixed to the fire box wall and which are spaced equidistant to each other around the circumference inside the fire box (See No. 13 Figure 2.2). The gasifying agent initially enters the system through a 2" bore pipe and is distributed by an internal cylinder jacket (See No. 12 Figure 2.2). This jacket also acts as a preheater for the gasifying agent.

The throat (See No. 10 Figure 2.2) is a size reduction in the cross sectional area of the fire box from 30.5 cm (12") in diameter to 12.7 cm (5") in diameter. Just above the grate are located two clean out ports for easy removal of ash and unburnt fuel (See No. 6 Figure 2.2).

(iii) The Ash Bin

The ash bin is a conical shaped chamber situated to the bottom of the gasifier (See lower section Figure 2.2).

Ash that remains after the combustion and reduction processes, are swept through the grate by the wiper and is collected by the bin. At the bottom of the ash bin is another clean out port.

The gasifier was supported by three legs all fixed to the storage bin. This construction facilitates easy dismantling by simply removing the connecting nuts and bolts.

2.3.2 Instrumentation

(i) Air Supply And Measurement

Air was supplied to the gasifier by a 0.38 Kw (0.5 HP) blower rated at about 0.56 M^3/min (20 cfm) through a 5.1 cm (2") bore pipe.

A suitable valve was used to regulate the air flow while the flow rate was measured through a calibrated orifice plate.

(ii) Gas Sampling

The gas sampling probe shown in Figure 2.3 consists of a perforated tube, 1.27 cm (½") diameter inserted in the gas supply pipe and through which the gas sampled was drawn.

(iii) Temperature Measurements

Shielded cromel alumel thermocouples were placed at suitable points in the system to record temperatures (See Figure 2.4). Kip & Zonen flat bed records were used to record the temperature continuously in the storage and drying section, the combustion zone and the reduction zone. In the combustion zone, a thermocouple was placed just above the air stream.

In the reduction zone, a thermocouple was placed just towards the lower section of the zone. For measuring the temperature in the storage and drying section, the thermocouple was placed at the top of the fuel bed (See No. 3 Figure 2.2).

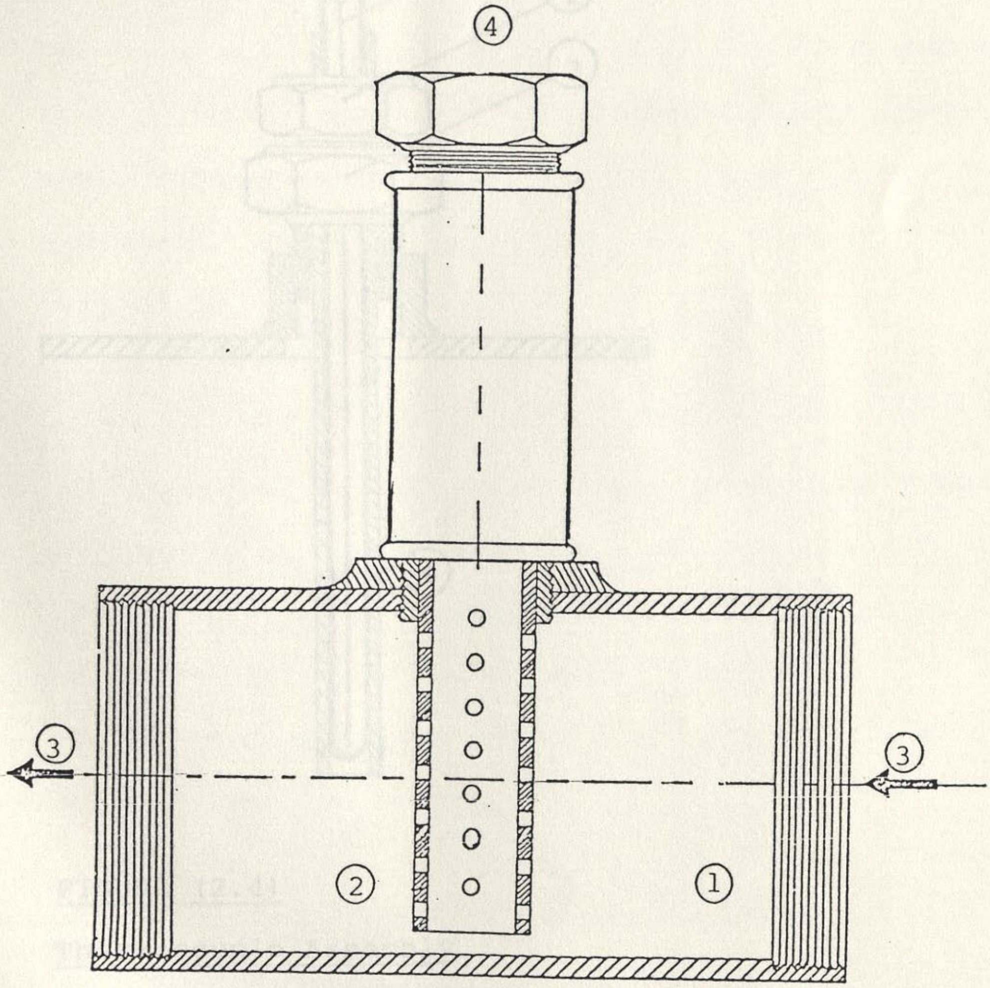


FIGURE (2.3)

Gas Sampling Probe Assembly

(1) Gas pipe

(2) Sampling tube

(3) Gas flow

(4) Gas collection point

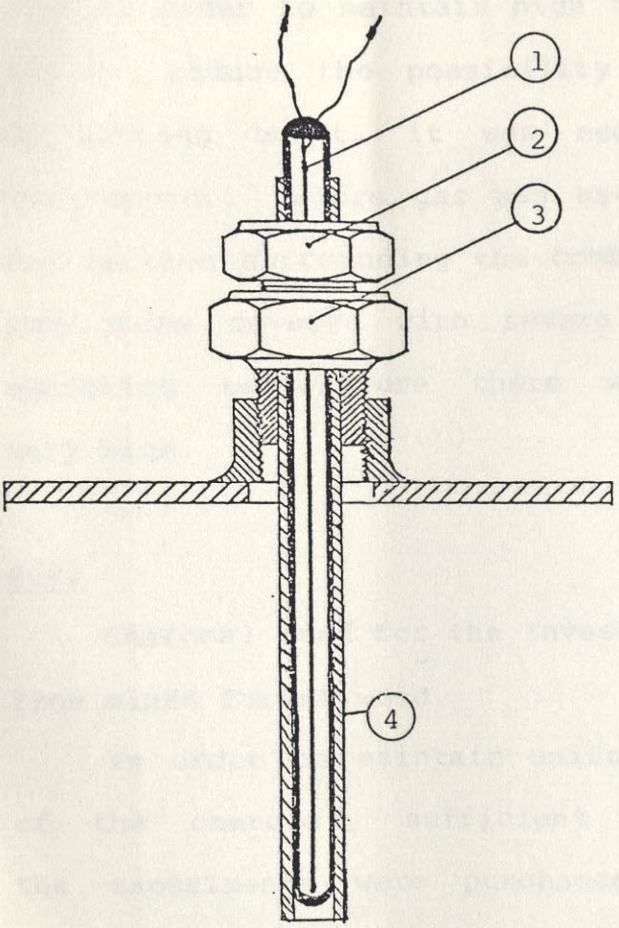


FIGURE (2.4)
Thermocouple Assembly

(1) Thermocouple wire

(2) Locking nut

(3) Fixing nut

(4) Stainless steel shield

2.3.3 Insulation

In order to maintain high reaction temperatures and to reduce the possibility of physical damage by getting burnt, it was necessary to insulate the reactor. Fibre gas was used for this purpose. The section surrounding the combustion and reduction zone were covered with several layers since, the operating temperature there was expected to be very high.

2.3.4 Fuel

Charcoal used for the investigation was produced from mixed forest wood.

In order to maintain uniformity in the quality of the charcoal, sufficient quantities for all the experiments were purchased at one time from one supplier and stored.

2.3.5 Producer Gas Analysis

(i) Fyrite Analysis

The percentage of carbon dioxide present in the gas was measured using a Fyrite analyser (See No. 3 Plate 2-2).

It consists principally of two chambers connected by a central base alongside of which is an adjustable scale.

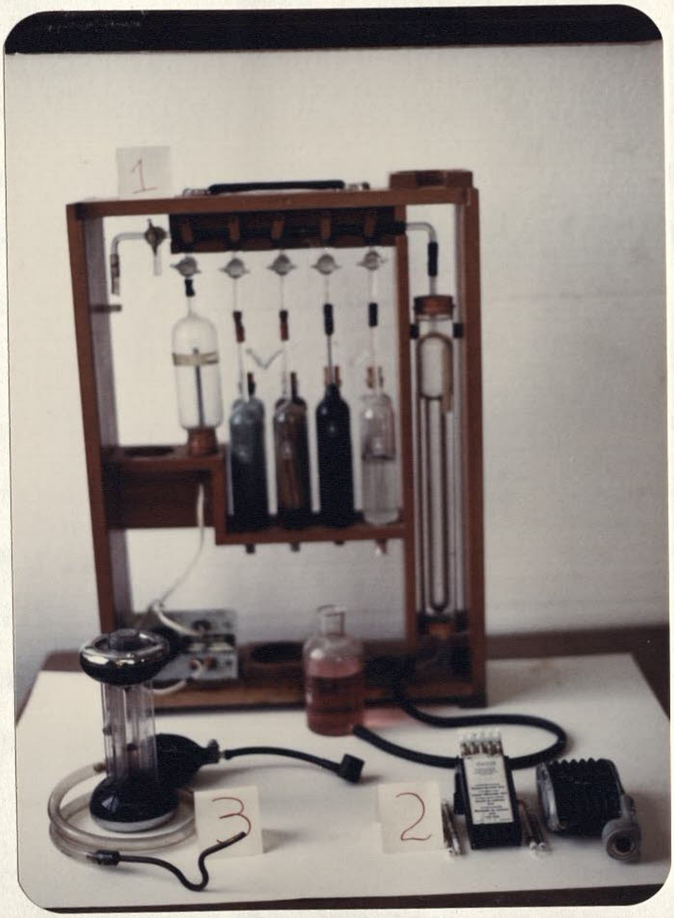


PLATE 2-2

GAS ANALYSING APPARATUS

1 - Orsat Gas Analyser

2 - Drager Gas Analyser

3 - Fyrite Gas Analyser

The scale is calibrated to measure the percentage of carbon dioxide present in the gas mixture.

The bottom chamber contains a solution of potassium hydroxide which rises to about ½" above the bottom of the bore.

The top chamber contains a plunger valve which in its normal position seals off the content of the sampler.

To admit the sample, the plunger valve is depressed. When all air has been displaced from the instrument, the valve is released and the sample is mixed with the solution of potassium hydroxide (coloured for easy visibility) by inverting the samples and then returning to its original position.

The carbon dioxide present in the sample is absorbed and a partial vacuum is created. This causes the solution to rise in the bore to a level corresponding to the carbon dioxide absorbed.

The simplicity of operation and easy reproducibility of results are two advantages of this method. The scale is graduated to read carbon dioxide to an accuracy of 0.5% by volume.

This is sufficiently accurate for qualitative analysis.

(ii) Orsat Gas Analyser

Number 1, Plate 2-2 shows the Orsat apparatus used to measure the concentration of carbon dioxide, carbon monoxide and oxygen in the gas mixture. The type used was a Fisher Scientific Model.

The principle of this method of analysis is similar to that of the Fyrite method described above. A measured sample of the gas mixture is passed into successive pippettes, each containing a reagent for absorbing a particular constituent of the sample.

For carbon dioxide, the absorbent used is potassium hydroxide.

For oxygen, alkalyine pyragallol is used and for carbon monoxide, alkalyine cuprous chloride. The levelling bottle, partially filled with a 10% sulphuric acid solution, coloured for easy visibility is used together with taps to:-

(1) Draw in the sample of gas and reduce it to atmospheric.

(2) Expell air initially from the apparatus.

(3) To ensure absorption of the constituent in the pipettes measuring the amount absorbed, again under atmospheric condition.

The burette is graduated to hold 100 ml of gas hence making it possible to obtain directly the percentage by volume of the constituent absorbed.

The volume of capillary tubing connecting the pipettes, is small compared with that of the burette used to collect the samples. Measurement of concentration by this method is usually more accurate than the fyrite analyser. However it can only be used to detect gases occuring in concentrations above 0.1% by volume.

(iii) Chromatography

This was the most effective method used for detailed analysis of the gas mixture and for a definite identification of the different components present in the gas mixture. It involved separating the mixture into its individual constituents so each could be analysed separately. The type of system used was a Perkin Elmer Type using a Thermal Conductivity detector along with a Pora pak-Q column.

2.4 PROCEDURE

Before the charcoal was supplied to the gasifier, it was first graded through a 2"x2" mesh size. The charcoal was then loaded into the gasifier making sure that there was a continuous flow through the combustion zone to the grate.

A small quantity of kerosene or diesel oil was then poured inside through the lighting port and the system ignited by a wick. After the charcoal was ignited, the blower was switched on and the air flow rate regulated to ensure continuous combustion of the charcoal in the combustion zone. The lid was left open in order to drive off any moisture in the charcoal that would affect the gas production.

The presence of a thick white smoke was taken as an indication of the pressure of moisture. After the excess moisture was driven off, the lid was closed.

The gas produced, was observed and tested with a flame at the burner, to see if it was of sufficient combustible quality. This continued until a flame was maintained. The total starting operation took about 15 minutes. At this point the gasification of charcoal using the various gasifying agents can proceed.

After each test setting, the system was allowed to operate for about 10 minutes to acquire steady running conditions. Gas samples were then taken for analysis and the quantity of gas generated determined from a calibrated orifice plate. The system temperature was monitored continuously.

Throughout the investigation, the burner was kept lit in order to eliminate the possibility of CO build up in the lab and also as an indication of the combustible characteristic of the gas.

CHAPTER 3

GENERAL CONSIDERATIONS FOR CHARCOAL GASIFICATION

3.1 INTRODUCTION

In this chapter the theoretical principles involved in the manufacture of producer gas is explained.

The main processes namely drying, pyrolysis, oxidation and reduction along with the various chemical reactions are described.

3.2 GENERAL CONSIDERATION

3.2.1 Chemistry Of The Gasification Process

Within the downdraft gasifier, four distinct processes take place; drying of the fuel, pyrolysis, combustion and reduction. Although there exists considerable overlaping between the various sections, particular processes may be considered to take place in separate and distinct zones. For total gasification, the fuel must pass through all these zones (See Figure 2.2).

(i) The Combustion, Oxidation on Hearth Zone

This zone is usually situated close to the base of the gasifier. It is within this area that the air or oxygen is fed, allowing combustion of the fuel to take place. It is very important to ensure that the air supply is restricted to the combustion zone since if this is not done the gasifier would simply operate as a stove producing incombustible gases. Within this zone, oxygen combines with carbon from the fuel to produce carbon dioxide (CO_2). This is an incombustible gas, and the process is exothermic i.e.

$$C + O_2 \rightarrow CO_2 \qquad (3.1)$$

(ii) Reduction Zone

The gas is then drawn from the combustion zone through to the reduction zone which is usually situated below the combustion zone in downdraft gasifiers. It is within this zone that the CO_2 formed in the combustion zone is reduced in the presence of glowing carbon to CO at sufficiently high temperatures. This is sometimes referred to as the "Boudouard" reaction and is endothermic i.e.

$$C + CO_2 \rightleftharpoons 2CO \qquad (3.2)$$

Idealy no oxygen is desired in this zone, since the chemical reactions is no more one of oxidation but reduction. This is not always the case and small quantities still pass through. The reduction reaction predominates however since there is an abundance of carbon available.

Another important reaction that takes place in the reduction zone is that between water vapour and carbon. This reaction is also endothermic and takes place at temperature above 900°C.

$C + H_2O \rightleftharpoons CO + H_2$ (3.3)

During this reaction water is dissociated yielding CO and H_2. The end result of these endothermic reactions is a progressive drop in temperature. As the temperature falls, a different set of reaction takes place, one of which is also between carbon and steam but of a different kind. This usually takes place at temperatures between 500 and 600°C and is endothermic i.e.

$C + 2H_2O \rightleftharpoons CO_2 + 2H_2$ (3.4)

If there is excess water in the reduction zone, the so called "Water Shift" reaction can take place in which CO reacts with water to give CO_2 and H_2 i.e.

$CO + H_2O \rightleftharpoons CO_2 + H_2$ (3.5)

This is exothermic and is unfavourable since it reduces the CO concentration.

Depending on the fuel used, methane (CH_4) can also be obtained in the reactor. With charcoal as the fuel, (from which most of the volatile components have been driven off in the manufacturing process) small quantities of hydrogen may be available and hence one of the reactions that can occur is

$$C + 2H_2 \rightarrow CH_4 \qquad (3.6)$$

This is exothermic. Methane again may conceivably be formed according to the following equation.

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad (3.7)$$

(iii) The Pyrolysis Zone

When the feed stock is not mainly carbonaceous, then it undergoes thermal disintegration and pyrolysis in the pyrolysis zone, which is generally located above the combustion and reduction zone and very little air is normally supplied there. Heat is drawn from the hotter adjacent zone and at about 400°C the fuel breaks down. This is similar to what goes on in a kiln in the manufacture of charcoal. Water vapour, methanol, acetic acid and a considerable quantity of heavy tars are evolved. The remaining solid material after pyrolysis is carbon in the form of charcoal. The tar laden gases then pass through the combustion and reduction zones.

If the temperature is high enough and the time taken to pass through is sufficiently long, the majority of the tars will be broken down thus giving a relatively clean final gas. However if the gases are to be used in an Internal Combustion engine, it has to be tar free. The gasifier system then would have to be designed with this in mind.

(iv) The Drying Zone

The drying zone is usually situated at the top of the gasifier. The temperature is relatively low and hence virtually no chemical reactions take place. Moisture present in the fuel is driven off in the form of water vapour.

3.3 CHEMICAL EQUILIBIUM

The composition of the gas produced by a gasifier depends on the degree of equilibium attained in the various reactions. The ratio of reactants in a gasifier at equilibium condition is usually expressed by the so called equilibium constant. This is a function of temperature and pressure and its value may be determined experimentally (50) (55). The equilibium state of the reaction described by equation 3.2 may therefore be expressed by the equilibium constant k_{pB} as

$$K_{PB} = \frac{[P_{CO}]^2}{[P_{CO_2}]} \qquad (3.8)$$

where p_i represents the partial pressure of the constituents -i

for reactions at 1Atm

$$K_{PB} = \frac{[V_{CO}]^2}{[V_{CO}]} \qquad (3.9)$$

where V_i represents the partial volume of the constituents -i

for eq. 3.3

$$K_{PW} = \frac{[V_{CO}].[V_{H_2}]}{[V_{H_2O}]} \qquad (3.10)$$

for eq. 3.5

$$K_V = \frac{[V_{CO}].[V_{H_2O}]}{[V_{CO_2}].[V_{H_2}]} \qquad (3.11)$$

V_{CO} - partial volume of CO

V_{CO_2} - partial volume of CO_2

V_{H_2O} - partial volume of water vapour

V_{H_2} - partial volume of H_2

V_{CH_4} - partial volume of CH_4

K_{PB} - equilibium constant for Boudouard reaction

K_{PW} - equilibium constant for carbon-steam reaction

K_V - equilibium constant for water gas reaction.

CHAPTER 4

THE GASIFICATION OF CHARCOAL USING AIR AS THE GASIFYING AGENT

4.0 SUMMARY

The following sections describe the results obtained using air as the gasifying medium with charcoal as the primary fuel in the fixed bed downdraft gasifier. The reaction temperatures and gas quality were observed for various air flow rates. It was found that as the air flow rate was increased, the heating valve of the gas reaches a maximum value and then decreases. The point at which the gas has its maximum energy content was noted. This point was used as the fixed point for the other investigations and also for fueling a C.I. engine at a later stage. The heating value of the gas mixture was calculated from a knowledge of the effective heating value of its constituents and the gas analysis.

Slagging occurred in the reactor bed and necessitated frequent cleaning.

4.1 INTRODUCTION

The Gasification of charcoal results in a gas mixture that stores a significant amount of the chemical energy of the charcoal. The chemical reactions that occur during further carbonization and combustion of the charcoal are complex and result in successive exothermic and endothermic phases which on balance are slightly exothermic.

The air used as the gasifying agent is forced through a deep bed of fuel in the closed gasifier. This yields a wide range of gases, as well as condensable vapours consisting of higher hydrocarbon. The products which normally contribute more than 1 percent (%) of the total gas volume are CO, CH_4, H_2, CO_2, N_2, O_2 and H_2O. CO, CH_4 and H_2 are combustibles and the value of the gas as a fuel depends on the proportion in which they are present. An important characteristic of the process is that no external heat is applied to the gasifier, once the burning of the fuel inside the gasifier has started, the air which is used to make the gas, sustains a continuous process of combustion and a sufficiently high temperature is maintained to effect the necessary reaction.

The temperatures, residence time and gas solid contacting methods employed in gasification equipment, strongly affects the degree to which equilibium is attained. Not having these parameters at the required levels can result in a gas mixture with low concentration of combustibles.

If in addition to the air, steam and/or CO_2 were to be passed through the reaction zone, these can be dissociated to H_2 and CO respectively provided the reaction temperatures are appropriate.

4.1.1 Object And Method Of Investigation

The main objective of this part of the investigation was to determine the effects of varying the quantity of air supplied on the gas quality produced. Since the temperature level may be considered a very important parameter in the system, it was considered useful to simultaneously study the effect of air flow rate on temperature and hence, the effect of temperature on gas quality produced.

The arrangement for the air supply is shown in Figure 4.1 and Plate 2-1 and is described in Section 2.3.2. Throughout the investigation, the combustion zone temperature was measured just above the nozzle while the reduction zone temperature monitored, was towards the bottom of the zone (See No. 3, Figure 2.2).

To obtain some degree of uniformity in the charcoal particle size supplied to the gasifier, a mesh size with 2"x2" sections was used for screening.

4.2 RESULTS

4.2.1 Charcoal Analysis

Charcoal samples were taken from several batches crushed and analysed in a Mahler-Cook Bomb calorimeter to determine its calorific value. The average value was found to be 33.2 MJ/kg.

(1) Blower

(2) Valve

(3) Orifice Plate

(4) Manometer

(5) Preheating Jacket

(6) Gas Burner

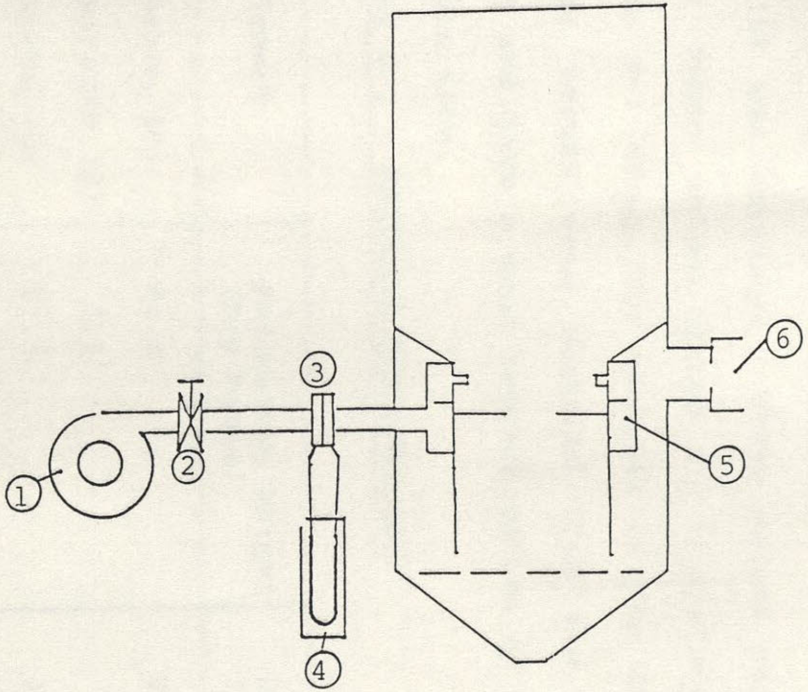


FIGURE 4.1

Arrangement for Air Supply to Gasifier

The moisture content was determined by heating a known weight of charcoal and calculating the loss in weight to a percentage. An average value of 10% was obtained. These values were comparable with other values given in literature (53) (54). Table 4-1 shows the analysis of the charcoal used. These values were obtained from the present work done and gave a good representation of the elemental composition.

TABLE 4-1 - ANALYSIS FOR CHARCOAL

Element	Percentage Weight (Dry basis)	Percentage Weight (Ash free)
Carbon (C)	81.4	84.2
Hydrogen (H)	3.1	3.2
Oxygen (O)	11.3	11.6
Nitrogen (N)	0.8	0.82
Ash	3.4	-

Higher Heating Value (HHV)[a]	33.2 MJ/kg
Lower Heating Value (LHV)	32.5 MJ/kg
Stoichiometric Oxidant Ratio[b]	
Stoichiometric weight O_2/dry charcoal	2.27kgO_2/kg fuel
Stoichiometric weight air/dry charcoal	9.78kg air/kg fuel

---

[a] HHV (LHV) = Heat of combustion with product water in liquid (vapour) form.

LHV KJ/g = HHV Kg/g - 0.2122 x wt% H (14)

[b] $O_{\text{stoichiometric}} = 2.667\ C + 7.94\ H + S - O$ kg/kg fuel (29)

4.2.2 Effect Of Air Flow Rate On The Composition And Energy Content Of The Gas Produced

(i) Equivalence Ratio (ER_{PG})

The concept of Equivalence Ratio (ER_{PG}) has been widely used in the study of hydrocarbon fuel combustion (14) (21). The equivalence ratio is defined as the actual oxidant to fuel ratio divided by the stoichiometric ratio. i.e.

$$ER_{PG} = \frac{\text{Weight of Oxygen/Weight of Charcoal}}{\text{Stoichiometric oxidant/charcoal}} \quad (4-1)$$

For complete combustion of the fuel to CO_2 and water vapour, one of the conditions to be satisfied is that the equivalence ratio must be greater than or equal to 1.0. An equivalence ratio of 0.0, corresponds to thermal decomposition without external oxygen introduced. For gasification as they occur in practice, the equivalence ratio is within the range 0.2-0.4 and this is normally in the partial combustion zone (6). This concept then can be used to describe the main reactions that take place in a gasifier, namely pyrolysis, gasification and combustion since the quality of gas produced can give an indication of the equivalence ratio levels.

(ii) Gasification of Charcoal Using Air

Figure 4.2 is a plot of percentage volume of the various gas constituents as a function of air flow rate. Carbon monoxide (CO) proved to be the main combustible in the gas mixture. With an air flow rate of 0.15 Nm^3/min, the CO concentration had a value of about 25 percent. With a further increase to 0.35 Nm^3/min, the CO concentration reached a maximum value of 32.5% and then decreased as the air flow rate increased further.

The Hydrogen (H_2) content shows a similar behaviour to the CO plot. Starting from a concentration of 3.5% at the lowest air flow rate, the H_2 concentration rose to a maximum value of 7.6%. This occurred at the corresponding air flow rate that gave the CO its maximum value. Beyond this point the H_2 concentration also decreases.

Methane was present in the gas mixture in relatively low quantities. Throughout this investigation the methane gas concentration maintained a value of about 0.05% and was not considered significant.

Carbon dioxide has its highest value of 2.1% at the lowest air flow rate. The concentration then fell to a minimum value

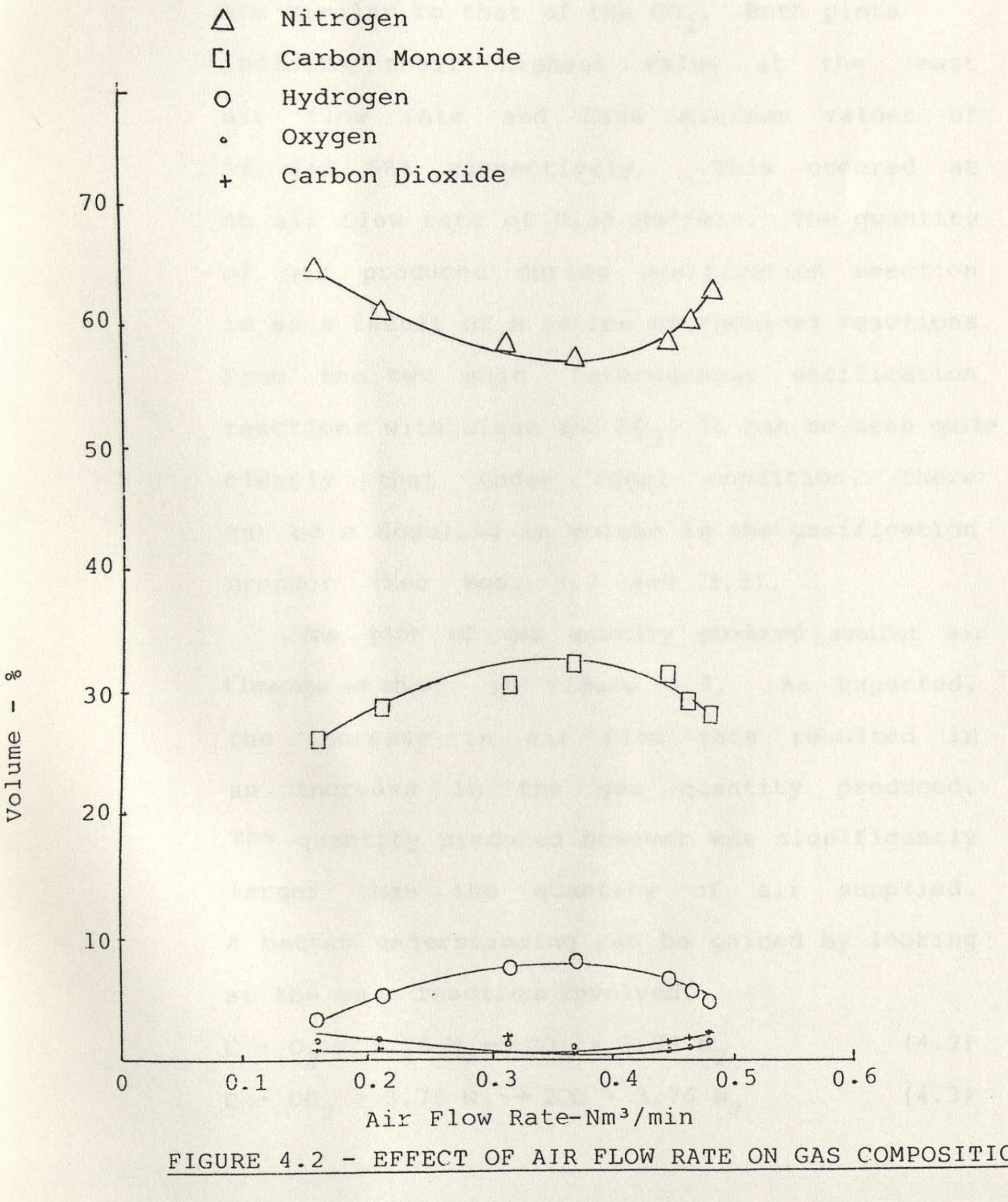


FIGURE 4.2 - EFFECT OF AIR FLOW RATE ON GAS COMPOSITION

of 0.9% at an air flow rate of about 0.4 Nm³/min and then increased steeply beyond this.

The oxygen and the nitrogen plots are similar to that of the CO_2. Both plots indicate their highest value at the least air flow rate and have minimum values of 1% and 58% respectively. This occured at an air flow rate of 0.35 Nm³/min. The quantity of gas produced during gasification reaction is as a result of a series of chemical reactions. From the two main heterogenous gasification reactions with steam and CO_2, it can be seen quite clearly that under ideal condition, there can be a doubling in volume in the gasification product (See Eqs. 3.2 and 3.3).

The plot of gas quantity produced against air flowrate is shown in Figure 4.3. As expected, the increase in air flow rate resulted in an increase in the gas quantity produced. The quantity produced however was significantly larger than the quantity of air supplied. A better understanding can be gained by looking at the main reactions involved.

$$C + O_2 + 3.76\ N_2 \rightarrow CO_2 + 3.76\ N_2 \qquad (4.2)$$

$$C + CO_2 + 3.76\ N_2 \rightarrow 2CO + 3.76\ N_2 \qquad (4.3)$$

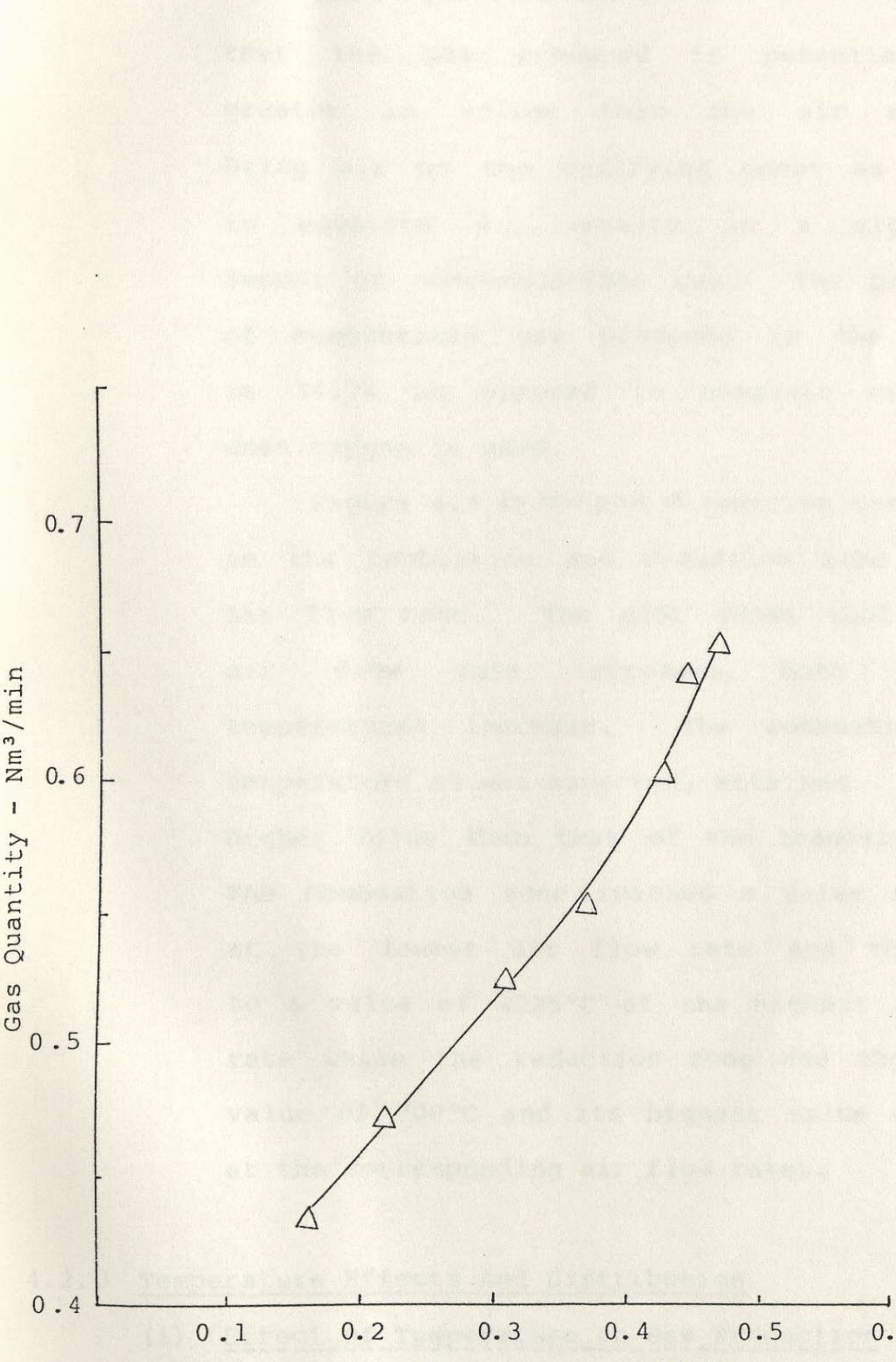


FIGURE 4.3 - EFFECT OF AIR FLOW RATE ON QUANTITY OF GAS PRODUCED

From equations 4.2 and 4.3 it can be seen that the gas produced is potentially 21% greater in volume than the air supplied. Using air as the gasifying agent as is seen in equation 4.3, results in a significant amount of noncombustible gas. The proportion of combustible gas produced in the mixture is 34.7% as opposed to complete conversion when oxygen is used.

Figure 4.4 is the plot of reaction temperature in the combustion and reduction zone against air flow rate. The plot shows that as the air flow rate increases, both reaction temperatures increase. The combustion zone temperature as was expected, attained a much higher value than that of the reduction zone. The combustion zone reached a value of 950°C at the lowest air flow rate and then rose to a value of 1225°C at the highest air flow rate while the reduction zone had its lowest value of 700°C and its highest value of 875°C at the corresponding air flow rates.

4.2.3 Temperature Effects And Distribution

(i) Effect of Temperature on Gas Production

The relationship between gas composition

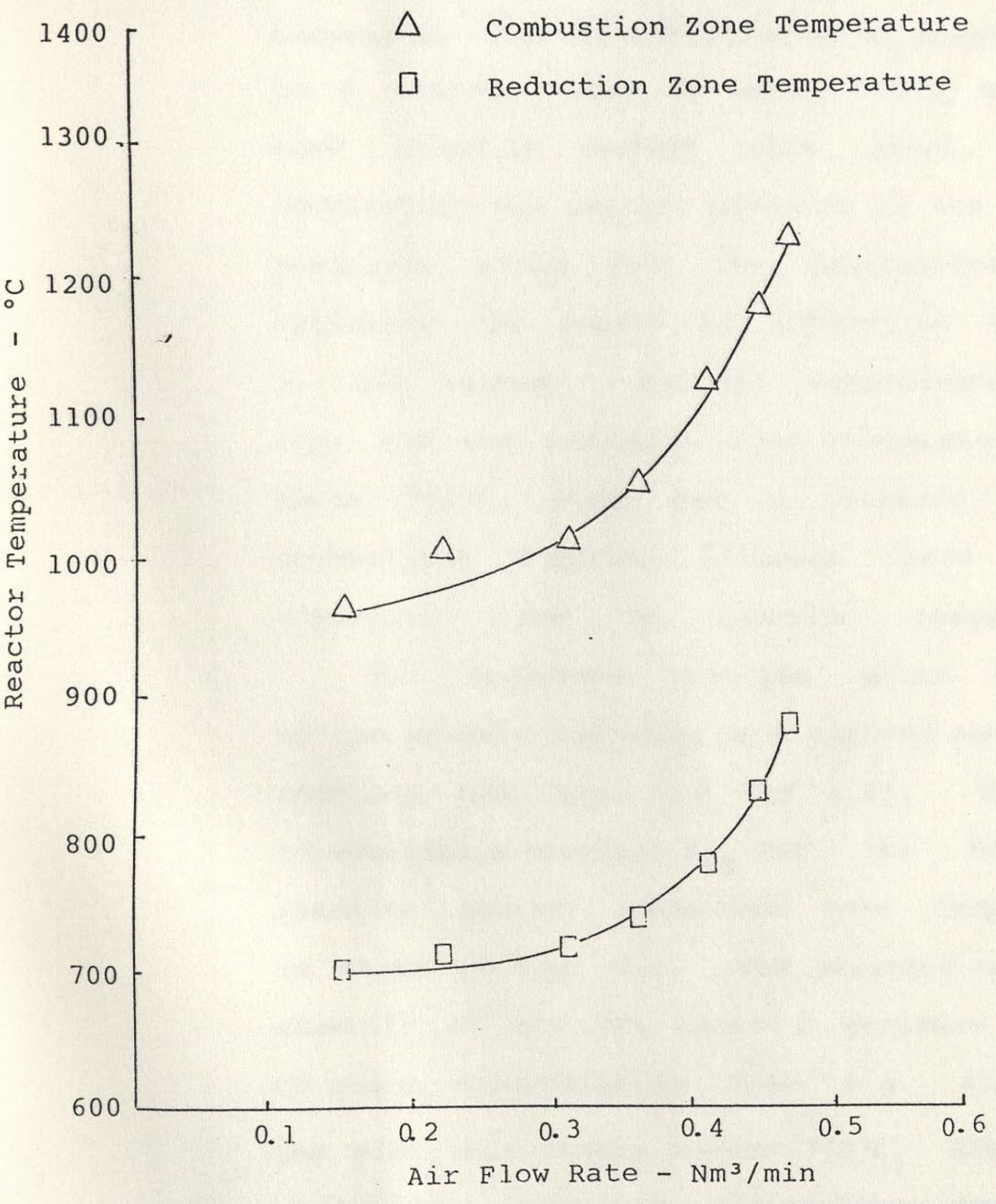


FIGURE 4.4 - EFFECT OF AIR FLOW RATE ON REACTION TEMPERATURE

and reduction zone temperature is shown in Figure 4.5. The plot shows that as the reduction zone temperature increased to 750°C, the levels of CO and H_2 reached their maximum values and beyond this point their concentration decreased. The concentration of CO_2 however fell to a minimum value at about 775°C and then rose steadily beyond this point. The temperature and partial pressure of the gaseous reactants along with the equivalence ratio influence the degree of conversion attained in the system. As the equivalence ratio rose and the reduction zone temperature rose above 775°C, there was a decrease in the combustible fraction although there was a continual rise in reaction temperature.

The Boudouard reaction which is one of the primary reaction, is a typical equilibium reaction (See Eqs. 3.2 and 3.8). The plot of equilibium constant K_{PB} for the Boudouard reaction against reduction zone temperature is shown in Fig. 4.6. The presence of large quantity of air can cause a decrease in the CO and H_2 concentration (See Fig. 4.2). For the plot this occurs beyond 775°C. Equilibium conditions which are temperature dependent,

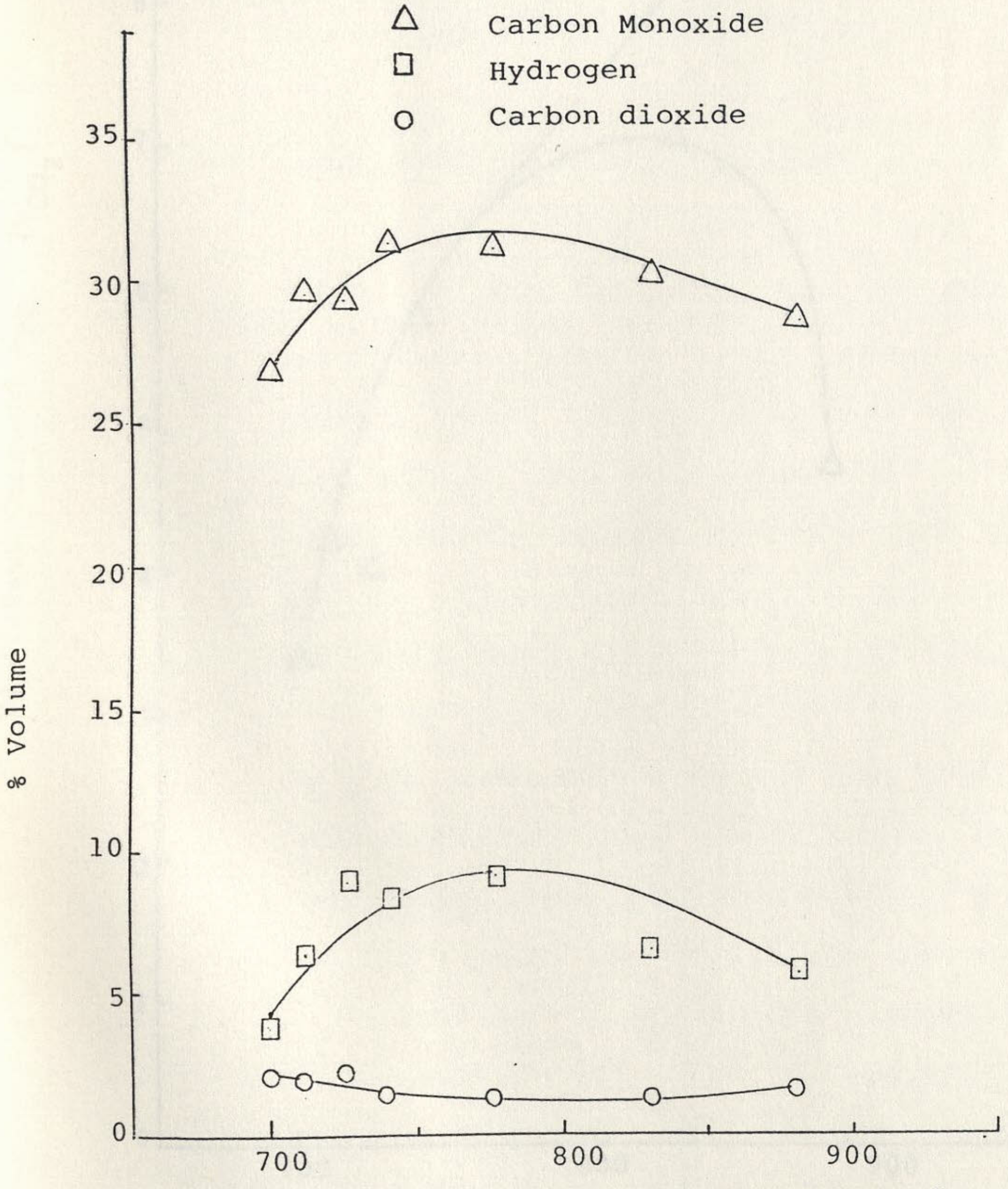


FIGURE 4.5 - GAS COMPOSITION AS A FUNCTION OF REDUCTION ZONE TEMPERATURE

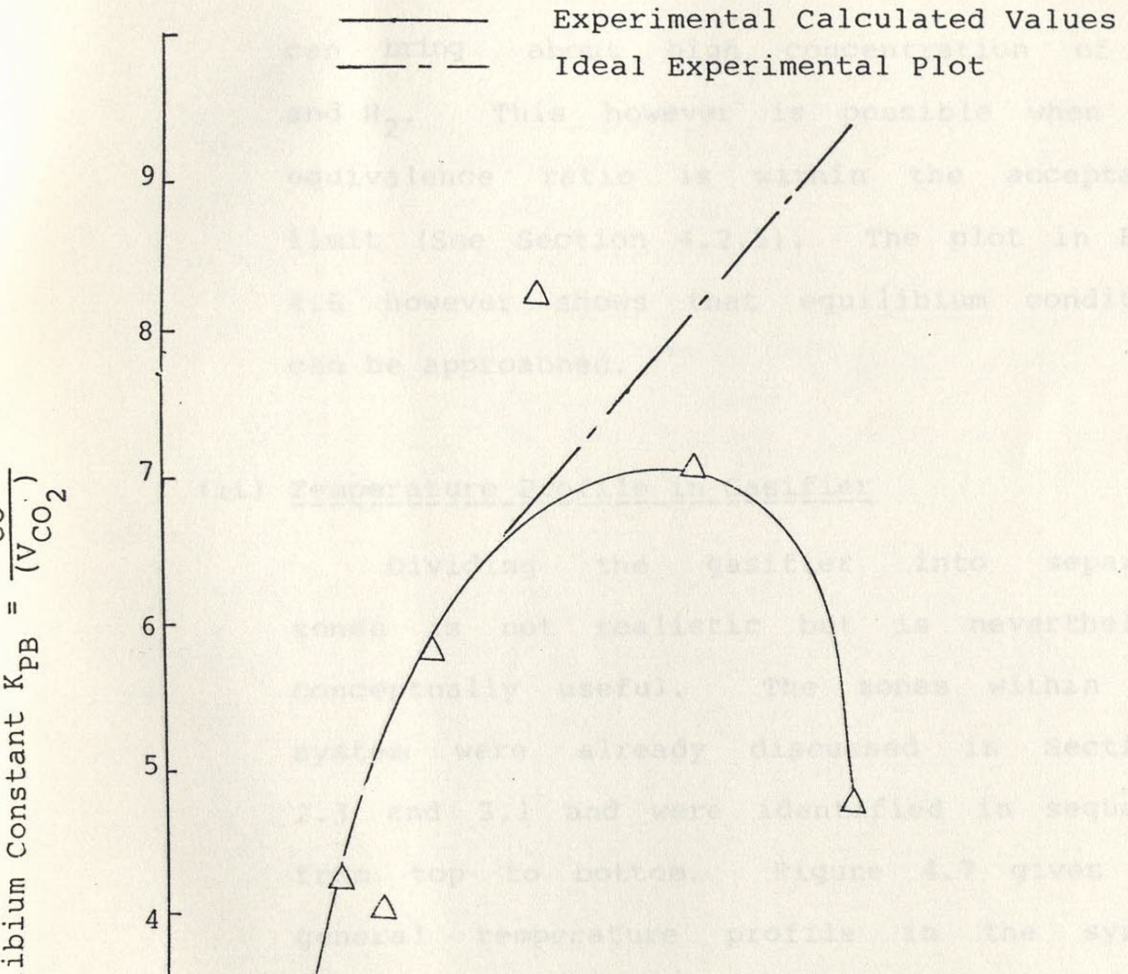


FIGURE 4.6 - EQUILIBIUM CONSTANT K_{PB} FOR BOUDOUARD REACTION

can bring about high concentration of CO and H_2. This however is possible when the equivalence ratio is within the acceptable limit (See Section 4.2.3). The plot in Fig. 4.6 however shows that equilibium condition can be approached.

(ii) Temperature Profile in Gasifier

Dividing the gasifier into separate zones is not realistic but is nevertheless conceptually useful. The zones within the system were already discussed in Sections 2.3 and 3.1 and were identified in sequence from top to bottom. Figure 4.7 gives the general temperature profile in the system at the highest air flow rate of 0.46 Nm^3/min.

The highest temperature as expected occurs in the combustion zone and was about 1250°C. The reduction zone which lies below the combustion zone maintained a temperature in the region 700-875°C. The pyrolysis zone lies immediately above the combustion zone. No temperature was taken in this zone. Within this section of the reactor however the devolatalization of the fuel usually takes place and it is expected that the zone would

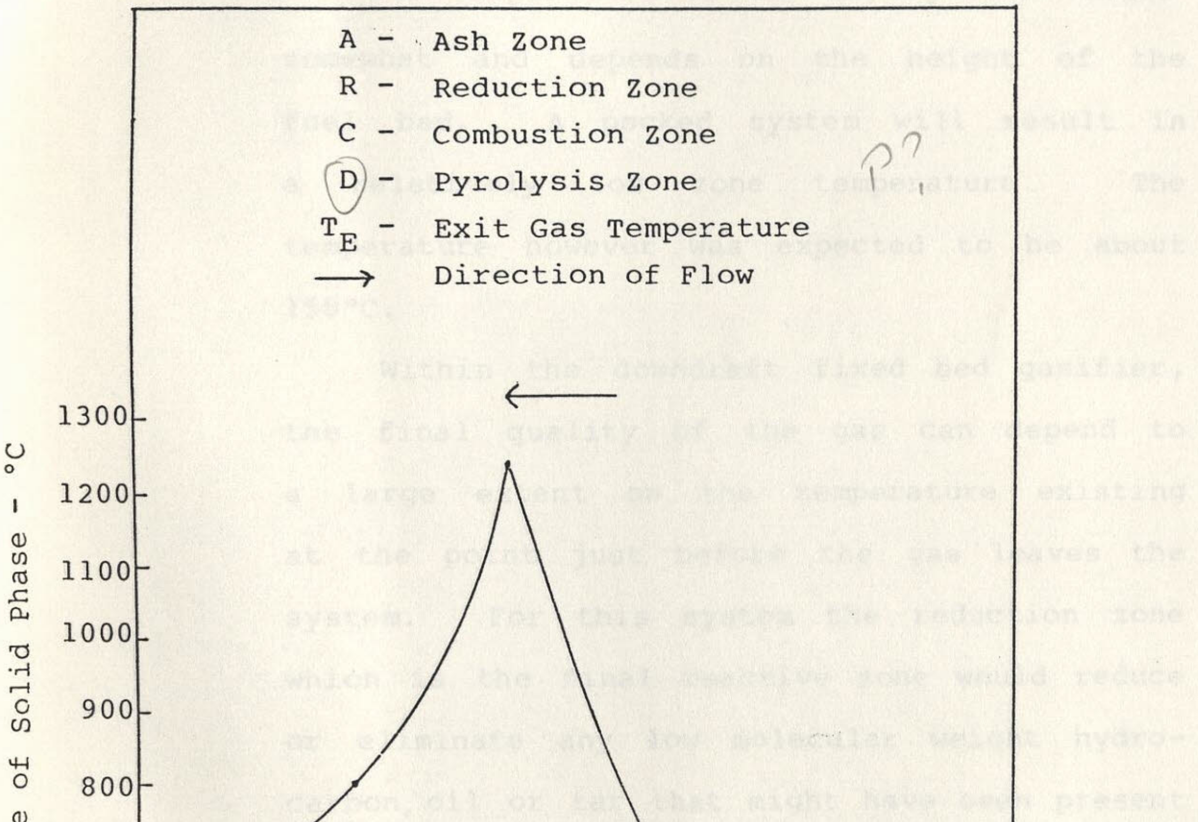


FIGURE 4.7 - TEMPERATURE PROFILE OF GASIFIER OF AIR FLOW RATE OF 0.46 Nm³/min

maintain a temperature in the range of 200-500°C.

The temperature of the drying zone varies somewhat and depends on the height of the fuel bed. A packed system will result in a relatively low zone temperature. The temperature however was expected to be about 150°C.

Within the downdraft fixed bed gasifier, the final quality of the gas can depend to a large extent on the temperature existing at the point just before the gas leaves the system. For this system the reduction zone which is the final reactive zone would reduce or eliminate any low molecular weight hydrocarbon, oil or tar that might have been present in the gas mixture (4) (50). No tests were performed to investigate the presence of oil and tars.

4.3 GENERAL EFFICIENCY OF PROCESS

4.3.1 Gas Heating Value

The curves in Fig. 4.8 illustrates the variation between the calorific value, sensible heat and total heating value of the gas with air flow rate. This was calculated after a gas analysis was done and the effective heating value of the gas

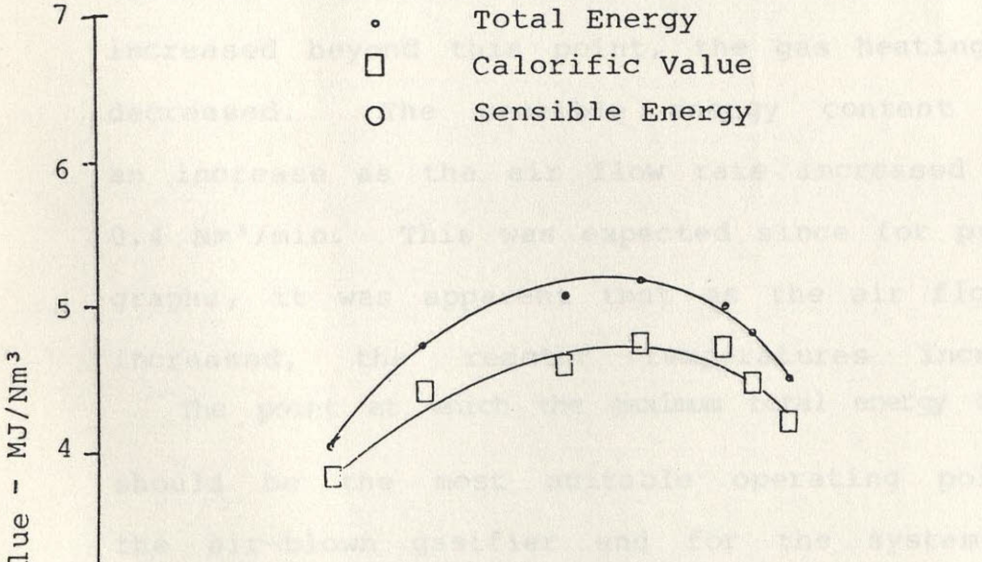


FIGURE 4.8 - HEATING VALUE OF GAS AS A FUNCTION OF AIR FLOW RATE

constituents determined. The sensible heat is effectively the quantity of heat carried by the gas from the gasifier and was based on the value of the gas temperature leaving the gasifier (See Figure 4.9). The calorific value of the gas had a maximum value of 4.75 MJ/Nm^3 at an air flow rate of 0.35 Nm^3/min and as the air flow rate increased beyond this point, the gas heating value decreased. The sensible energy content showed an increase as the air flow rate increased beyond 0.4 Nm^3/min. This was expected since for previous graphs, it was apparent that as the air flow rate increased, the reactor temperatures increased.

The point at which the maximum total energy occurred should be the most suitable operating point of the air-blown gasifier and for the system under study, the optimum air flow rate is 0.35 Nm^3/min.

4.3.2 Charcoal Consumption

The efficiency of the system may be assessed in terms of the gas produced to the charcoal consumed. Figure 4.10 shows the effect of air flow rate on charcoal consumption*. As is expected, the charcoal consumption increases with air flow rate almost linearly but tends to fall off at higher

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* See Appendix 1(ii) for method used to determine charcoal quantity consumed.

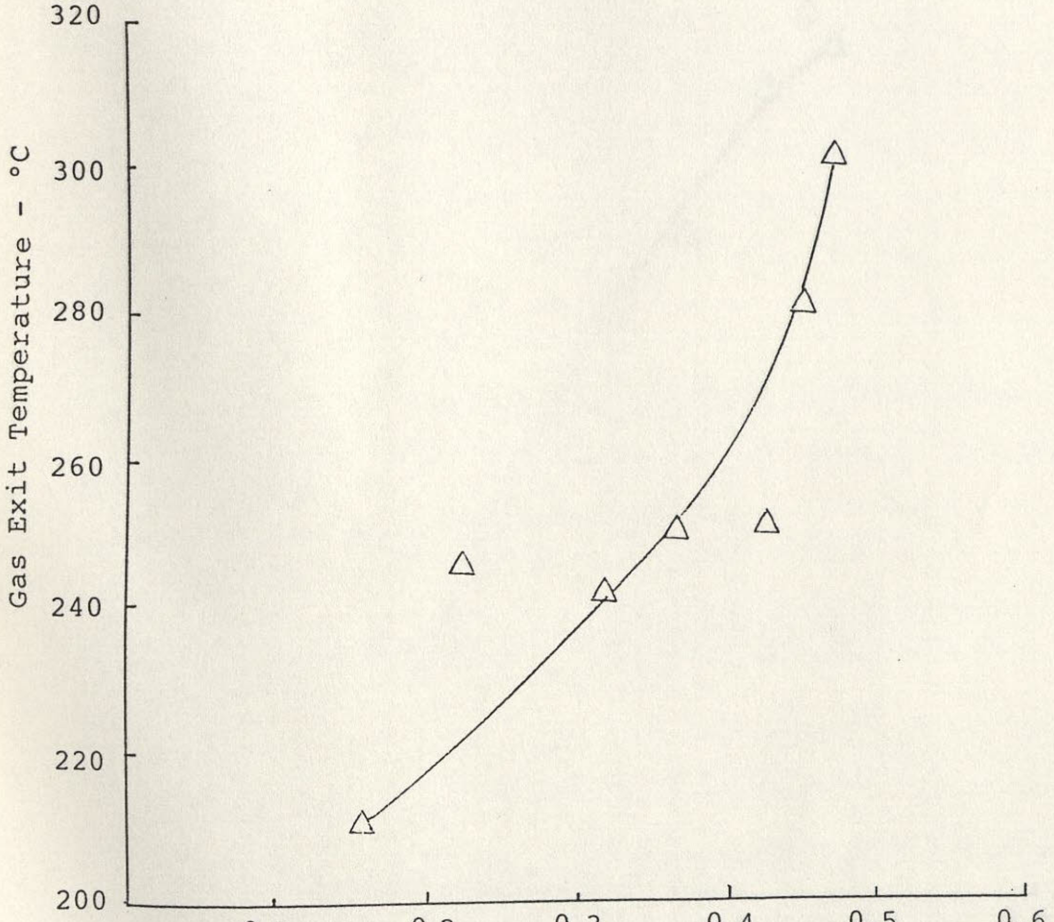


FIGURE 4.9 - EFFECT OF AIR FLOW RATE ON GAS EXIT TEMPERATURE

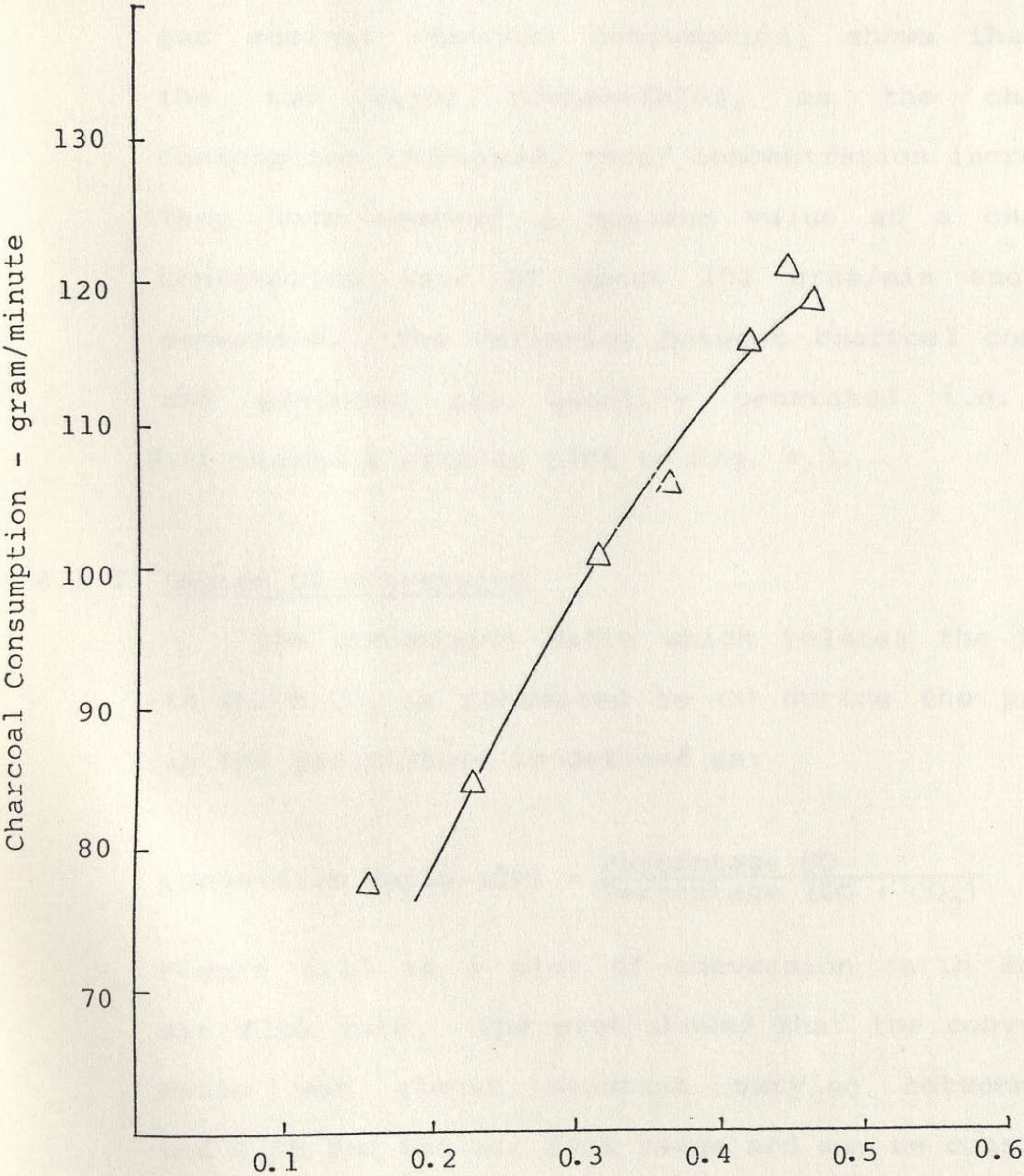


FIGURE 4.10 - EFFECT OF AIR FLOW RATE ON CHARCOAL CONSUMPTION

air flow rates.

Figures 4.11 and 4.12 show the variation of other parameters with charcoal consumption. Figure 4.11 which is a plot of percentage volume of the various gas constituents in the producer gas against charcoal consumption, shows that for the two major combustibles, as the charcoal consumption increased, their concentration increased. They both reached a maximum value at a charcoal consumption rate of about 100 gram/min and then decreased. The variation between charcoal consumed and producer gas quantity generated i.e. Fig. 4.12 showed a similar plot to Fig. 4.3.

4.3.3 Degree Of Conversion

The conversion ratio which relates the degree to which CO_2 is converted to CO during the process in the gas mixture is defined as:

$$\text{Conversion Ratio (CR)} = \frac{\text{Percentage CO}}{\text{Percentage } (CO + CO_2)} \qquad (4.4)$$

Figure 4.13 is a plot of conversion ratio against air flow rate. The plot showed that the conversion ratio was almost constant varying between 0.9 and 0.95 for the air flow range and may be considered very satisfactory. In addition to Conversion Ratio, the conversion efficiency can be expressed

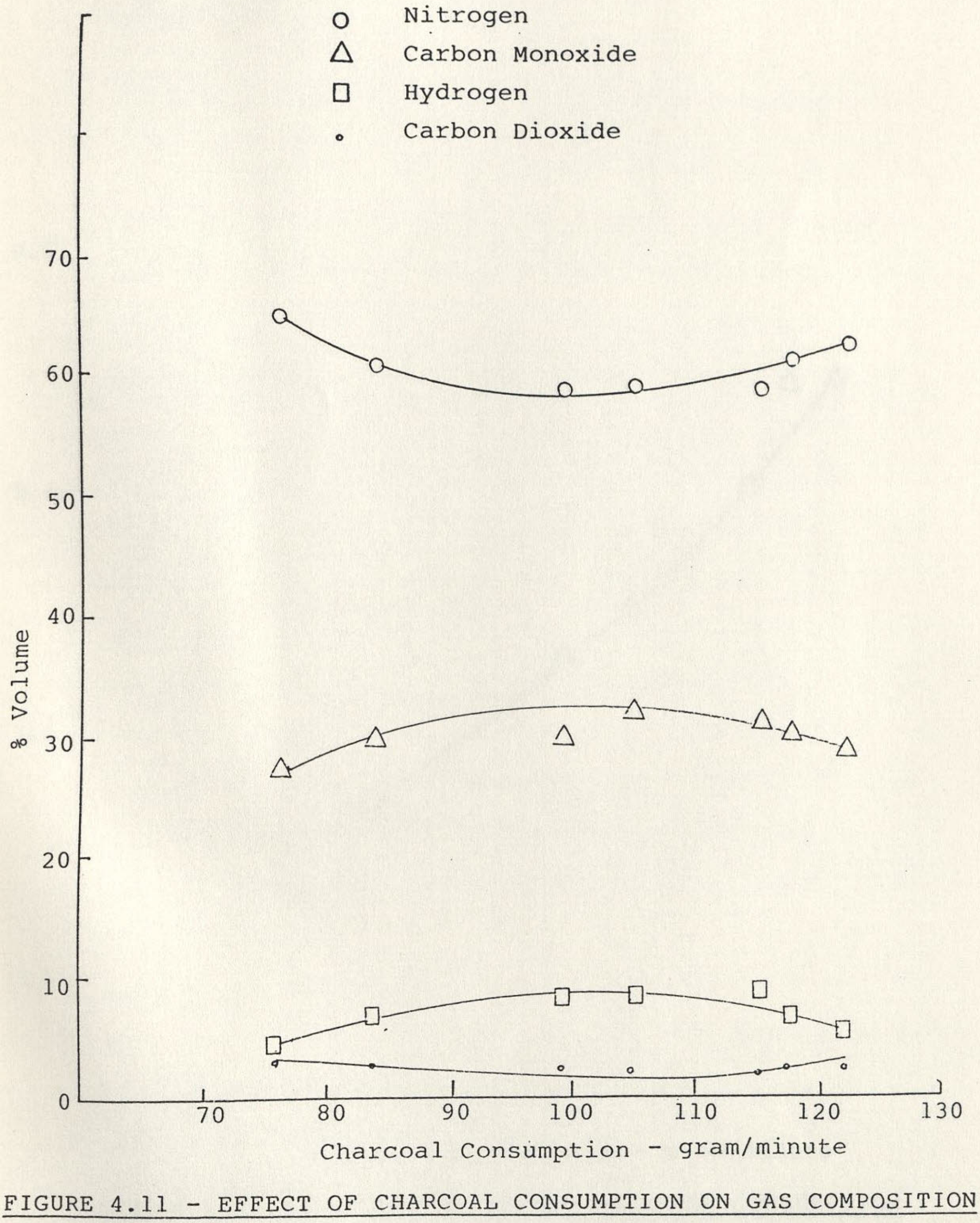


FIGURE 4.11 - EFFECT OF CHARCOAL CONSUMPTION ON GAS COMPOSITION

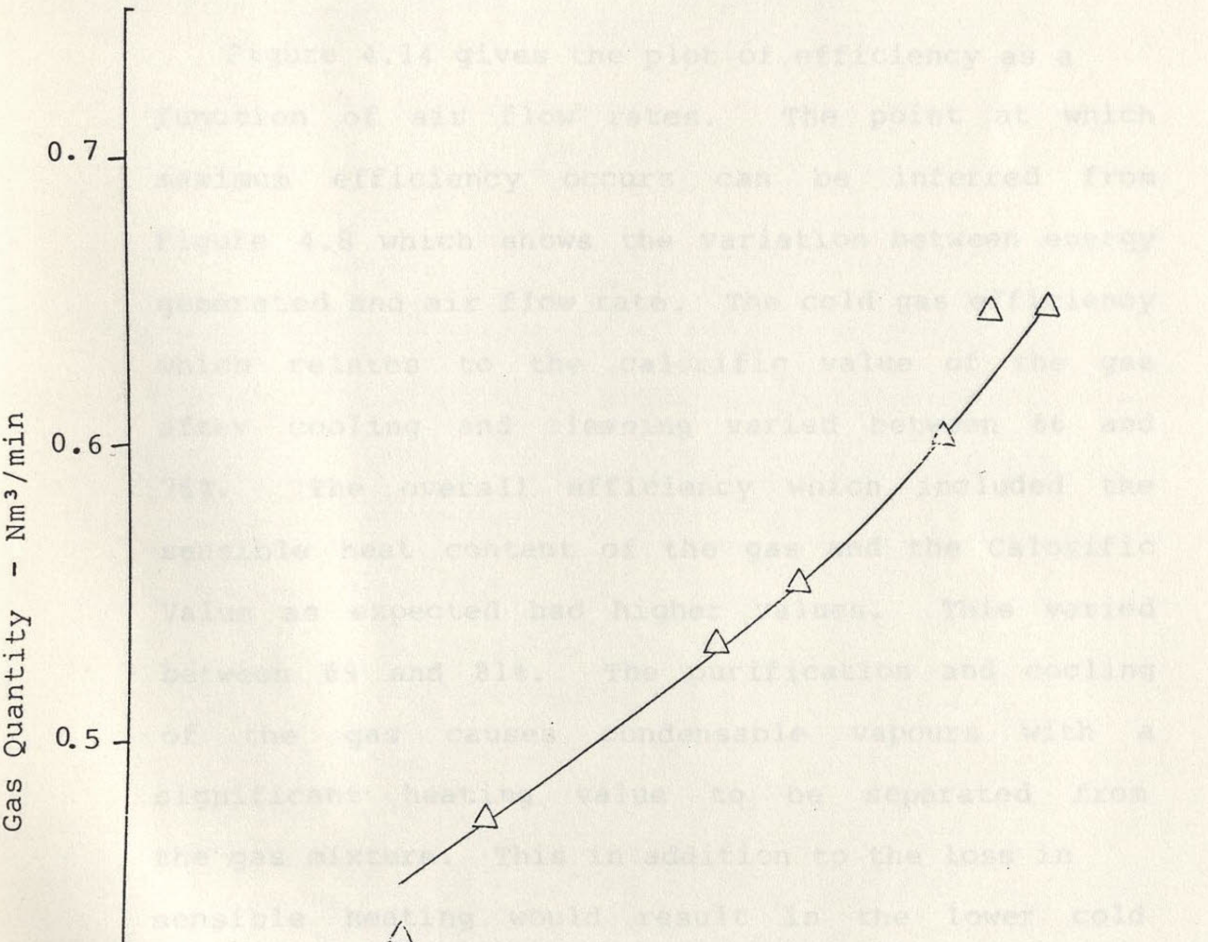


FIGURE 4.12 - GAS QUANTITY VERSUS CHARCOAL CONSUMPTION

in terms of overall heating value of the gas produced and that of the quantity of charcoal consumed during the process i.e.

$$\text{Efficiency} = \frac{\text{Heating value of gas}}{\text{Heating value of charcoal consumed}} \quad (4.5)$$

Figure 4.14 gives the plot of efficiency as a function of air flow rates. The point at which maximum efficiency occurs can be inferred from Figure 4.8 which shows the variation between energy generated and air flow rate. The cold gas efficiency which relates to the calorific value of the gas after cooling and cleaning varied between 66 and 76%. The overall efficiency which included the sensible heat content of the gas and the Calorific Value as expected had higher values. This varied between 69 and 81%. The purification and cooling of the gas causes condensable vapours with a significant heating value to be separated from the gas mixture. This in addition to the loss in sensible heating would result in the lower cold gas efficiency.

4.4 SLAGGING IN GENERATOR

The mineral content in the fuel that remains in oxidised form after complete combustion is usually termed ash. From the initial analysis of the charcoal, it was noted that the ash content

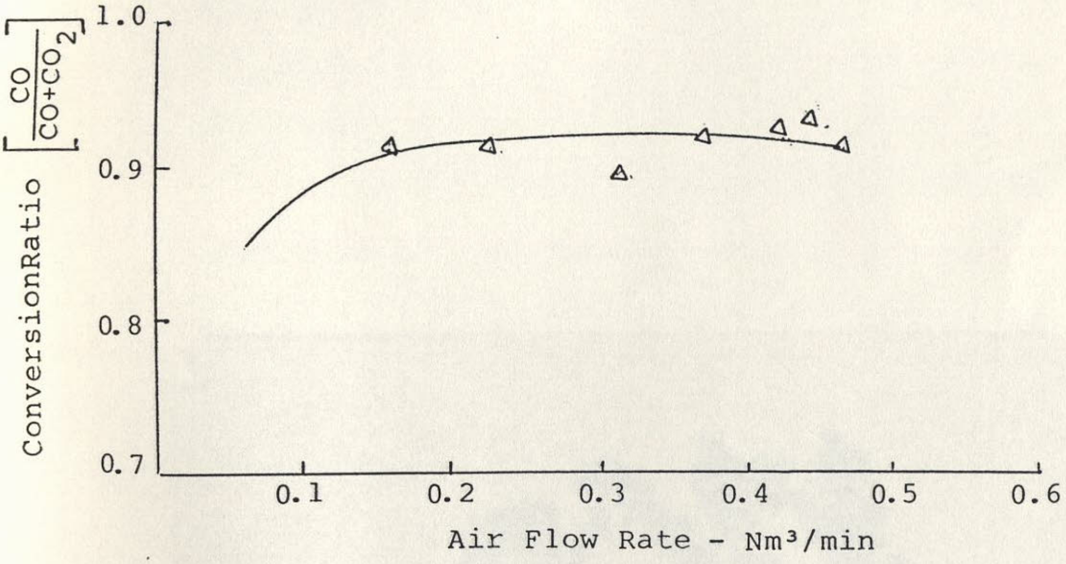


FIGURE 4.13 - EFFECT OF AIR FLOW RATE ON CONVERSION RATIO

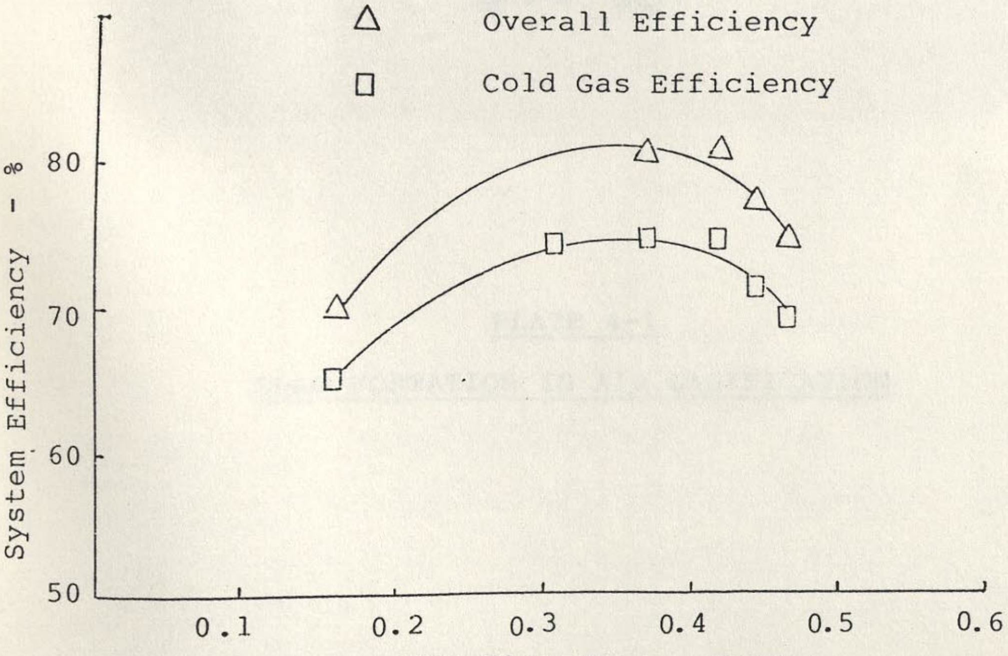


FIGURE 4.14 - EFFECT OF AIR FLOW RATE ON SYSTEM EFFICIENCY

PLATE 4-1

SLAG FORMATION IN AIR GASIFICATION

was 3.4% (See Table 4.1). The silicon element content was found by digesting the other minerals present in the ash mixture with a strong solution of acid and calculating the percentage weight difference and was found to be about 60% of the ash content. The high temperatures reached during reactions can cause the silicon dioxide to melt and form slags. This occurs at temperatures above 2000°C (6) (21).

Frequently, particularly when there is significant variation in the feed size, there occurs a phonemenon known as "Bridging" in which contact between feed stock masses, cause a mal-distribution of air flow rate leading to local "hot spots" in which melting of the silicon dioxide takes place. The molten silica tends to flow together to form large clinkers which adhere to internal surfaces thereby, reducing the reactor volume and obstructing fuel flow and air flow. Typical clinker obtained are shown in Plate 4-1.

4.5 DISCUSSION

As mentioned earlier (in Section 4.2.4) the level of temperature attained in the system is of primary importance to the overall operation of the gasifier. The combustion zone which starts the initial oxidation process does this with sufficient oxygen to favour almost complete CO_2 formation. The gas stream which issues from this zone is hot and rich in CO_2 and steam. The high temperature favours kinetically and thermodynamically the Boudouard reaction and the Water Gas reaction. The products of pyrolysis and combustion which are drawn through the bed of charcoal with temperatures between 650°C and 875°C approach equilibium closely. This can be seen in Figure 4.2 where the concentration of CO_2 reached its mimimum value while the concentration of CO reached its maximum value at an air flow rate of about 0.35 Nm^3/min.

Throughout the investigation, as was expected the combustion zone temperature maintained much higher values than those in the reduction zone (See Figure 4.4). The reduction reactions that occur in the zone are temperature controlling and controls the upper limit of the temperature in the zone. The temperature stabilization phonemenon (14) helps to explain what happens. When the system attempts to attain a temperature higher than usual, then the endothermic reactions are thermodynamically favoured and begins to moderate the temperature. At very high temperatures, the reduction reaction constitutes an effective heat sink and limits further rise in temperature. Hence as the reaction temperature increases, the percentage of CO and hydrogen will rise if the equivalence ratio is within the allowable limit (See Sections 4.2.3 and 4.2.4).

The concept of equivalence ratio which was introduced earlier can play a major role in:

(1) Determining the size of the reactor.
(2) Determining the quantity of air to be supplied.
(3) Determining the quantity of charcoal that should be available for the reaction.

For the gasifier system used, a knowledge of the air flow rate and the equivalence ratio required for gasification, made it possible to estimate the charcoal requirement for the reactor. Using the bulk density of the charcoal, a suitable volume could be arrived at.

From the definition of equivalence ratio, it is apparent then that too high a value, could contribute to the production of unfavourable gas quality. This to some extent could have been the case at the latter part of the investigation where the levels of combustibles in the gas mixture fell while the levels of the CO_2 and O_2 in the gas mixture was increased (See Figure 4.2). For the initial stage of the reaction a high equivalence ratio is required for a successful combustion process. Following this reaction low equivalence ratio are desired for the gasification process.

In addition to the effects of temperature and equivalence ratio on the gas quality and quantity produced, the uniformity of the charcoal particle size and shape can play a significant role in the efficient performance of the system. The physical process that transports one reactant to the other is referred to as mass exchange or mass transport. This is extremely essential if the reaction sequence is to proceed in the order pyrolysis, combustion and reduction. This transfer depends to a great deal on the characteristic of the gas flow and on the fuel flow. The amount of surface area, the particle size and the bulk density are some of the more important parameters that governs the actual consumption rate of charcoal.

With the obvious irregularities in particle shape and size, the air blast and partially converted gas can be forced through the uneven fuel bed caused by the separation of the fine and the coarse particles. This would then mean that the rate of gasification and hence the rate of fuel consumption will be reduced. Undersized particles can cause large variation in pressure drop and inability of the oxygen to penetrate the fuel bed.

The use of a mesh for screening of the charcoal particle used in the gasifier, was largely successful in eliminating larger particles although as could be expected, the smaller particles got through. The process however significantly reduced the variation in particle size.

When the air supplied is excessive, oxygen can pass over to the reduction zone and find its way into the gas produced. This undesirable occurence can be as a result of bridging (See Section 4.6). One of the effect of bridging is that, the residence time for the reacting gas, can be significantly reduced, and hence low quality gas can result. Bridging can cause high reaction temperature and in addition to slagging, the excessive temperature can cause reactor burn out. This would then require periodic repairs of reaction chamber.

Throughout the investigation it was quite noticeable that the concentration of methane (CH_4) in the gas mixture was below 1%. This is due possibly to the fact that the most favourable temperature for methane formation is between 300 and 400°C (6) (15) (16) (50). The reactor was operated at much higher temperatures the lowest being 650°C. At these high temperatures the equilibium is shifted towards rapidly decreasing quantities of CH_4. The charcoal which was used throughout the investigation had already undergone devolatilization when manufactured from mixed forest wood and in effect got rid of most of the lower molecular weight hydrocarbon, alcohol, acids, oil and tars present. If however there were volatiles in the charcoal, because of the high temperatures that exists in the reaction zone the hydrocarbons would undergo cracking and reforming to H_2, CO and CO_2. This hydrogenation process is exothermic and therefore supplies heat for endothermic reactions.

Theoretically when carbon is converted to carbon monoxide in the producer, a significant amount of the heat of combustion of the carbon is liberated; the remaining depending on end use will be liberated when the CO is burnt to CO_2 afterwards. All the heat set free however in the producer is not wasted but will be carried in the form of sensible heat by gas as it leaves the system at high temperatures. If the gas is used at this stage, not much of this sensible heat will be lost. Theoretically it may be possible for the energy content of the gas to approach the same energy content as that of the solid fuel. In practice however this is not possible. The chief difficulties lie in the fact that, all the CO_2 in the oxidation reaction will not be converted to CO; that there must be some loss of heat by radiation from reactor surface and that it is not possible to transport sensible heat from one point to the other without loss, especially at high prevailing temperatures.

The total energy supplied by the gas as mentioned before was as a result of the calorific value and sensible energy generated. The plot in Figure 4.8 showed that as the air flow rate increased to 0.4 Nm^3/min the calorific value of the gas started to decrease. This was not the case with the sensible heat since its value is dependent on the exit temperature which increased continueously with increasing air flow rate.

Internal burning of the combustible fraction CO and H_2 can occur when there is oxygen present towards the end of the combustion zone. This can result in several things taking place.

(1) The content of CO_2, steam and N_2 increasing and thereby reducing the quantity of gas produced.

(2) There will be an increase in the sensible

heating value of the gas.

(3) A reduction in the calorific value of the gas.

The occurrence beyond 0.35 Nm³/min of air flow suggests that this could have in fact affected the reduction in combustibles since, as the air flow rate and the reactor temperatures were increased, the level of the combustible fraction decreased.

4.6 CONCLUSIONS

The foregoing investigation describes the effects of varying air flow rate on the performance of a fixed-bed downdraft gasifier. Several conclusions were drawn and they may be summarised as follows:-

(1) The gasifier produced gas with a maximum calorific value of 4.7 MJ/Nm³.

(2) The maximum CO concentration in the producer gas was 32% by volume.

(3) The maximum H_2 concentration in the producer gas was 7.6%.

(4) The CH_4 content was very low.

(5) The quantity and quality of the gas does not depend totally on temperature but also on the quantity of air supplied. This was observed during the investigation when although

the temperature was increasing with increasing air quantity, the quality of the gas produced decreased.

(6) Significant amount of slagging can occur in a fixed bed downdraft gasifier using air and charcoal.

CHAPTER 5

THE GASIFICATION OF CHARCOAL USING A MIXTURE OF AIR AND STEAM AS THE GASIFYING AGENT

5.0 SUMMARY

This chapter deals with the effect of using a mixture of air and steam as the gasifying agent. The air flow rate was fixed at 0.36 Nm^3/min. This flow rate gave the highest heating value of the gas produced in the previous test. The steam which was generated in the system from water supplied was increased in gradual steps. Gas quality and temperatures were monitored. It was found that as the water feed was increased, the reaction temperatures decreased and beyond a certain feed rate, the gas heating value decreased. It was however possible to obtain a gas with a heating value comparable to that of the previous test at the lower reaction temperature levels.

5.1 INTRODUCTION

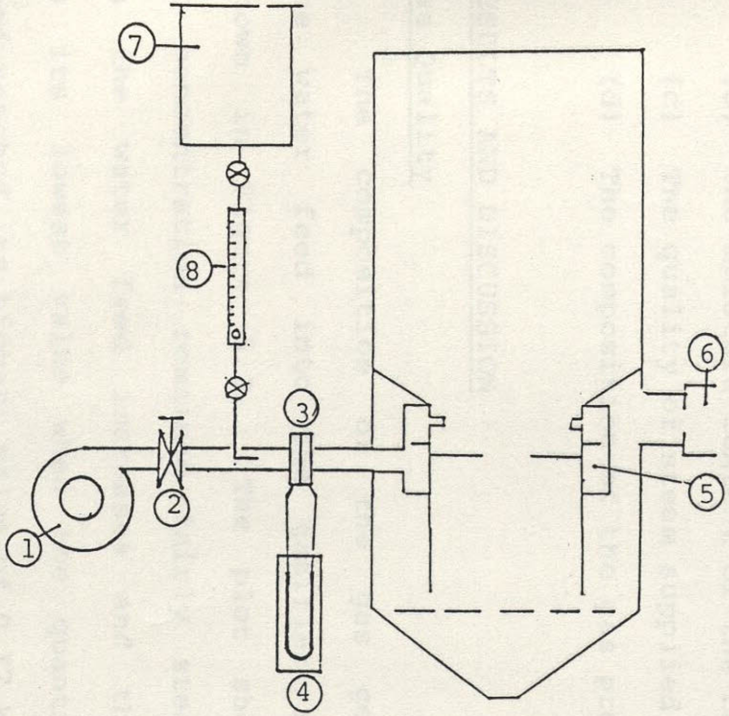
The chief objective of this part of the investigation was to determine the influence of steam on the general working and efficiency of the system. The supply of air to the gasifier was therefore kept fixed at 0.36 Nm^3/min while the steam supply was varied between 0.005 and 0.17 kg/kg charcoal consumed. The air flow rate was chosen from the results described in Chapter 4 and was the value that gave the gas its highest energy content. The steam required for this purpose was generated within the gasifier while the air was supplied in the same manner as in the previous test.

Large quantities of steam can affect the gasifier's operating efficiency since, too large a steam quantity could infact significantly affect the reaction temperatures and thereby, affect the gas quality and quantity. Throughout the experiment, the parameters relevant to the air and steam gasification process were noted and from the findings, it was expected that they would be appropriate for similar systems and hence throw some more light on the topic.

5.1.1 Method of Approach

(i) Steam Generation and Supply

Water stored in a tank was metered through a Gilmount shielded flow meter. The water was transported by the primary air stream to the manifold adjacent to the combustion zone (See Figure 5.1) where it was converted to steam. The steam then entered the fixed fuel bed in the combustion zone through nozzles. The temperature of the steam generated was monitored by a chromel alumel thermocouple



(1) Blower
(2) Valve
(3) Orifice Plate
(4) Manometer
(5) Pre-heating Jacket
(6) Gas Burner
(7) Water Reservoir
(8) Water Flow Meter

FIGURE 5.1

Gasifier with Water Feed System

placed in the steam jacket (See general arrangement in Plate 2-1).

(ii) Steam Decomposition

The quantity of steam decomposed during the thermal reactions, was determined based on a mass balance. The mass balance took into account the following:

(a) The elemental composition of the charcoal used.

(b) The moisture content of the charcoal.

(c) The quality of steam supplied.

(d) The composition of the gas produced.

5.2 RESULTS AND DISCUSSION

5.2.1 Gas Quality

The composition of the gas generated when the water feed into the gasifier is varied is shown in Figure 5.2. The plot shows that the CO concentration remained fairly steady initially as the water feed increases and then decreases to its lowest value when the quantity of water feed reached its highest value of 0.17 kg/kg charcoal consumed.

The H_2 concentration rose from a value of about 5.5% at the lowest water feed to a maximum

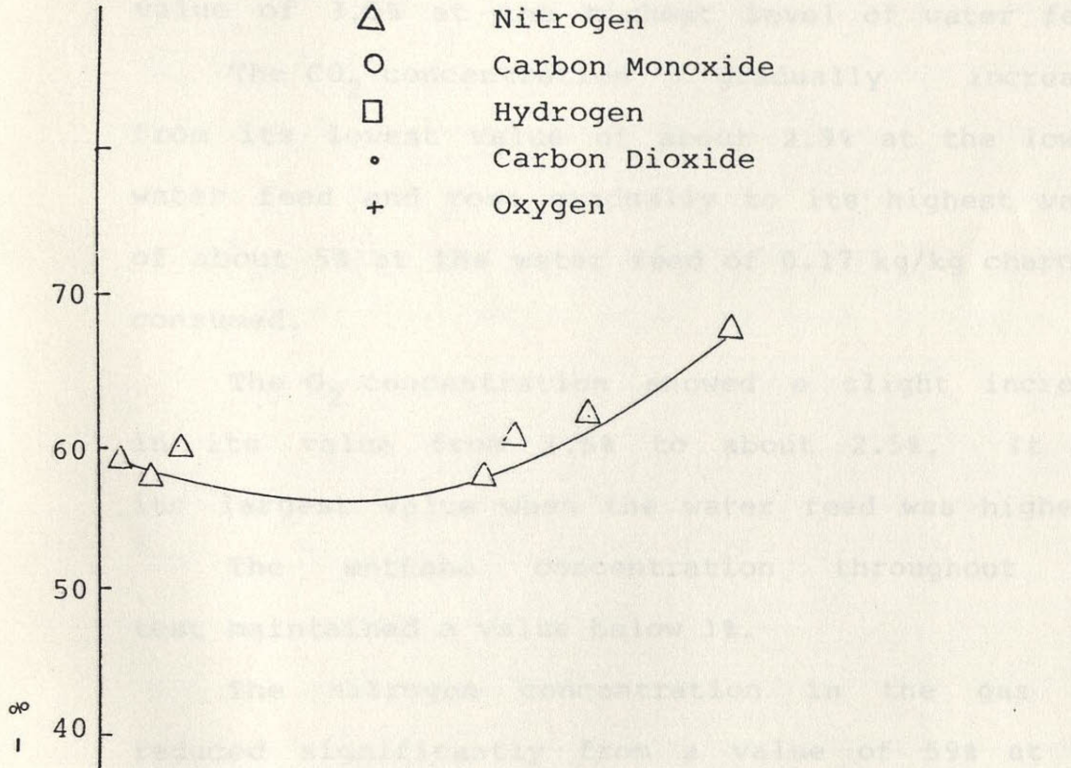


FIGURE 5.2 - GAS COMPOSITION VERSUS WATER INJECTED

value of about 8.25% at a water feed of 0.07 kg/kg charcoal consumed and then decreased to its lowest value of 3.5% at the highest level of water feed.

The CO_2 concentration gradually increased from its lowest value of about 2.9% at the lowest water feed and rose gradually to its highest value of about 5% at the water feed of 0.17 kg/kg charcoal consumed.

The O_2 concentration showed a slight increase in its value from 1.5% to about 2.5%. It had its largest value when the water feed was highest.

The methane concentration throughout the test maintained a value below 1%.

The nitrogen concentration in the gas was reduced significantly from a value of 59% at the lowest water feed, to its minimum value of 55% at a water feed of about 0.07 kg/kg charcoal consumed and then steadily increased to its highest value of 67.5% at the largest water feed.

It is interesting to note that the concentration of CO_2 gradually increased as the water feed was increased. This of course is apparent since the CO concentration showed the reverse in its level. This appears to be as a result of the cooling down of the reactor.

Another noticeable point that showed up in the test was that there was an increase in the H_2 concentration as the water feed was increased to 0.07 kg/kg charcoal and beyond that point the H_2 concentration fell from its maximum value to its lowest value. It was also beyond this point, where the H_2 had its maximum concentration of 8.25%, that the CO level started to decrease significantly. This point as seen in Figure 5.3 corresponds to a water decomposition of about 15% of the total weight of water supplied to the gasifier. These observations seems to relate to the water shift reaction Eq. 3.5 i.e.

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

and is very important as it shows that there is a maximum amount of steam that can be decomposed by the charcoal at the prevailing operating temperatures.

Figure 5.3 show that total water decomposition never occured throughout the investigation and that the fraction of steam that was decomposed gradually fell from 77% to below 5% as the water feed was increased.

Figure 5.4 shows the variation between water feed and water decomposed per kilogram charcoal consumed. The plot shows that as the water feed was increased from 5 x 10^{-3} to about 0.06 kg/kg

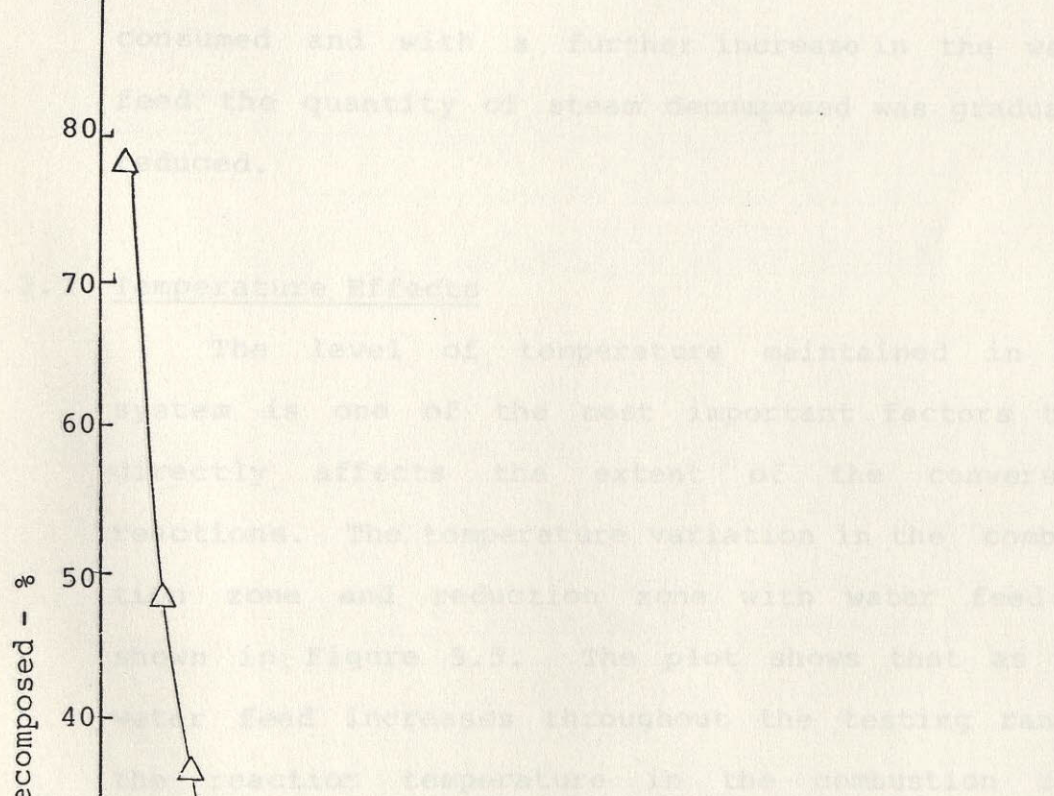


FIGURE 5.3 - PERCENTAGE WATER DECOMPOSED

charcoal consumed, the quantity of steam that was decomposed by the charcoal gradually increased to a maximum value of about 0.016x10^{-2} kg/kg charcoal consumed and with a further increase in the water feed the quantity of steam decomposed was gradually reduced.

5.2.2 Temperature Effects

The level of temperature maintained in the system is one of the most important factors that directly affects the extent of the conversion reactions. The temperature variation in the combustion zone and reduction zone with water feed is shown in Figure 5.5. The plot shows that as the water feed increases throughout the testing range, the reaction temperature in the combustion zone fell from 975°C to about 750°C and the reduction zone temperature rose to a maximum value of about 820°C and then fell to a value of about 725°C. Between the water feed of 0.025 and 0.104 kg/kg charcoal, the combustion temperature remains fairly steady at a value of about 830°C. It is also between this range that the reduction zone temperature reached its maximum value.

It seems apparent from the temperature plot that with the combustion zone temperature above

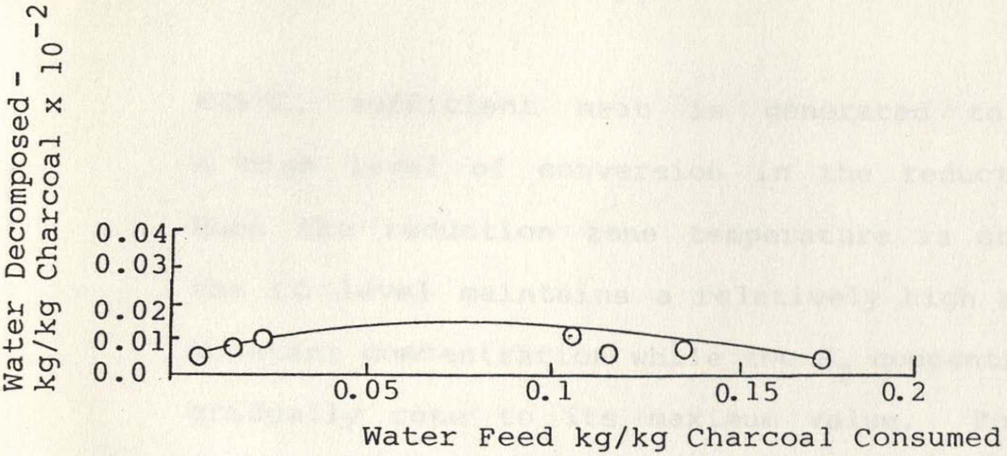


FIGURE 5.4 - QUANTITY OF WATER DECOMPOSED

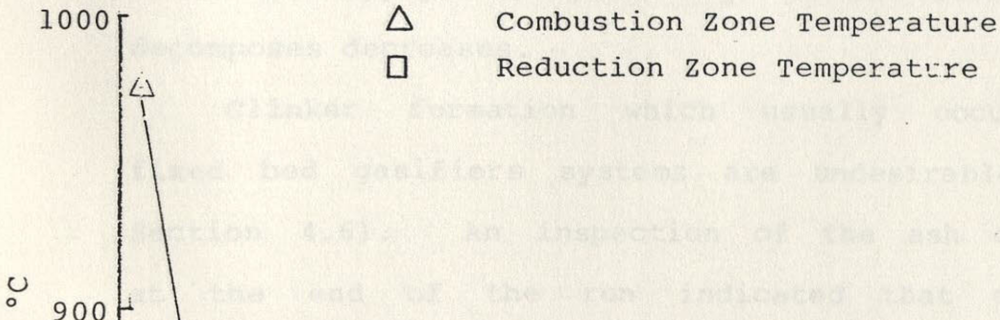


FIGURE 5.5 - REACTION TEMPERATURE AS A FUNCTION OF WATER INJECTED

825°C, sufficient heat is generated to maintain a high level of conversion in the reduction zone. When the reduction zone temperature is above 800°C, the CO level maintains a relatively high and almost constant concentration while the H_2 concentration gradually rose to its maximum value. For further decrease in temperature the concentration of the combustibles in the gas mixture gradually decreased. The effect of temperature is then clearly seen on the degree of steam decomposition, since as the temperature falls from the resulting increase in steam supply, the percentage of the steam that decomposes decreases.

Clinker formation which usually occurs in fixed bed gasifiers systems are undesirable (See Section 4.6). An inspection of the ash content at the end of the run indicated that clinker formation was in fact reduced when compared to the previous test using air. Hence one of the objective of reducing clinker production by the use of water feed was in fact shown to be possible.

5.2.3 Fuel Consumption and Efficiency

(i) Charcoal Consumption

The variation of charcoal consumption with quantity of steam injected is shown in Figure 5.6. The plot shows that from the lowest steam quantity of 1.04 x 10^{-3}Nm³/min to 20 x 10^{-3} Nm³/min the change in charcoal consumption was marginal. Beyond this range however, the charcoal consumption showed a noticeable decrease. The quantity of charcoal consumed at the highest steam quantity supplied was 98 gm/min as compared to a maximum consumption of about 112 gm/min at a steam supply of 20 x 10^{-3} Nm³/min.

The decrease in CO concentration as the steam quantity supply increases (See Figure 5.2) is an indication that the Boudouard reaction has been shifted to the left (See Eq. 3.2) i.e.

$CO_2 + C \rightleftharpoons 2CO$

This is as a result of the lowering of reactor temperature and hence the reaction temperature. The decrease in charcoal consumption then can be seen to be as a direct result of the lowering of the reaction temperatures that result from the increase in steam supply. A fuel savings of about 7% was obtained when the quantity of charcoal consumed to provide the maximum calorific value in the present test, was compared to the quantity of charcoal consumed to give a Calorific Value of similar magnitude in the previous test using air.

(ii) Heating Value of Gas

The variation of gas heating value and water feed is shown in Figure 5.7. The total energy content of the gas leaving the gasifier was in the range of 3.30 to 5.1 MJ/Nm³ while the calorific value was in the range of 3-4.7 MJ/Nm³. Higher values appear to be possible however, this relatively low value may be seen due to the relatively low percentage of hydrogen which was the outcome of a high air to steam ratio.

The temperature of the gas at exit (See Figure 5.8), showed a decrease as the water feed increased. This reduced appreciably the sensible energy since a significant amount of heat was used up for steam generation. The nature of the fuel used also is accountable for the level of CH_4 in the gas. Its constituents mentioned earlier in Chapter 4, can largely influence the calorific value of the gas mixture. It is quite noticeable from Figure 5.2 that the combustible had their highest overall concentration at a water feed of

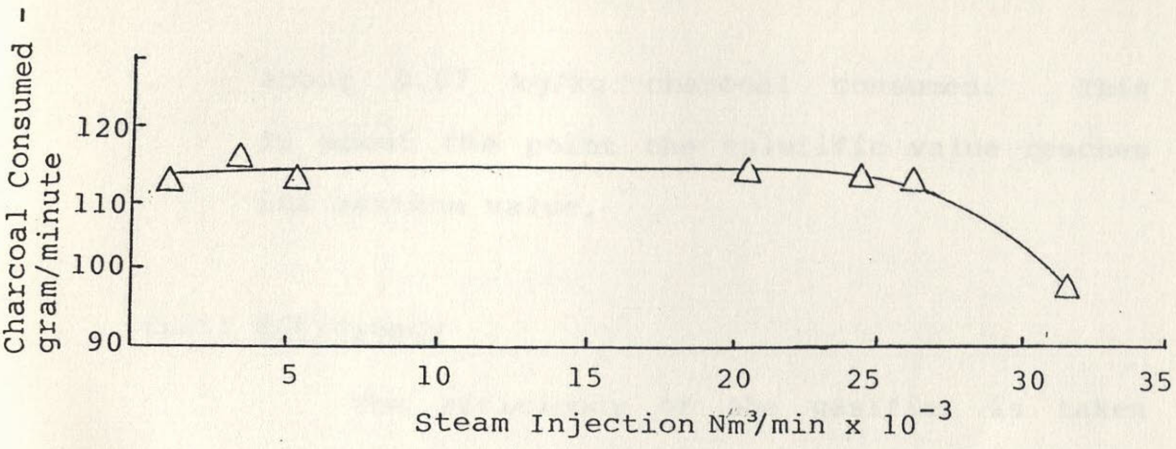


FIGURE 5.6 - EFFECT OF STEAM INJECTION ON CHARCOAL CONSUMPTION

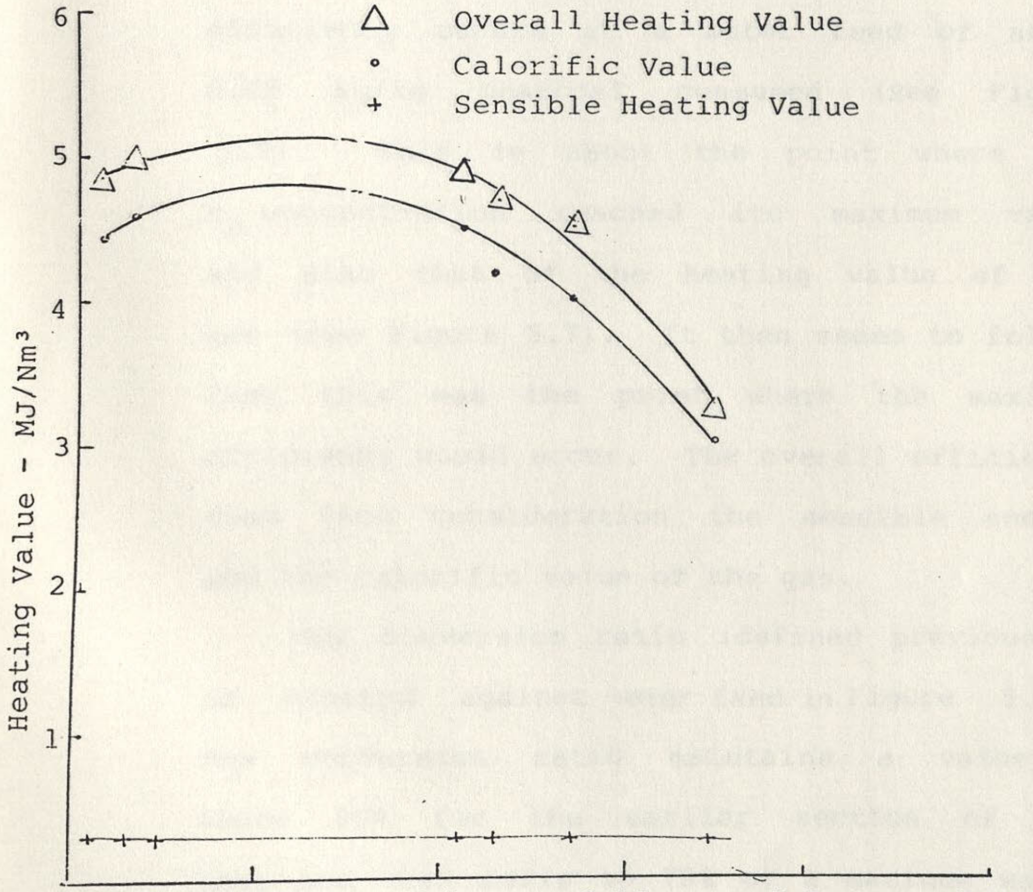


FIGURE 5.7 - HEATING VALUE OF GAS

about 0.07 kg/kg charcoal consumed. This is about the point the calorific value reaches its maximum value.

(iii) Efficiency

The efficiency of the gasifier is taken to be the ratio of the energy provided by the gas and the calorific value of the charcoal consumed (See Section 4.5.3). The maximum efficiency occurs at a water feed of about 0.08 kg/kg charcoal consumed (See Figure 5.9). This is about the point where the H_2 concentration reached its maximum value and also that of the heating value of the gas (See Figure 5.7). It then seems to follow that this was the point where the maximum efficiency would occur. The overall efficiency took into consideration the sensible energy and the calorific value of the gas.

The conversion ratio (defined previously) is plotted against water feed in Figure 5.10. The conversion ratio maintains a value of about 92% for the earlier section of the test and then falls to 78% at a maximum water feed.

The quantity of gas produced is shown

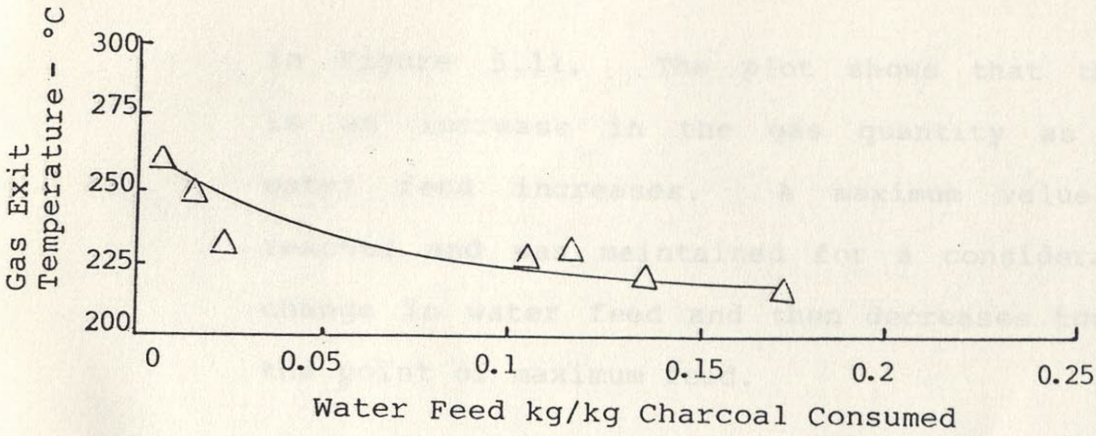


FIGURE 5.8 - GAS EXIT TEMPERATURE

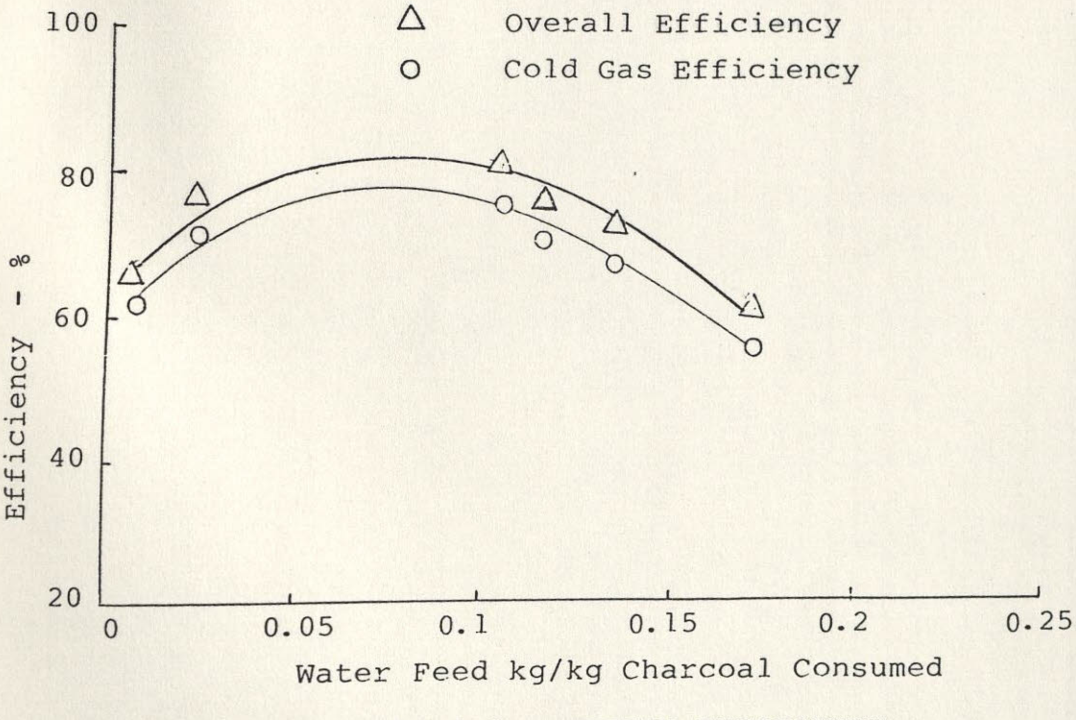


FIGURE 5.9 - SYSTEM EFFICIENCY

in Figure 5.11. The plot shows that there is an increase in the gas quantity as the water feed increases. A maximum value is reached and was maintained for a considerable change in water feed and then decreases toward the point of maximum feed.

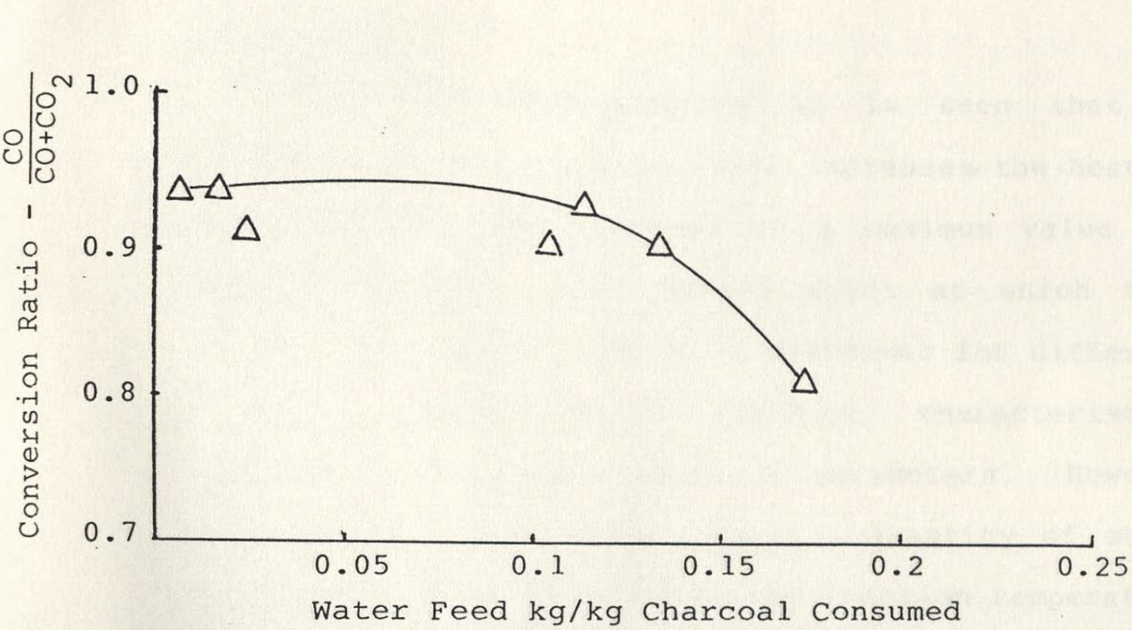


FIGURE 5.10 - CONVERSION RATIO AS A FUNCTION OF WATER FEED

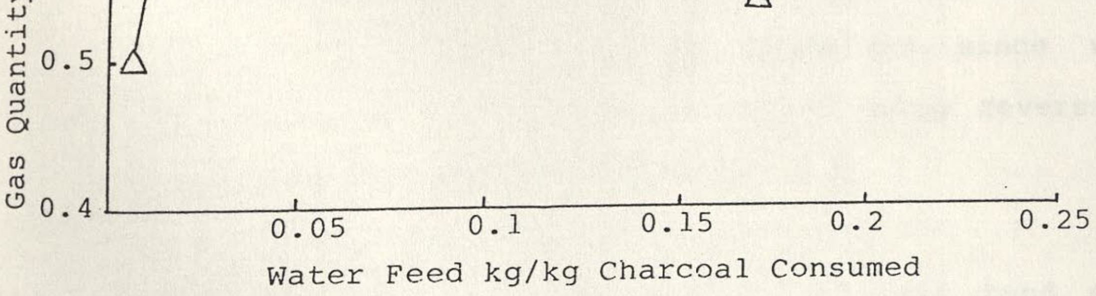


FIGURE 5.11 - GAS QUANTITY GENERATED

5.3 DISCUSSION

From the investigation it is seen that as the water feed to the gasifier increases, the heating value of the gas increase to a maximum value and then decreases. The actual point at which this occurs would quite likely be different for different systems, since their reaction characteristics depends on a varied number of parameters. However it is clear that if too large a quantity of steam is allowed into the system, the reaction temperature and hence the gas quality will be reduced.

In its reaction with charcoal, the steam 1? could have done it the following ways: i.e. Eqs. 3.3 and 3.4.

$$C + H_2O \rightarrow CO + H_2 \qquad (3.3)$$

$$C + 2H_2O \rightarrow CO_2 + 2H_2 \qquad (3.4)$$

These are both endothermic and require a significant amount of heat. It is clear that Eq. 3.3 gives a richer gas and would require the greater amount of heat. The actual reactions in the gasifier however are by no means as simple as it would appear from the foregoing equations since when CO and steam are present, the following reversible reaction can take place i.e. Eq. 3.5.

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

At high temperatures (1000°C) the left hand side predominates and at lower temperatures CO_2 and H_2 are formed. The steam then determines the predominance of oneside or the other of the reversible reaction and so controls the composition and yield of the gas and hence the efficiency of the process.

The charcoal used had an initial moisture content of about 10%. This along with the water feed would have considerably increased the amount of water per kg charcoal, which as was seen, significantly affected, the reaction temperatures. The combustion zone temperatures had its highest value of about 975°C while the reduction zone had its maximum temperature of about 825°C. These temperatures apparently were not high enough to give a greater degree of decomposition of the steam and as can be seen in Fig. 5.3 a significant amount of the steam left undecomposed with the gas mixture. It is interesting to note however that a gas with a calorific value comparable to that which was obtained in the previous test was possible at a reduced reaction temperature.

The maximum calorific value obtained from the test using air at a maximum measured reactor temperature of about 1050°C was about 4.8 MJ/Nm³ (See Figs. 4.4 and 4.8) while that for the present investigation measured at 825°C was 4.7 MJ/Nm³ (See Figs. 5.5

and 5.7). The cold gas efficiency obtained in the above investigation was comparable to the values obtained in the previous test using air. The maximum value obtained was 75 and 76% respectively (See Figs. 4.14 and 5.9).

This is of major significance since the possibility of hot spots and reactor burn out occuring is significantly reduced and in the process, still being able to get gas of suitable quality.

The degree of decomposition of steam with charcoal as stated by Clement and Adams (50) depends to a large extent on the reaction temperature and the residence time of the gas. It is important to note however that for most systems and especially small ones, the possibility of undecomposed steam in the gas is highly probable since a compromise usually has to be made between total reduction and decomposition of the gas as against increase in reactor volume. The quantity of steam supplied per kilogram charcoal however cannot be excessive. The effect of this was seen in the investigation when, the H_2 concentration showed a gradual increase, as the water feed was increased to 0.07 kg/kg charcoal consumed. The quantity of steam up to this point could be termed reactive since; it did not significantly affect the gas quality although, the reaction temperature was always decreasing.

Beyond this point however, the steam took on a different characteristic as is seen from the temperature plot. The reaction temperature was significantly reduced thereby lowering the heating value of the gas. This proved to be an important observation since in the interest of improving the hydrogen concentration by increasing steam supply, the reaction rate and hence the temperature could be significantly affected. It would appear that the maximum advantage that can be obtained with the use of steam may be dependent to some extent on the thickness of the fuel bed. A shallow fuel bed with a relatively high mean temperature may be able to accommodate a significant quantity of steam and thereby increase the reactive limit of the steam quantity.

The formation of clinker which is primarily as a result of high reaction temperature, was significantly reduced when steam was supplied to the gasifier. The problems associated with its formation were discussed in Chapter 4. This method then seems to be useful in reducing clinker formation when feedstocks with high ash content are gasified in fixed-bed gasifiers. However in the interest of reducing its formation, it may not be necessary to use too large a quantity of steam since excessive amount as was shown can be harmful to the gas generation process.

The heating value of the gas can be significantly affected by the sensible energy obtainable from the reactions. This becomes extremely important whenever the gas is to be used for direct combustion purposes. The increase in water feed results in a decrease in the gas exit temperature and hence a decrease in the sensible energy obtainable. The difference in temperature was about 50°C for the exit gas throughout the test. Exit gas with a high proportion of undecomposed steam will require larger gas coolers than gas with low moisture content if cooling of the gas is necessary before usage (50). This can mean additional equipment cost and is not desirable.

5.4 CONCLUSIONS

In the foregoing test, a mixture of air and steam was used to gasify charcoal in a fixed bed downdraft gasifier. The following are the main findings:

(1) Combustible gas with calorific value of 4.7 MJ/Nm³ was obtained from the system at temperatures lower than that of the air operated system (see Chapter 4).

(2) A gas with CO concentration of 31% was produced by the system.

(3) The H_2 concentration was 8.5%.

(4) The CH_4 content was below 1%.

(5) Total decomposition of steam never usually occur with charcoal in practical systems operating at temperatures below 1000°C (See Figure 5.3).

(6) The addition of water to the system will cause a temperature reduction in the reactor.

(7) The occurence of slagging is reduced and this may be due to the relatively lower reaction temperatures.

CHAPTER 6

GASIFICATION OF CHARCOAL USING A MIXTURE OF AIR, STEAM AND CO_2

6.0 SUMMARY

This chapter describes the effects of using a mixture of Air, Steam and CO_2 as the gasifying agent in the production of gas from charcoal in a fixed bed downdraft gasifier. As the CO_2 concentration in the mixture introduced was varied, the gas quality and reaction temperatures were monitored. Too high a CO_2 supply reduced reaction temperatures and decreased the gas quality produced.

The general findings demonstrated that it would be possible to regenerate the CO_2 in products of combustion to combustible fuel through the gasifier if their levels were controlled.

6.1 INTRODUCTION

One of the main reactions that occur in a gasifier is the reduction of CO_2 (produced in the combustion zone) to CO in the reduction zone. If therefore CO_2 was to be passed from an external source through the gasifier, it appears possible that this CO_2 could also be reduced in the reduction zone. This leads to the possibility of recirculating with advantage, the products of combustion from any combustion system in which the producer gas is burnt such as the internal combustion engine.

In the previous section the effect of addition of H_2O (also a constituent of engine exhaust) has been studied. In this chapter are reported the effects of the addition of CO_2 to the gasifier stream.

(i) Object and Method of Investigation

The main object of the investigation was to see the effect of injecting a mixture of air, steam and CO_2 in the fixed fuel bed of the gasifier. From the previous analysis using air and steam, the point at which maximum efficiency and heating value occured in the gas produced was when an air flow rate of 0.36 Nm³/min and a steam injection rate of 5.5×10^{-3} Nm³/min were used. This point was kept fixed throughout the investigation while the quantity of CO_2 was varied. The CO_2 injected was varied between 8×10^{-3} Nm³/min and 48×10^{-3} Nm³/min which represented a concentration range of 1.8 to 11.3%, values representative of concentration available in engine exhaust.

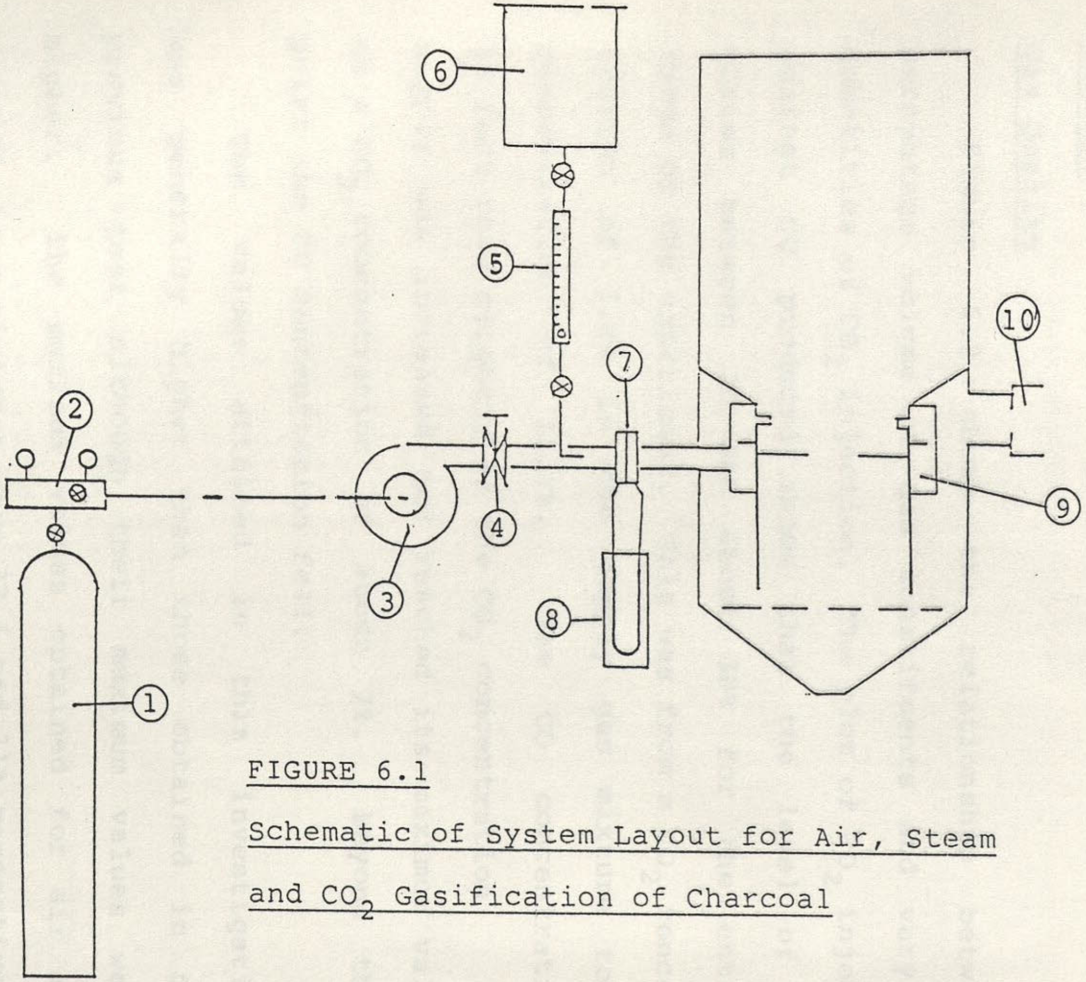
(ii) Method of CO_2 Supply

The CO_2 used in the investigation was tank CO_2. The gas pressure was firstly regulated

PLATE 6-1

LAYOUT OF SYSTEM FOR AIR, STEAM AND

CO_2 GASIFICATION OF CHARCOAL



1 - CO_2 Bottle
2 - Gas Regulator
3 - Blower
4 - Valve
5 - Water Flow Meter
6 - Water Reservoir
7 - Orifice Plate
8 - Manometer
9 - Pre-heating Jacket
10 - Gas Burner

FIGURE 6.1

Schematic of System Layout for Air, Steam and CO_2 Gasification of Charcoal and then metered through a "Victor Gas Flow Orifice Meter and Pressure Regulator". The CO_2 was then injected in the air-steam mixture, preheated and then injected into the fuel bed. (See Figure 6.1). The general system arrangement is shown in Plate 6-1.

6.2 RESULTS

6.2.1 Gas Quality

Figure 6.2 shows the relationship between percentage volume of gas constituents and varying quantities of CO_2 injection. The plot of CO_2 injected against CO produced shows that the level of CO varies between 28 and about 30% for the entire range of the experiment. This was from a CO_2 concentration of 1.8% in the supply gas mixture to a concentration of 11.3%. The CO concentration in fact rose slightly as the CO_2 concentration supply was increased and reached its maximum value at a CO_2 concentration of about 7%. Beyond this point the CO concentration fell.

The values attained in this investigation was generally higher than those obtained in the previous test although their maximum values were higher. The maximum values obtained for air and air and steam mixtures were 32.5 and 31% respectively (See Figures 4.2 and 5.2).

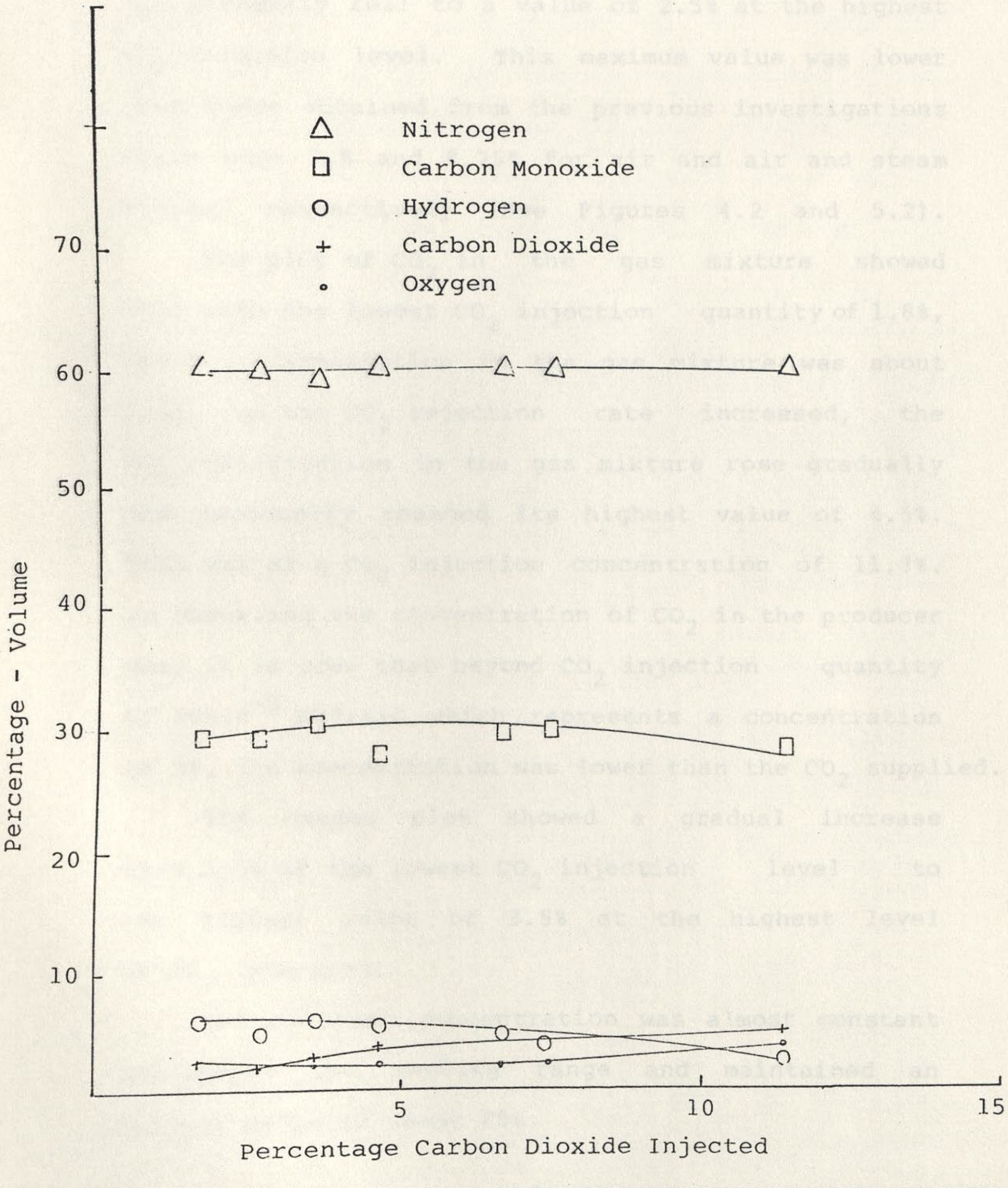


FIGURE 6.2 - EFFECT OF VARYING CO_2 INJECTION RATE ON GAS COMPOSITION

The hydrogen concentration had its highest value of 5.5% at the lowest CO_2 concentration level and gradually fell to a value of 2.5% at the highest CO_2 injection level. This maximum value was lower than those obtained from the previous investigations which were 7.6 and 8.25% for air and air and steam mixture respectively (See Figures 4.2 and 5.2).

The plot of CO_2 in the gas mixture showed that with the lowest CO_2 injection quantity of 1.8%, the CO_2 concentration in the gas mixture was about 2.5%. As the CO_2 injection rate increased, the CO_2 concentration in the gas mixture rose gradually and eventually reached its highest value of 4.5%. This was at a CO_2 injection concentration of 11.3%. In observing the concentration of CO_2 in the producer gas, it is seen that beyond CO_2 injection quantity of $20x10^{-3}$ Nm³/min which represents a concentration of 5%, its concentration was lower than the CO_2 supplied.

The oxygen plot showed a gradual increase from 2.5% at the lowest CO_2 injection level to its highest value of 3.5% at the highest level of CO_2 injection.

The nitrogen concentration was almost constant throughout the testing range and maintained an average value of about 60%.

6.2.2 CO_2 Effect on Reactor Temperature

Figure 6.3 is the plot of quantity of CO_2 injected against reaction temperature in the combustion and reduction zones. At minimum CO_2 injection, the combustion temperature was at its maximum value of 1060°C. It then fell gradually to about 900°C as the CO_2 injection concentration increased to about 8% and then remained almost constant for the remainder of the testing range. The reduction zone showed much less variation as is seen in the plot. The temperature rose from 700°C to a maximum value of about 720°C and then fell gradually to its lowest value of 690°C. Beyond a CO_2 concentration of about 7% in the supply mixture, the rate of CO_2 formation appeared to remain fairly constant. This is inferred from the steady combustion temperatures. This condition clearly is desirable since the reaction temperature as with the previous test with steam (See Chapter 5) could be controlled to operate at much lower levels and the rate of charcoal consumption possibly reduced.

6.2.3 Heating Value and Efficiency

The plot of heating value of the gas against CO_2 injection rate is shown in Figure 6.4. the maximum heating value occurs at an injection rate

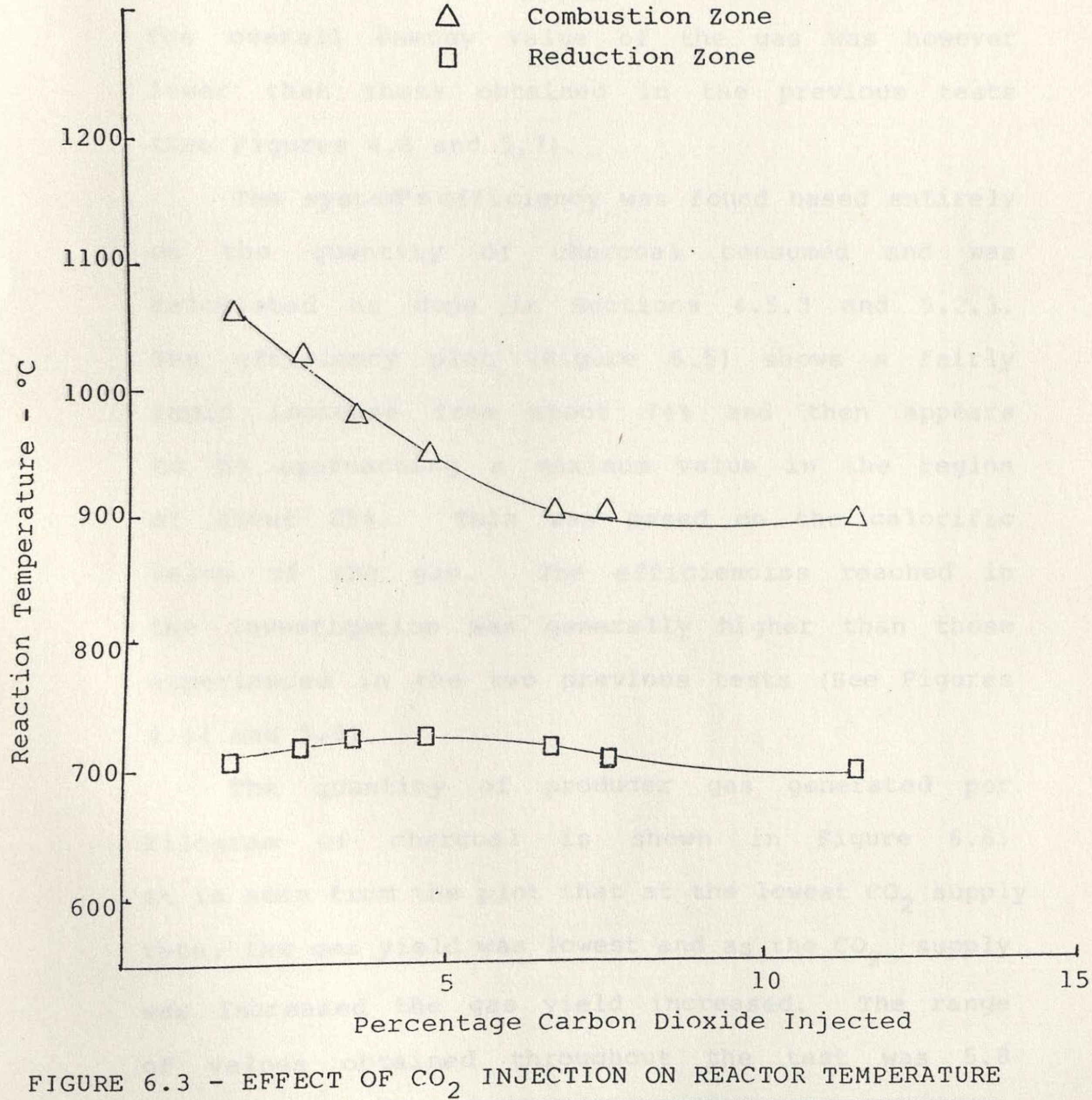


FIGURE 6.3 - EFFECT OF CO_2 INJECTION ON REACTOR TEMPERATURE

of 20×10^{-3} Nm³/min of CO_2. Because the variation in the reduction zone temperature was small, the sensible heat generated throughout the investigation was fairly constant. This then caused the maximum calorific value of 4.5 MJ/Nm³ to occur the same point at which maximum total energy occurred. The overall energy value of the gas was however lower than those obtained in the previous tests (See Figures 4.8 and 5.7).

The system's efficiency was found based entirely on the quantity of charcoal consumed and was calculated as done in Sections 4.5.3 and 5.2.3. The efficiency plot (Figure 6.5) shows a fairly rapid increase from about 74% and then appears to be approaching a maximum value in the region of about 85%. This was based on the calorific value of the gas. The efficiencies reached in the investigation was generally higher than those experienced in the two previous tests (See Figures 4.14 and 5.9).

The quantity of producer gas generated per kilogram of charcoal is shown in Figure 6.6. It is seen from the plot that at the lowest CO_2 supply rate, the gas yield was lowest and as the CO_2 supply was increased the gas yield increased. The range of values obtained throughout the test was 5.8

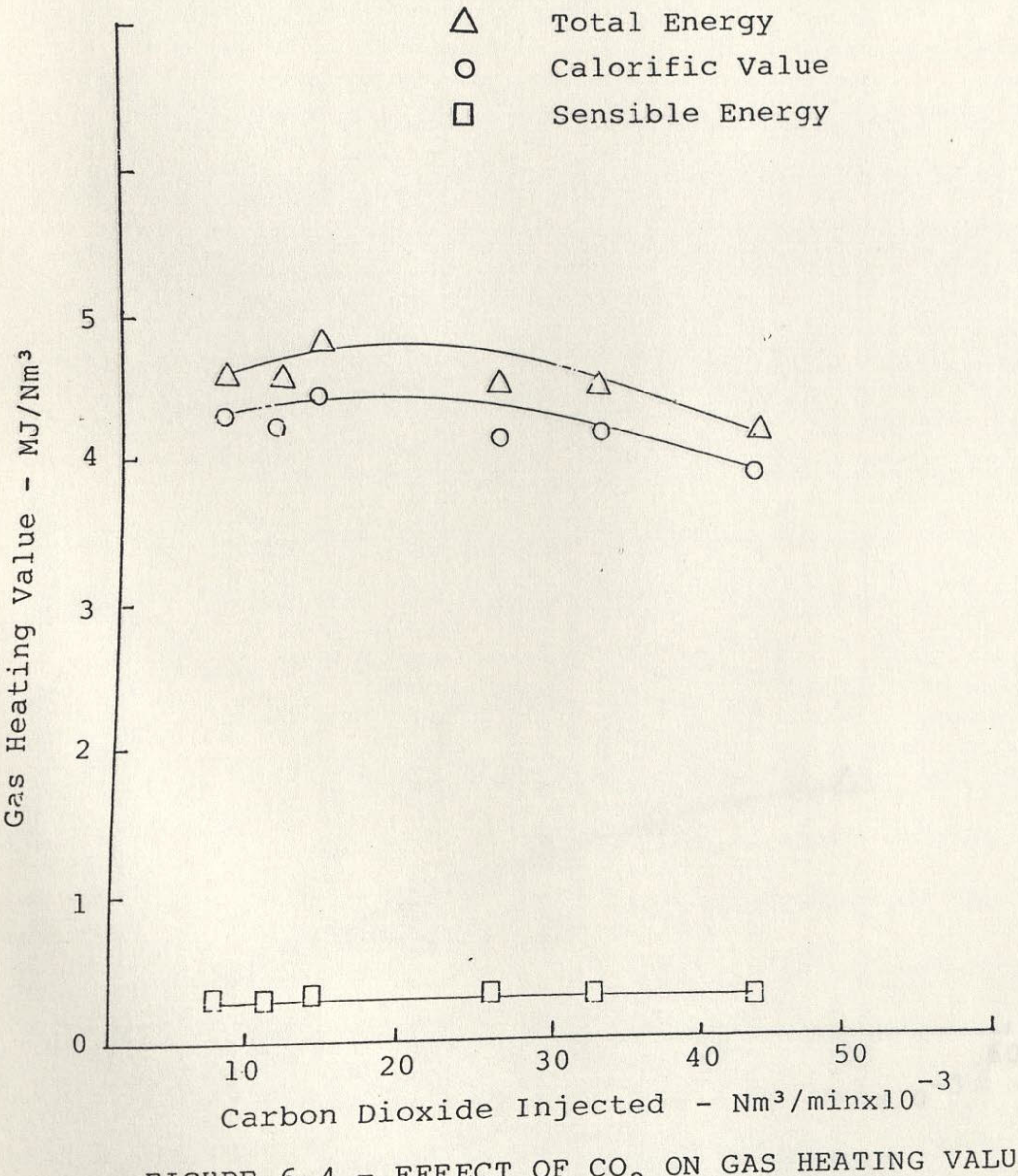


FIGURE 6.4 - EFFECT OF CO_2 ON GAS HEATING VALUE

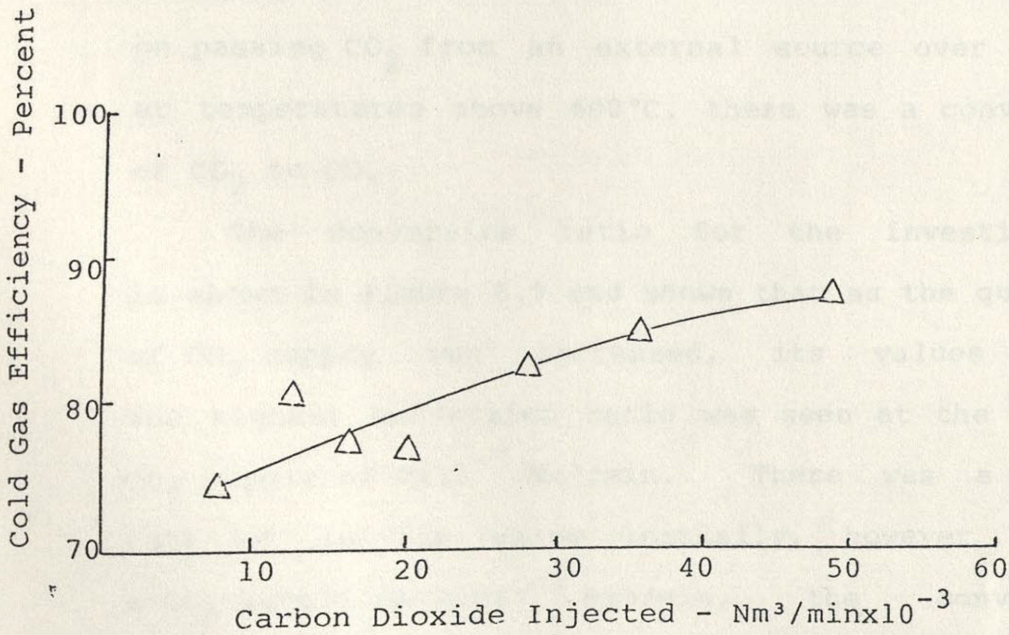


FIGURE 6.5 - SYSTEM EFFICIENCY

to 8.3 Nm³/kg. Although there was an increase in the gas yield as the quantity of CO_2 supplied was increased, Figure 6.7 which is the plot of calorific value against percentage fuel savings, shows that an increase in CO_2 supply also results in a decrease in the calorific value of the gas. The plot also shows that there was a gradual increase in the calorific value of the gas as the percentage in fuel saving increased to about 7.6% and with further increase in fuel savings, the calorific value fell to its lowest value of about 3.9 MJ/Nm³ at the largest CO_2 supply quantity.

The resulting fuel savings from the CO_2 supplied (See Figure 6.8) is in keeping with the findings of Gulbransen and Andrews (56) who found that on passing CO_2 from an external source over carbon at temperatures above 600°C, there was a conversion of CO_2 to CO.

The conversion ratio for the investigation is shown in Figure 6.9 and shows that as the quantity of CO_2 supply was increased, its values fell. The highest conversion ratio was seen at the lowest CO_2 supply of $8x10^{-3}$ Nm³/min. There was a rapid fall of in its value initially, however beyond a CO_2 supply of $20x10^{-3}$ Nm³/min, the conversion ratio continued to fall gradually for further increase in

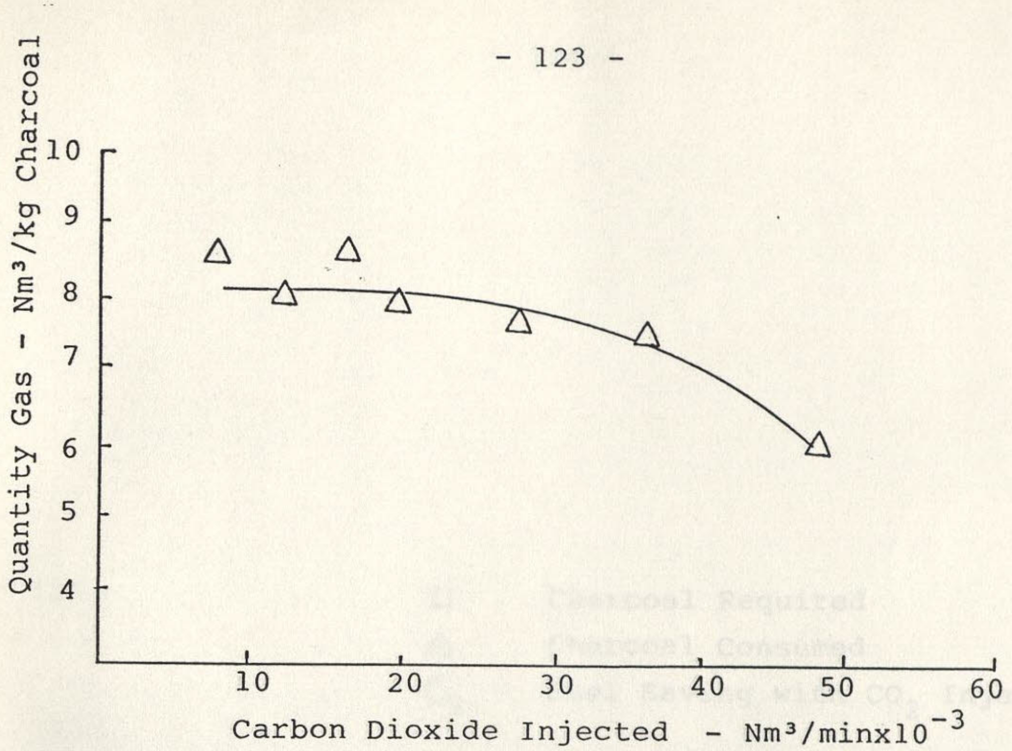


FIGURE 6.6 - GAS QUANTITY PRODUCED

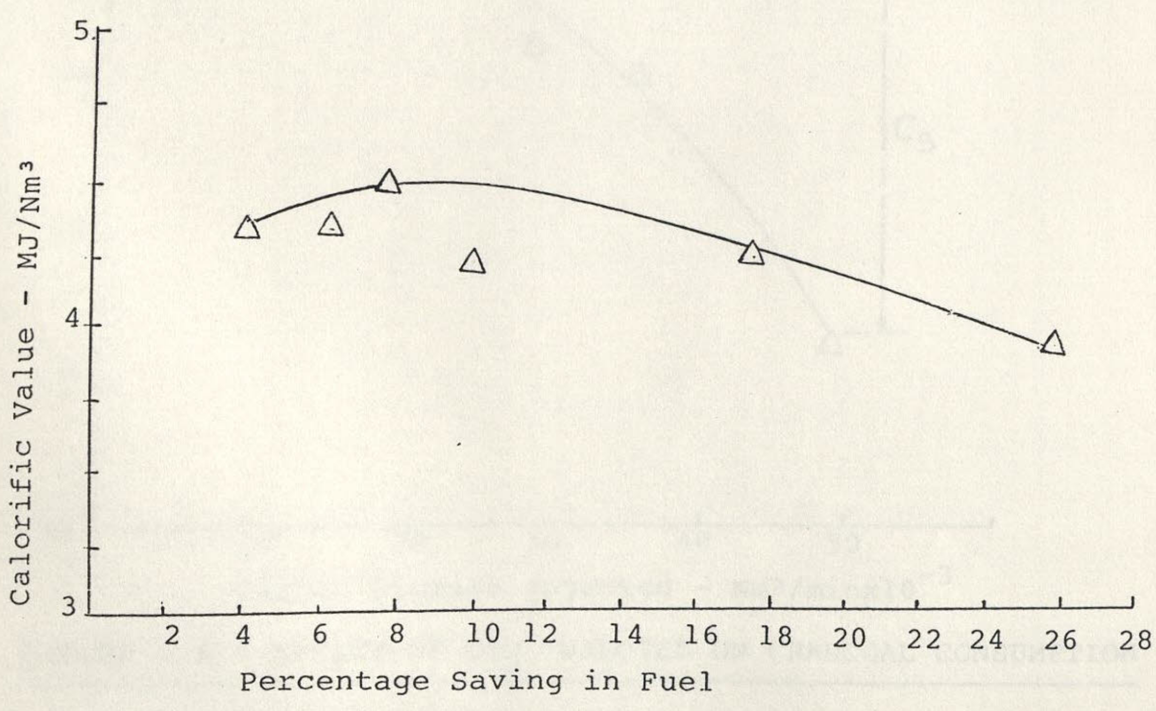


FIGURE 6.7 - CALORIFIC VALUE VERSUS FUEL SAVINGS

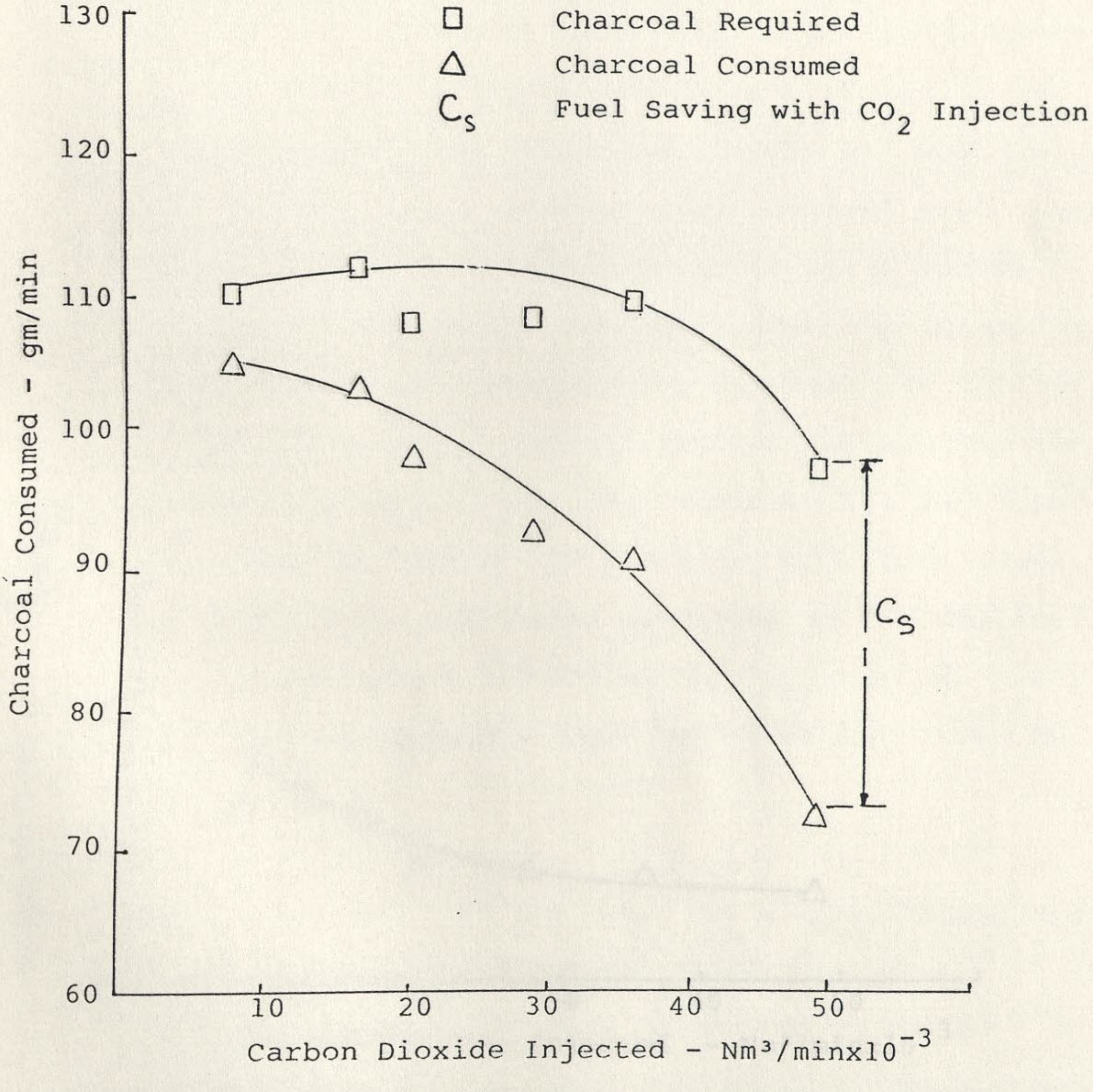


FIGURE 6.8 - EFFECT OF CO_2 INJECTED ON CHARCOAL CONSUMPTION

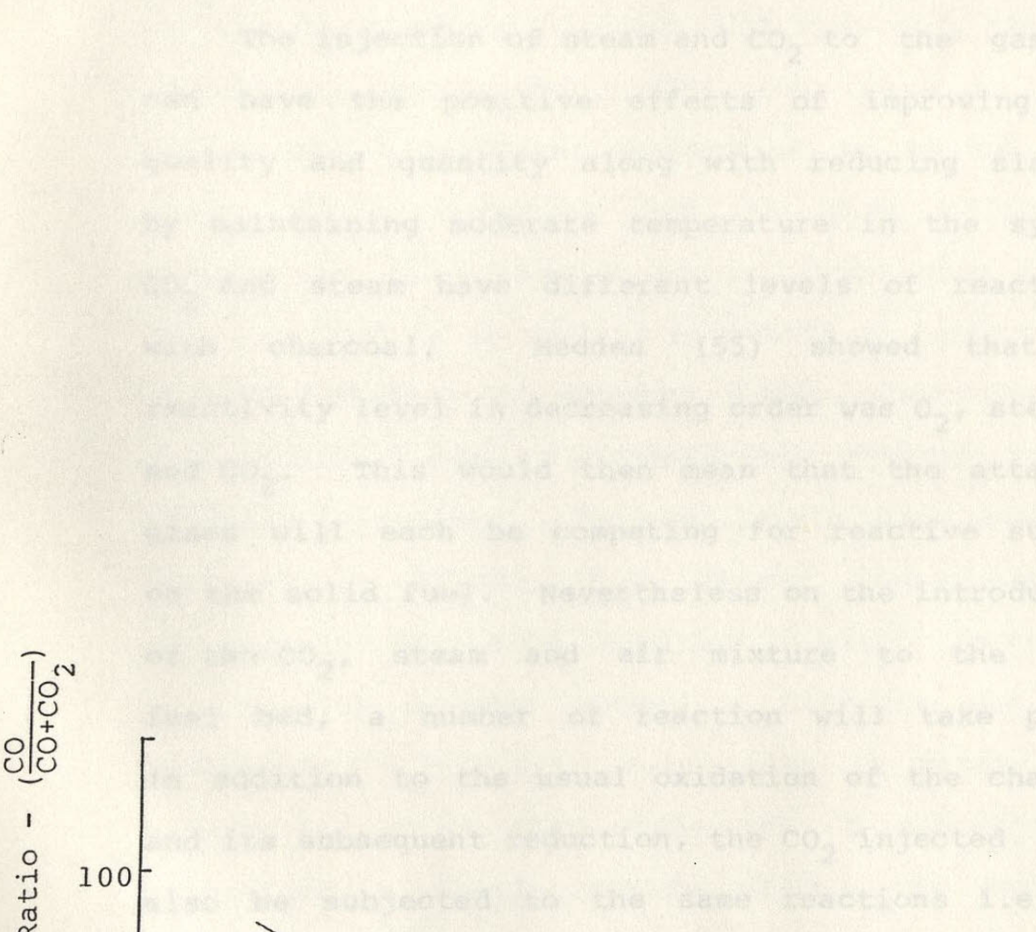


FIGURE 6.9 - CONVERSION RATIO VERSUS CO_2 SUPPLIED

CO_2 supply. The general level of conversion ratio obtained for this test was lower than those obtained in Sections 4.5.2 and 5.2.3.

6.3 DISCUSSION

The injection of steam and CO_2 to the gasifier can have the positive effects of improving fuel quality and quantity along with reducing slagging by maintaining moderate temperature in the system. CO_2 and steam have different levels of reactivity with charcoal. Hedden (55) showed that the reactivity level in decreasing order was O_2, steam and CO_2. This would then mean that the attacking gases will each be competing for reactive surface on the solid fuel. Nevertheless on the introduction of the CO_2, steam and air mixture to the fixed fuel bed, a number of reaction will take place. In addition to the usual oxidation of the charcoal and its subsequent reduction, the CO_2 injected will also be subjected to the same reactions i.e. Eq. 3.2.

$CO_2 + C \rightarrow 2CO$

This will occur at the high prevailing temperature and in regions with depleated oxygen supply.

From the initial stage of the CO_2 injection, it was quite noticeable that the reaction temperature started to decrease (See Figure 6.3). As the CO_2 concentration was increased, the concentration of O_2 in the gasifying agent was lowered. This then placed an early limitation on the maximum attainable temperature. In addition to this, for the CO_2 supplied to react with charcoal, reaction temperature above 400°C (55) (56) have to exist before any significant conversion to CO can take place. The CO_2 supplied had to then raise its temperature from ambient to or above this value. This resulted in an obvious reduction in temperature.

The ability to produce large quantities and good quality gas is a desirable feature in gas producing systems. The gas yield from charcoal consumed in Figure (6.6) showed improvement in gas quantity as the CO_2 supplied was increased. The quality however showed a decrease and this is seen from the calorific value plot in Figure 6.7. Figure 6.2 shows that while the CO concentration maintained a fairly steady value, the hydrogen concentration fell gradually. The reverse shift reaction Eq. 3.5.

$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$

could have resulted in the reduction of the gas calorific value.

The reverse shift method has been studied by Berkley et al (63) and was found to be an effective way in controlling the ratio of hydrogen to carbon monoxide in synthetic gas. The injection of CO_2 can be deleterious if high hydrogen fraction is required in the gas mixture. However for fueling I.C. engines where hydrogen concentration beyond 20% is not desirable (6) this method seems adequate.

The quantity of gas produced per kg charcoal (See Figure 6.6) increased as the CO_2 supply increased and seems to be approaching its maximum value for CO_2 quantities in excess of those used in the investigation. The plot suggests that there is a maximum volume of gas to be obtained during CO_2 supply. However if the optimum CO_2 supply is exceeded, the quantity of gas produced decreases. As shown in Section 4.2.3, the Boudouard reaction results in an increase in the volume of gas produced over the quantity of gasifying agent supplied. With a lowering of the reaction temperature as experienced in the investigation, the level of conversion will reduce and cause high quantities of CO_2 to leave with the gas generated.

With CO_2 supplied, from external sources, it is quite possible to attain higher fuel efficiencies. In Figures 6.6, 6.7 and 6.8 it is seen that as the quantity of CO_2 supplied increases and the percentage savings in fuel improves, the system efficiency rose gradually and appears to be reaching its maximum value. An increase in CO_2 quantity obviously means an increase in available carbon, however too high a CO_2 quantity can cause severe cooling of the reactor (See Figure 6.3) and at the same time make available, quantities of carbon for conversion. High efficiency and high gas yield does not necessarily mean high heating value. This is seen in Figures 6.6, 6.7 and 6.9 where the highest efficiency and the highest gas yield did not occur at the highest calorific value. Although the temperature in the reactor did not reach significantly low values to stop the conversion process, it can be seen in Figure 6.9 that approaching $30x10^{-3}$ Nm³/min CO_2 supply or about 11% CO_2 concentration in the supply mixture, the conversion ratio showed signs of a gradual slowing down of the process. Further decrease in temperature would see an increase in CO_2 leaving in the gas mixture and much lower conversion ratios.

With regards to the level of CO obtained throughout the test, it was seen that the concentration obtained were much higher than those in the other two investigation at corresponding temperature (See Figures 4.5, 5.5 and 6.3). This fact is of major significance since the ability to maintain high conversion ratios at relatively lower reaction temperature is always desirable since it extends the working life of the system.

6.4 CONCLUSION

From the foregoing investigation where a mixture of air, steam and CO_2 was used as the gasifying agent in the gasification of charcoal, the following main conclusions may be drawn:-

(1) There is no significant increase in the percentage of CO in the producer gas mixture.

(2) The concentration of H_2 in the gas mixture is reduced as the CO_2 supply is increased.

(3) Methane concentration below 1% was obtained.

(4) Higher system efficiency is obtained when CO_2 is added to the air/steam stream from an external source through the fixed fuel bed.

(5) Optimum fuel savings of about 7.5% is obtained.

(6) The effect of slagging is reduced.

CHAPTER 7

RECIRCULATION OF EXHAUST EMISSION IN GASIFIER

7.0 SUMMARY

The following chapter deals with the effects of recirculating exhaust emissions from a C.I. engine through a fixed bed, downdraft gasifier using charcoal as the primary fuel.

The concentration of the exhaust emission in the gasifying agent was varied by fixing the air flow rate and varying the exhaust gas in the mixture. The resulting producer gas generated was analysed.

The quantity of charcoal consumed based on the content of the producer gas generated along with the fuel saving if any, was determined. In addition to the above, the exhaust concentration that gave maximum efficiency in the gasifier was found.

7.1 INTRODUCTION

The main constituent of exhaust emission from C.I. engines are CO, CO_2, water vapour, unburnt or partially burnt hydrocarbon, oxides of nitrogen and oxides of sulphur.

In the previous investigation, a mixture of air, steam and CO_2 was passed through the gasifier with a view to generating combustible gases of comparable heating values with those of using air and a mixture of air and steam. A maximum calorific value of 4.4 MJ/Nm³ (See Figure 6.4) was obtained from the gas mixture produced. The investigation therefore demonstrated that it would be possible to regenerate the exhaust emission from C.I. engine in a gasifier. Regeneration of exhaust emission in the gasifier, is taken to be the conversion of CO_2 and steam in the exhaust primarly to H_2 and CO.

The main aim of this section of the investigation was to see the effects of passing exhaust emission from a stationary C.I. engine through a downdraft fixed bed gasifier. A successful operation would then seem to suggest that:-

(1) Engines fueled by producer gas could in fact recirculate a fraction of its exhaust emission for regeneration and re-using through a gasifier.

(2) Exhaust products from combustion systems could be regenerated in a gasifier.

7.2 APPARATUS

A single cylinder Petter C.I. engine rated at 9KW at 1800 rpm was used to supply its exhaust emission to the gasifier. The pipe taking the exhaust gas from the engine, was branched with a Tee fitting in order to take a portion of the exhaust gas to the gasifier and the remainder to waste

(See Figure 7.1 and Plate 7-1). The pipes taking the exhaust gas to the gasifier, was insulated with fibre glasswool to eliminate the possibility of condensation of water vapour. The pipe transporting the exhaust gas to the gasifier system, was connected to the system through the air supply. Allowance was made to throttle both the exhaust gas supply and the primary air supply. Orifice plates were used to meter the gasifying agent to the system and thermocouples were used to monitor the gas/air mixture temperature supplied to the generator.

7.3 METHOD

After the gasifier was lit and the combustible gas obtained was lit at the gas burner, the engine was started. The engine was set to run at full load at a speed of about 1500 rpm. The air supply rate was fixed at 0.36 Nm^3/min which was the operating point of the gasifier using air and the quantity of exhaust gas in the air mixture was gradually increased in steps. The percentage of constituents in the gas mixture supplied to the system was noted. As the exhaust gas-air mixture was passed through the gasifier, it was ensured that the level was such as to maintain a flame at the burner.

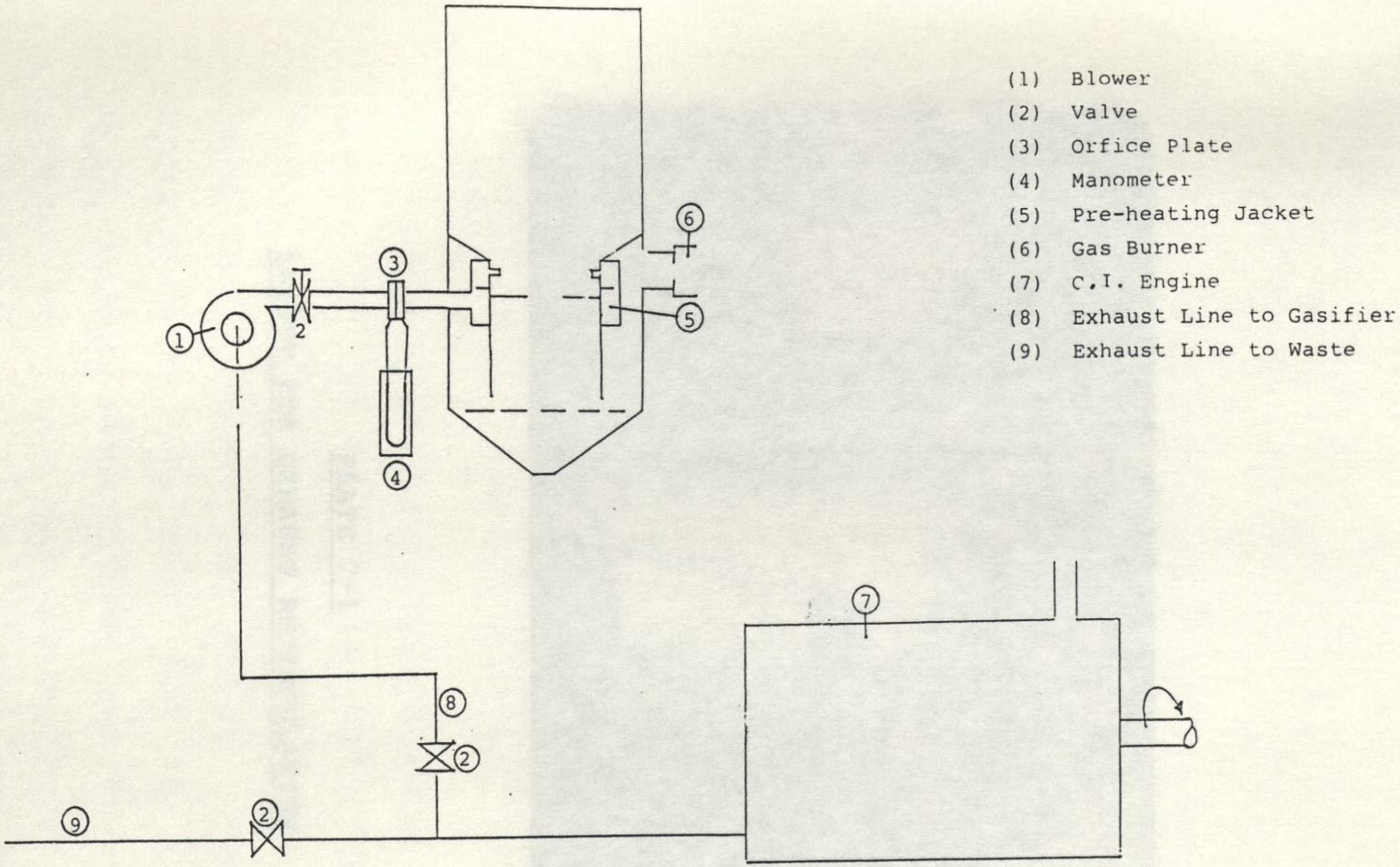


FIGURE 7.1 - Engine and Gasifier Layout for Exhaust Recirculation

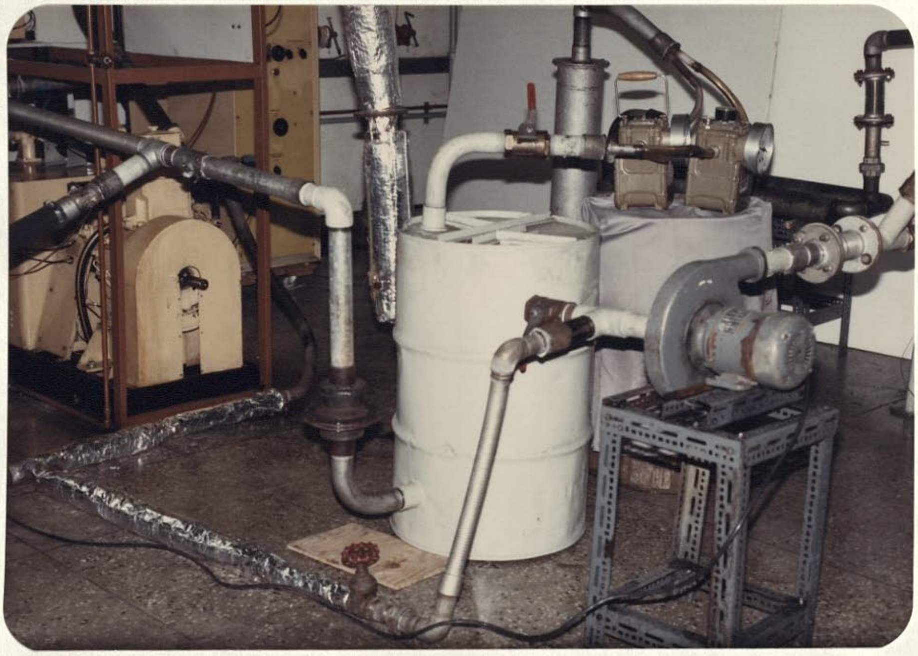


PLATE 7-1

LAYOUT FOR EXHAUST RECIRCULATION

Samples of the gas produced in the gasifier were taken for analysis.

7.4 RESULTS

The variation between percentage constituents of the gas mixture produced and the quantity of exhaust emission in the supply mixture to the gasifier is shown in Figure 7.2.

The CO concentration shows a gradual increase from a value of 26% at the lowest exhaust concentration of 5.1%, to a maximum concentration of about 26.5% at an exhaust emission quantity of about 11% and then decreases for a further increase in exhaust concentration.

The H_2 concentration had a gradual increase from 3% to a maximum value of about 4.5% at a exhaust emission concentration of about 12% and then decreased for a further increase in exhaust concentration.

Throughout the investigation, the CO_2 concentration in the gas mixture generated, showed a gradual increase as the exhaust concentration was increased throughout the testing range. It is interesting to note also that the concentration of CO_2 leaving the gasifier in the gas mixture produced was lower than the concentration supplied in the gasifying agent mixture (See Figure 7.3).

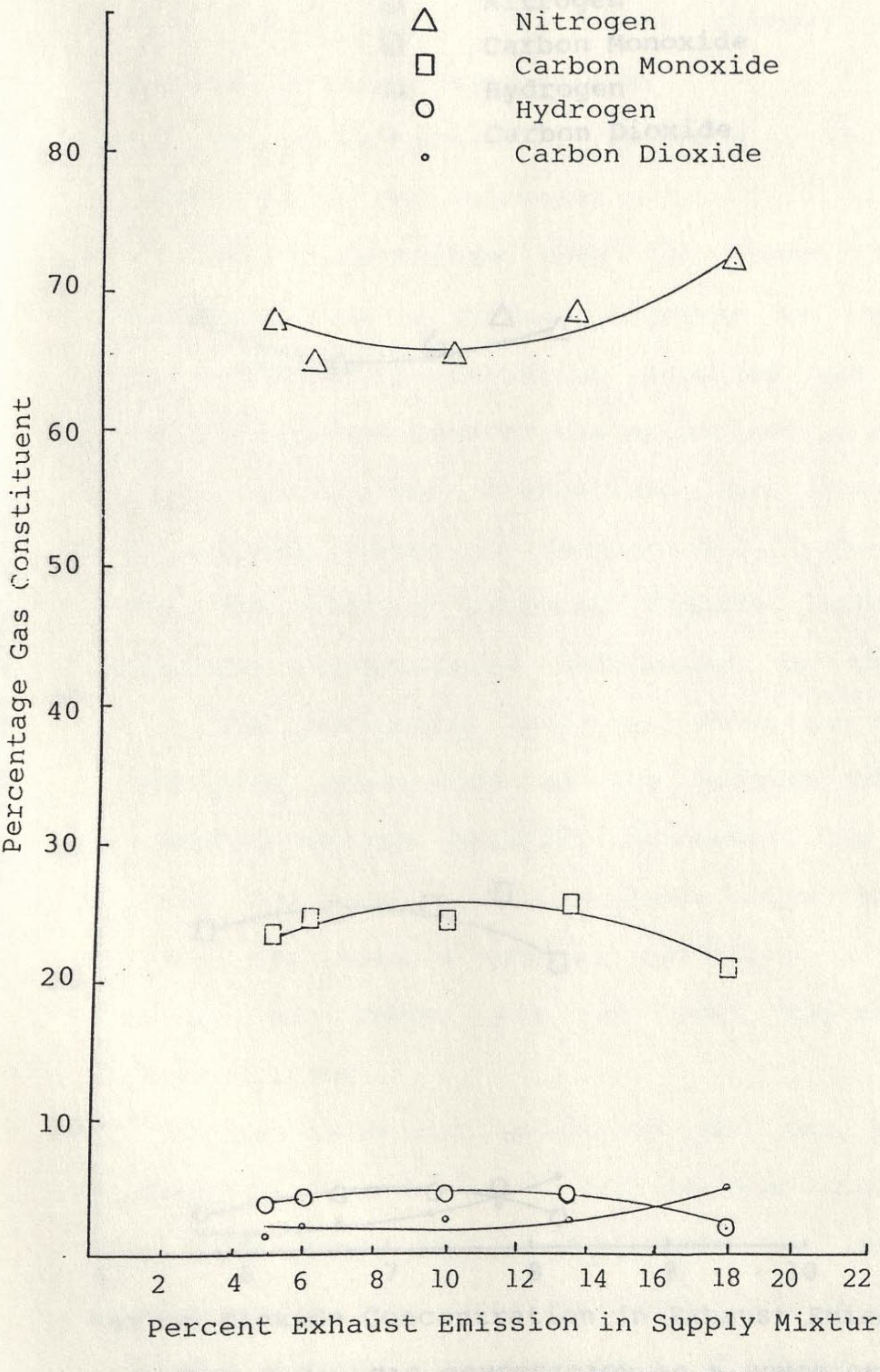


FIGURE 7.2 - GAS COMPOSITION VERSUS EXHAUST CONCENTRATION

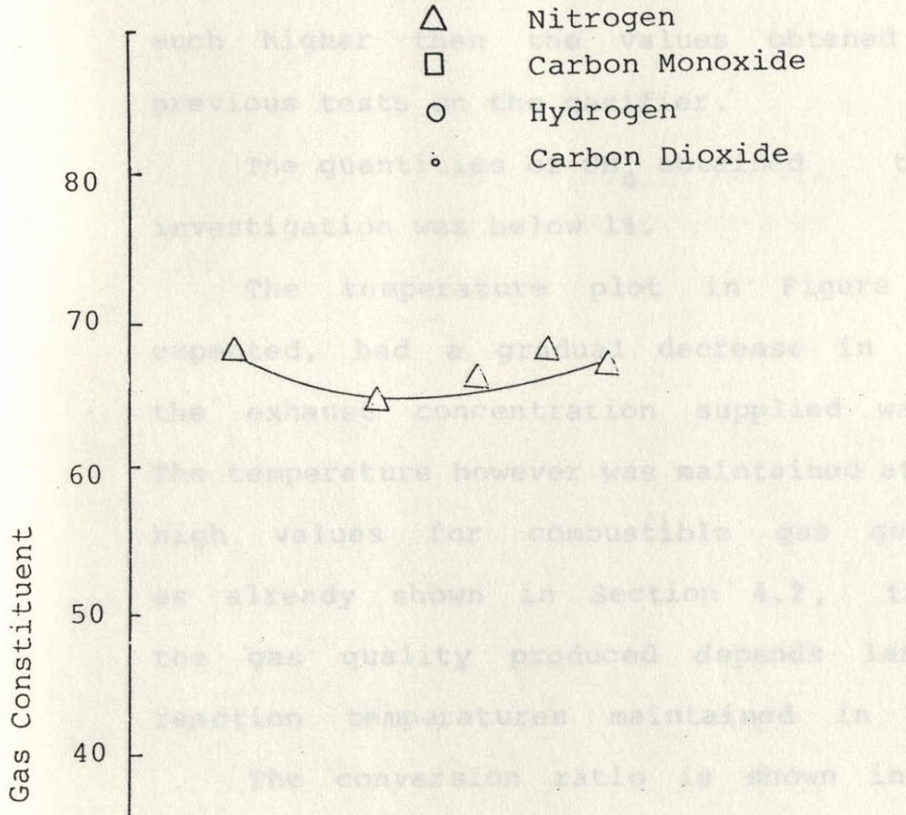


FIGURE 7.3 - GAS COMPOSITION AS A FUNCTION OF CO_2 CONCENTRATION IN EXHAUST MIXTURE

The N_2 concentration was high overall. Its concentration varied between 65 and 67.5% and was much higher than the values obtaned in all the previous tests on the gasifier.

The quantities of CH_4 obtained throughout the investigation was below 1%.

The temperature plot in Figure 7.4 as was expected, had a gradual decrease in its value as the exhaust concentration supplied was increased. The temperature however was maintained at sufficiently high values for combustible gas generation and as already shown in Section 4.2, the extent of the gas quality produced depends largely on the reaction temperatures maintained in the reactor.

The conversion ratio is shown in Figure 7.5. The plot shows that as the exhaust concentration supplied to the gasifier increases, the conversion ratio decreases. The highest value obtained was about 94% with a gradual reduction to its lowest value of about 81% at the highest exhaust concentration.

The calorific value of the gas produced is shown in Figure 7.6. Its maximum value could be inferred from Figure 7.2 where the concentration of CO and H_2 were seen to reach their maximum values at an exhaust concentration of about 11%. The

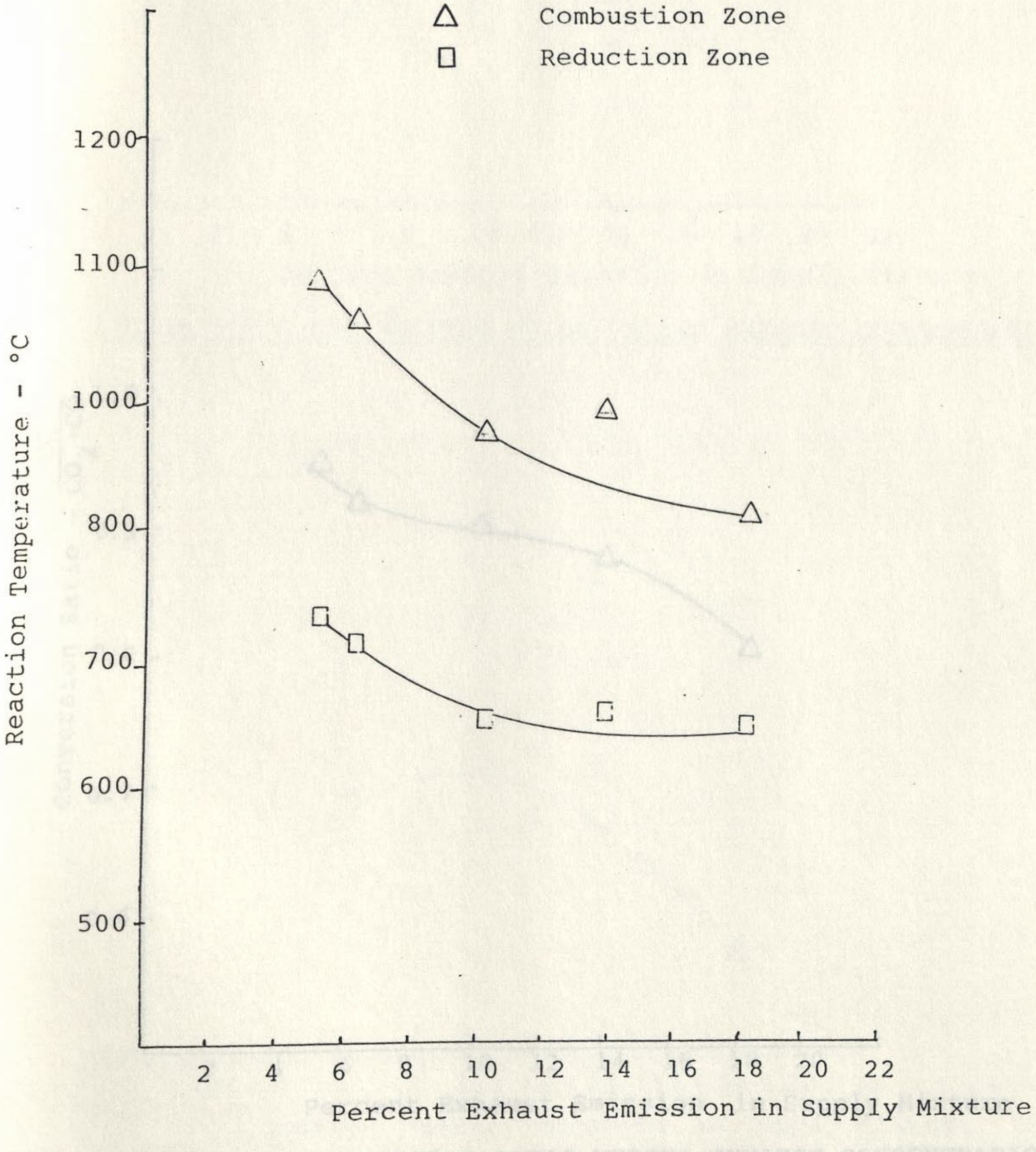


FIGURE 7.4 - EFFECT OF EXHAUST CONCENTRATION ON REACTOR TEMPERATURE

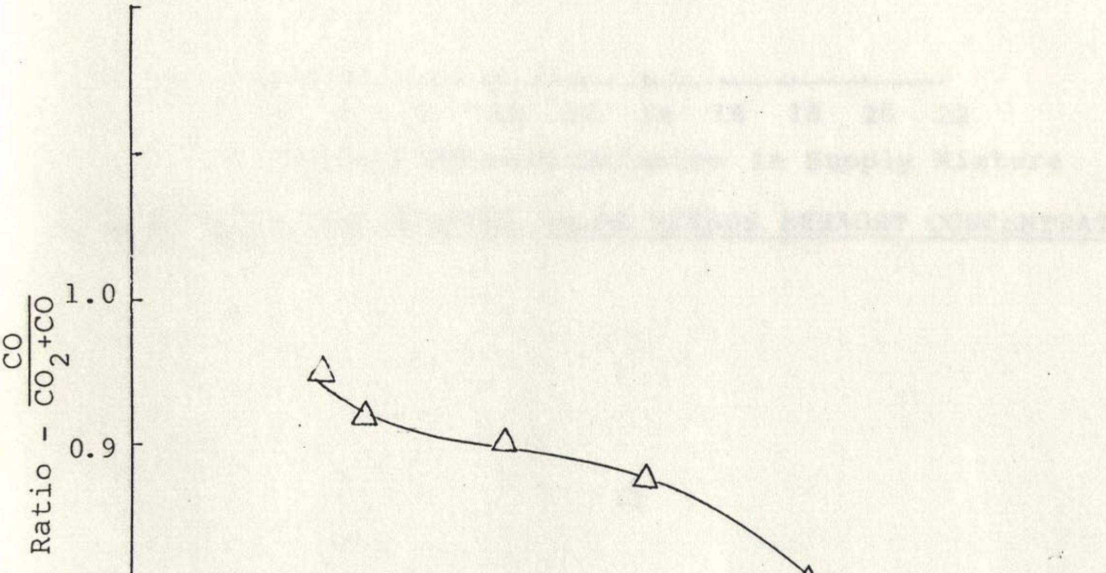


FIGURE 7.5 - CONVERSION RATIO VERSUS EXHAUST CONCENTRATION

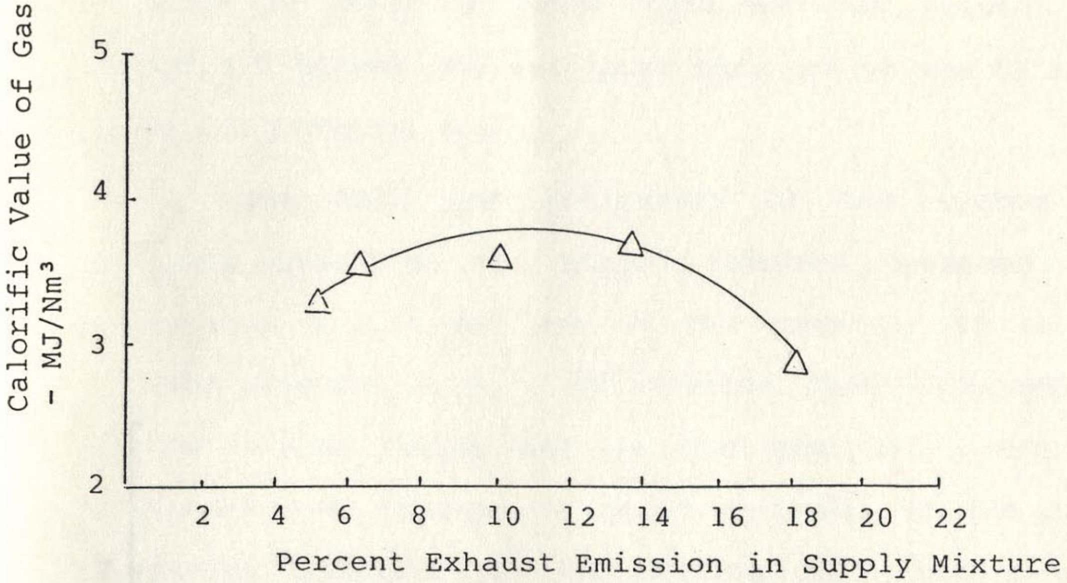


FIGURE 7.6 - GAS HEATING VALUE VERSUS EXHAUST CONCENTRATION

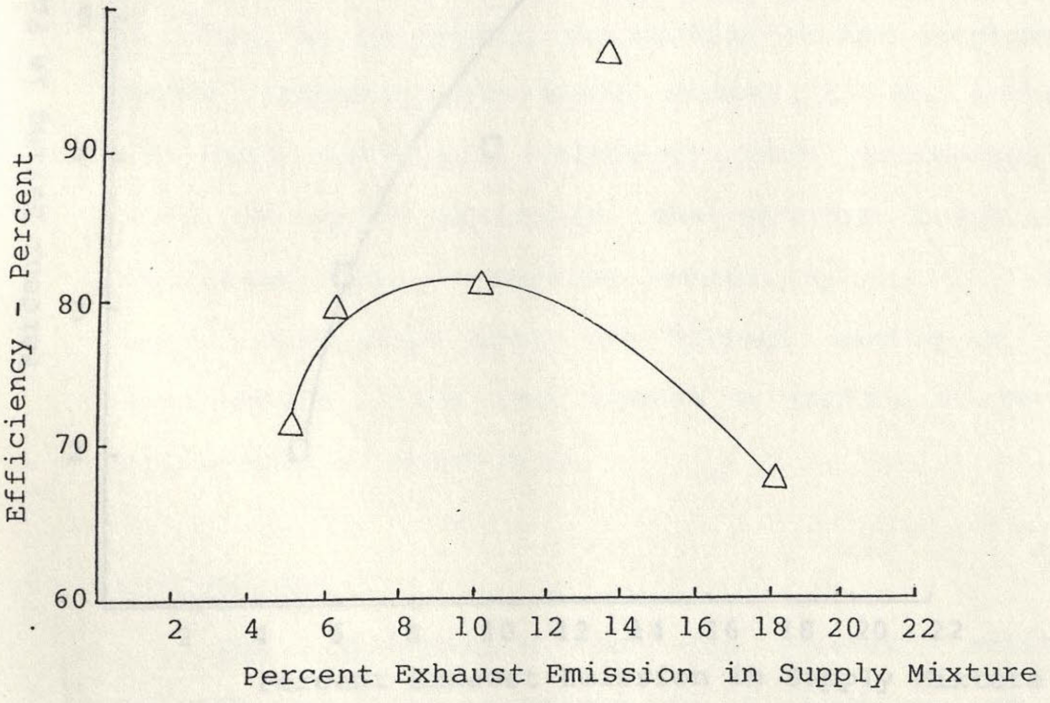


FIGURE 7.7 - EFFICIENCY AS A FUNCTION OF EXHAUST CONCENTRATION

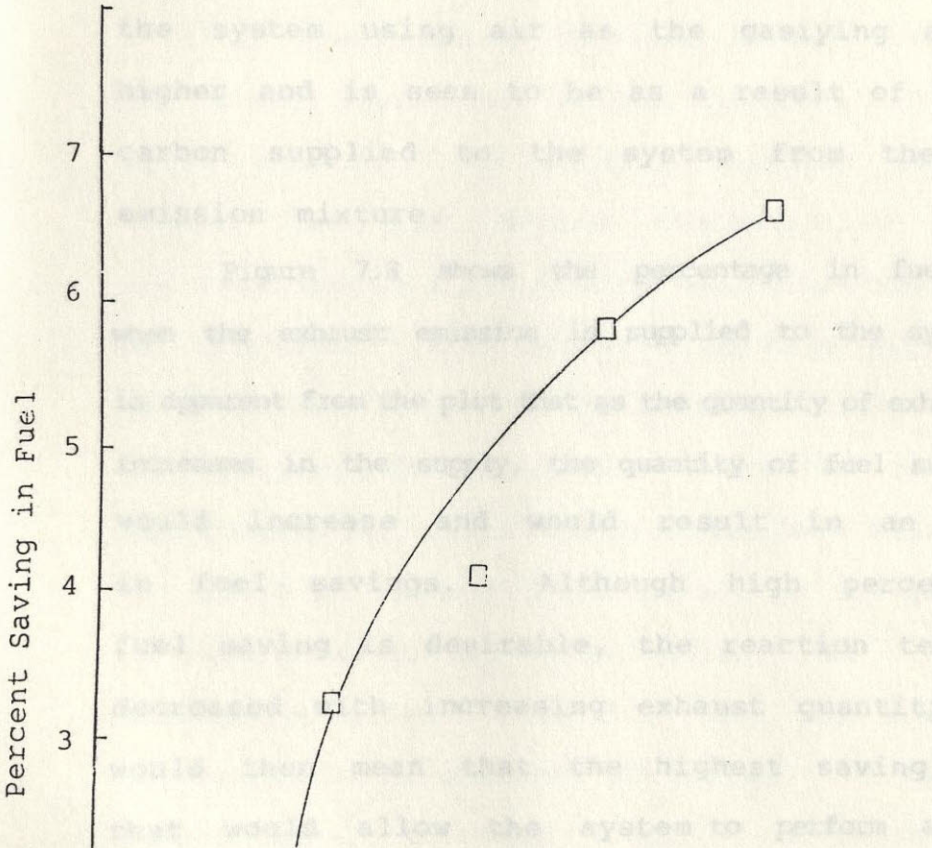


FIGURE 7.8 - FUEL SAVING WITH EXHAUST REGENERATION

range of heating value obtained was between 2.8 and 3.7 MJ/Nm³ and was lower than the values obtained in the previous tests.

The cold gas efficiency of the system was found based on the actual charcoal consumed (See Section 6.2.3) and was in the range of 68 to 83% (See Figure 7.7). This value when compared to the system using air as the gasiying agent was higher and is seen to be as a result of the extra carbon supplied to the system from the exhaust emission mixture.

Figure 7.8 shows the percentage in fuel savings when the exhaust emission is supplied to the system. It is apparent from the plot that as the quantity of exhaust emission increases in the supply, the quantity of fuel supplemented would increase and would result in an increase in fuel savings. Although high percentage in fuel saving is desirable, the reaction temperature decreased with increasing exhaust quantity. This would then mean that the highest saving in fuel that would allow the system to perform at maximum efficiency is about 4.5%.

7.5 DISCUSSIONS

The regeneration of the exhaust emission in the gasifier resulted in a lowering of the reactor temperature (See Figure 7.4). This decrease in temperature may have been as a result of some of the factors mentioned in Chapter 6 and appears to have an adverse effect on the levels of combustible gas obtained. This is seen when compared to those in Sections (4.2.4) (5.2.2) and (6.2). It is quite noticeable from Figure 7.3 that the level of combustibles obtained in the investigation was lower than the values reported in Chapters 4, 5 and 6. The exhaust emission leaving the engine had its oxygen concentration depleated and resulted in a gas mixture with high concentration of nitrogen. This appeared to have significantly reduced the levels of combustible gases produced. The reverse shift reaction described in Eq. 3.5 and Section 6.3 quite likely could have also affected the level of combustible attained in the gas mixture by supressing the H_2 concentration in the gas mixture produced. The low level of combustibles then seem to be primarly as a result of low reactor temperatures, the high level of nitrogen supplied in the gasifying agent and the resulting reverse shift reaction described in Eq. 3.5 and Section 6.3.

Resoring to duel fuel operation with gaseous fuel containing little or no nitrogen eg. natural gas, LPG etc. could effectively reduce the excess air available for engine operation and thereby reducing the level of nitrogen produced in the engine exhaust.

For optimum operation a exhaust concentration of about 10% resulted in a fuel savings of about 4.5% (See Figures 7.6 and 7.8). This is an important finding since it suggests that similar systems attempting to operate in this mode should not use exhaust quantities far in excess of 10% for satisfactory operation.

In addition to supplementing the charcoal, the exhaust emission enters the system in a preheated state. This would then mean that the amount of heat that would be required normally for raising such a mixture temperature would be lowered.

It is highly unlikely that the gasifier will operate satisfactorily working entirely with the products of combustion as the primary gasifying agent since high oxygen concentration is necessary to maintain the reactor at sufficiently high working temperature. Throughout this investigation, the oxygen concentration supplied was maintained at levels between 17.8 and 19%. The exhaust emission as stated in Section 7.1 had quantities of hydrocarbon, sulphur dioxide and oxides of nitrogen.

These were however in parts per million and data as to their effect were not available. It is quite possible though, that the hydrocarbon present would have been oxidised in the combustion zone and take part in the subsequent reduction reactions.

Between 200 and 250°C, sulphur dioxide reacts with oxygen and water to give sulphuric acid. This is always undesirable since the acid is highly corrosive. At the prevailing temperatures which were higher than 250°C (See Figure 7.4) there can be a reduction of the sulphur dioxide by CO to sulphur (See Equation 7.1) and an oxidation of H_2 to water and sulphur, Equation 7.2:-

$$2CO + SO_2 \rightarrow 2CO_2 + S \qquad (7.1)$$

$$2H_2 + SO_2 \rightarrow 2H_2O + S \qquad (7.2)$$

These effects however will be very low in magnitude since their contribution in the exhaust quantity is relatively small.

The ability to regenerate combustion products from operating system in a gasifier has demonstrated that it is possible to obtain substantial fuel savings in systems operating in this dual mode if proper conditions are maintained. These would include sufficient O_2 for maintaining suitable reaction temperature and a controlled supply of exhaust emission.

In addition to the obvious fuel saving, lower reaction temperature can be maintained and as mentioned in Chapter 6 reduces the occurrence of slagging and reactor burnout.

7.6 CONCLUSION

From the foregoing investigation, several conclusions were drawn. They are as follows:-

(1) It is possible to regenerate exhaust emission from a C.I. engine in a fixed bed downdraft gasifier.

(2) A gas with a CO concentration of 26.5% can be obtained from similar systems.

(3) A H_2 concentration of 4.5% can be generated in the gas mixture.

(4) A gas with a heating value of 3.65 MJ/Nm^3 can be generated in the system.

(5) The maximum concentration of exhaust emission allowable in the air supply for satisfactory operation is about 10% though this may depend on the design of the system and the composition of the exhaust.

(6) Fuel savings of about 4.5% can be obtained when the system is operating at maximum efficiency.

CHAPTER 8

APPARATUS FOR ENGINE TEST WITH PRODUCER GAS

8.1 INTRODUCTION

As described in Chapter 4, producer gas was generated in a fixed bed downdraft gasifier using charcoal as the fuel and air as the gasifying agent. A gas with a calorific value of 4.7 MJ/Nm^3 and a CO and H_2 concentration of 32 and 7.6% respectively was obtained. The CH_4 content obtained was below 1%.

A C.I. engine can be operated on producer gas with the injection of a small quantity of diesel fuel to initiate the combustion of the air-gas mixture. Dual fueling and pilot injection are the two possible modes in which a C.I. engine can operate using producer gas as the primary fuel. The essential difference between the two modes is that the pilot injection system allows for a fixed diesel fuel while the dual fuel system allows for varying diesel feed to match loading requirements.

The gaseous nature of the fuel can produce a better engine-transient operation and response together with improved fuel control. The gas can have exceptionally high resistance to knock thereby, allowing high compression ratio operation to be made without the onset of knock under a fairly wide range of operating condition. Moreover since the fuel is gaseous under normal conditions, a simple carburetion and control system is adequate. Excellent mixture with the air is assured when the gas is introduced into the engine intake and results in a much better mixture control and charge distribution in single and multi-cylinder engines. This inherently is advantageous in term of engine performance and torque characteristic. The gaseous homogeneous nature of the charge, allows for a smoother engine heat release by combustion following the ignition of the pilot diesel fuel. Producer gas can have quite a varied flame temperature and flame speed in air since, it is possibe to control to some extent the constituents of the primary combustible fraction in the gas mixture i.e. CO, H_2 and CH_4.

A desirable feature of a duel fuel engine is its ability to be converted to gas or oil operation without dismantling or adding any parts. This change over from one fuel to the other can in fact take place without the engine being stopped or any change in its load.

8.2 APPARATUS USED

8.2.1 The Engine

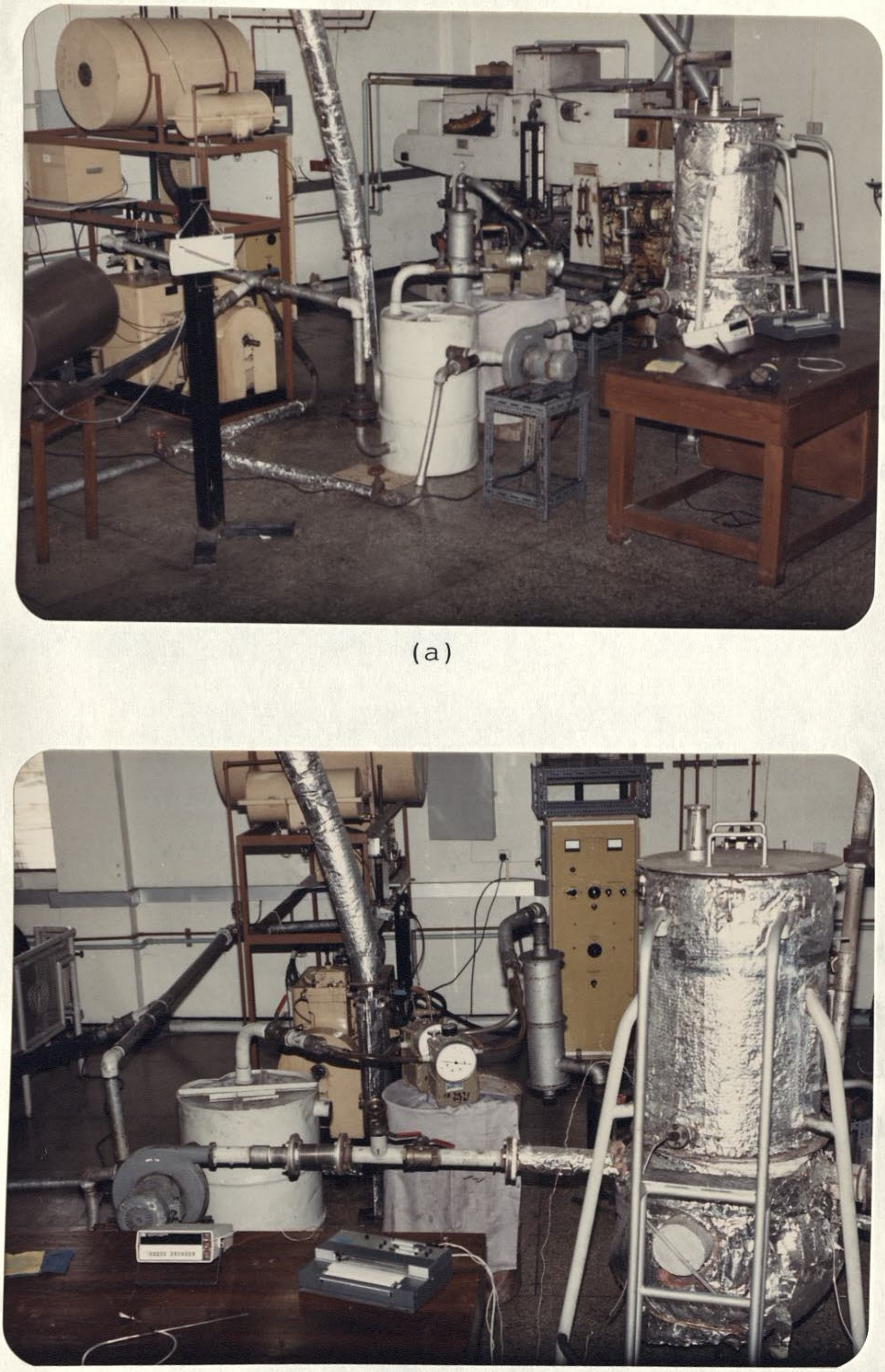
(i) The engine used for the investigation was a Petter PHW Single Vertical cylinder, naturally aspirated, water cooled direct injection engine. Its general arrangement and interconnection with the gasifier system is shown in Figures 8.1, 8.2, 8.3 and Plate 8-1. Specification and other particulars of the engine are listed below:

Cycle of Operation : 4 stroke diesel cycle
Engine rater output : 9 KW
Maximum speed : 1800 rpm
Bore : 87.3 mm
Stroke : 110 mm
Displacement : 659 cm^3
Compression ratio : 16.5:1
Dynamometer type : BK compound 1800 rpm maximum speed
Torque arm : 220 mm

The fuel injection release pressure is between 140-221 Kg/cm^2 with injection starting 24° before TDC for speeds up to 1650 rpm. The inlet valve opens at 4½° before TDC and closes at 35½° after BDC and the exhaust valve opens at 35½° before TDC and closes at 4½° after TDC.

Power and speed ratings (manufacturers)

2.9 KW at 1000 rpm
3.7 KW at 1200 rpm
4.7 KW at 1500 rpm



(a)

(b)

PLATE 8-1

LAYOUT OF GASIFIER ENGINE SYSTEM

(ii) The Fuel System (Diesel)

The fuel was supplied to the engine from a storage tank of capacity 27 litres. The fuel flowed by gravity to a glass burette with a capacity of about 100 cc in 25 cc graduations. From the burette the fuel flowed through a filter to the fuel pump and finally to the injector.

(iii) Cooling Water System

Cooling water was supplied to the engine through the use of a circulating pump. Fresh make up water at a controlled rate from the main, was constantly added to the system to maintain a constant acceptable temperature in the cylinder block. Cooling temperatures were monitored by observing temperature readings of the inlet and exit point of the cooling water system.

(iv) Engine Loading System

The engine was coupled to a DC dynamometer with a rating of 7 KW which supplied current to a loading bank. The desired load can be obtained by suitably connecting the loading banks in parallel to the dynamometer terminal. A variable resistance was included in the circuit for further fine adjustment of the load. A voltmeter and ammeter were provided in the circuit to determine the load applied to the engine. For determining the brake power on the engine using the dynamometer, the following formula was used:-

$$BP = \frac{F \times RPM}{43.41}$$

F = Force measured in Newtons at the reaction arm at 0.22 m long.

(v) Exhaust Gas Sampling Probe

The exhaust gas sampling probe used is similar to the one described in Figure 2.3 for producer gas sampling. It was placed at a suitable point in the exhaust line.

8.2.2 (i) Exhaust Gas Analysis

Some of the instruments used for exhaust gas analysis were the same as those used for producer gas analysis. The CO_2 fyrite analyser and the orsat gas analyser were used as described earlier in Section 2.3.5. These analysers however measured the concentration of oxygen, carbon dioxide and carbon monoxide when they were present in concentrations above 0.2%. The other exhaust constituents namely oxides of nitrogen, formaldehydes (and low concentration of carbon monoxide) that were noted had to be measured with a drager gas detector. (See No. 2, Plate 2-2).

The principle of the Drager gas detector is that a sample of the exhaust gas is sucked by means of a hand operated bellows type pump through glass tubes containing special absorbers, one for each gas to be analysed in the sample. The concentration of a particular constituent in the exhaust gas, is measured by the length of the discoloured zone of the reagent in the tube, which is graduated in ppm. The drager tube was chosen because of its simplicity and reproducibility of results. However its accuracy was limited and the results were of a qualitative rather than of a quantitative nature.

(ii) Exhaust Gas Temperature Measurement

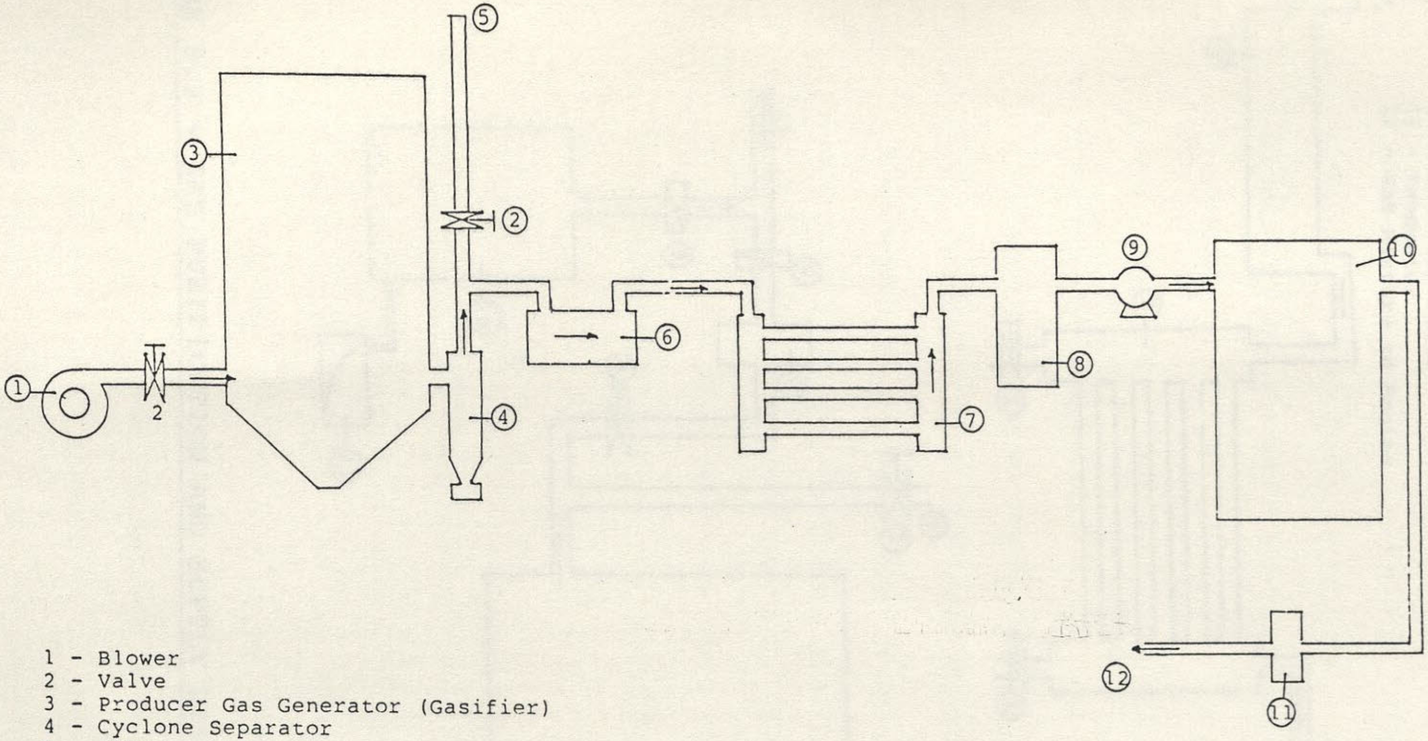
The exhaust temperature was measured using a shielded cromel alumel thermocouple. The emf measured was converted to the corresponding temperature by a calibration plot done before the analysis. The thermocouple was placed just down stream of the exhaust valve in the exhaust manifold.

8.2.3 The Gas Producer System

The gas producer system essentially consisted of the gas generator in addition to the cleaning and cooling system. The gas generator has already been described in Section 2.3. The cleaning and cooling system comprises of a cyclone separator, a wet scrubber, a gas cooler, a dry bed filter and a safety filter (See Figures 8.1 and 8.2). They are described in the following section.

(i) The Cyclone Separator

The gas firstly passes through the cyclone separator (See No. 4, Figure 8.1). This piece of equipment is a dust collector without any moving parts, in which the velocity of the inlet gas stream is transformed into a confined vortex. The dust separation from the gas stream takes place through centrifugal forces. The entrained fly ash tends to be driven to the wall of the cyclone and is collected in an ash bin at the bottom. This is the first



1 - Blower
2 - Valve
3 - Producer Gas Generator (Gasifier)
4 - Cyclone Separator
5 - Flare
6 - Scrubber
7 - Gas Cooler
8 - Dry Filter
9 - Gas Meter
10 - Surge Tank
11 - Safety Filter
12 - Gas Flow

FIGURE 8.1 - SCHEMATICS OF PRODUCER GAS DEVICE WITH CLEANING AND PURIFICATION SYSTEM

1 - Scrubber
2 - Gas Cooler
3 - Valves
4 - Dry Filter Bed
5 - Gas Meter
6 - Surge Tank
7 - Flare
8 - Safety Filter
9 - Throttle Valve
10 - Air Flow Meter
11 - Manometer
12 - Gas Mixture to Engine

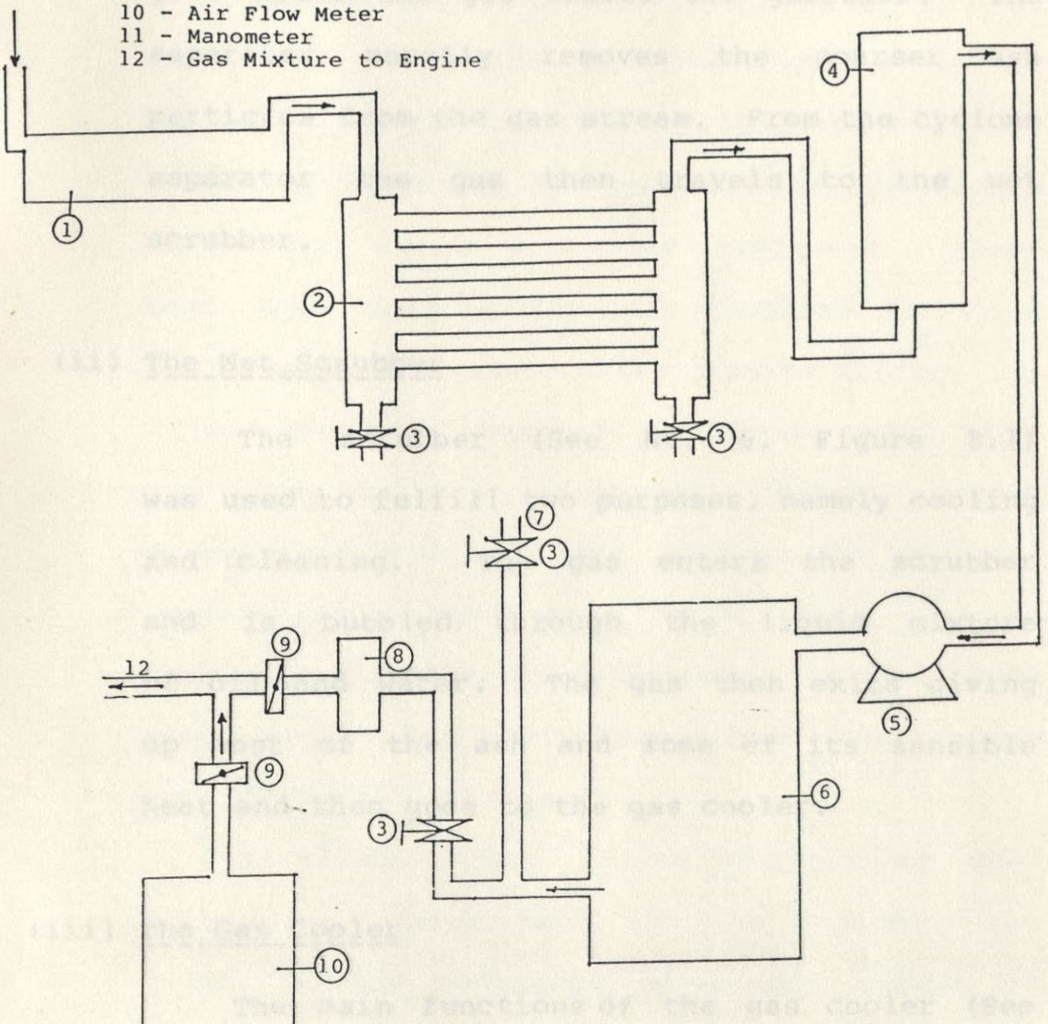


FIGURE 8.2 - GAS PURIFICATION AND SUPPLY SYSTEM TO ENGINE

stage of cleaning for the raw gas and is located just after the gas leaves the gasifier. The separator usually removes the coarser ash particles from the gas stream. From the cyclone separator the gas then travels to the wet scrubber.

(ii) The Wet Scrubber

The scrubber (See No. 6, Figure 8.1) was used to fulfill two purposes, namely cooling and cleaning. The gas enters the scrubber and is bubbled through the liquid mixture of oil and water. The gas then exits giving up most of the ash and some of its sensible heat and then goes to the gas cooler.

(iii) The Gas Cooler

The main functions of the gas cooler (See No. 7, Figure 8.1) are to reduce the high temperature of the gas to a value acceptable for engine use i.e. about 40-60°C, and to collect condensate. For stationary engine systems, a rather large cooling area is needed since natural convection is used. The system was made simply from galvanized piping and the surface area was increased by using relatively small bore pipes.

(iv) The Dry Bed Filter

Within the dry bed filter (See No. 8, Figure 8.1) the gas passes through a bed of charcoal where additional filtering takes place as well as the removal of additional water that would have been condensed. Steel wool was used after the charcoal bed for additional filtering. After leaving the dry filter bed of charcoal and steel wool, the gas was metered using two Singer Rotary gasmeters. Between the gas meters and the engine, was a drum used as a surge tank to act as a buffer, to eliminate the pulsation that would be transmitted from the engine suction back to the meter.

A final safety filter was placed just between the surge tank and the engine. The safety filter consisted of a wire screen of very fine mesh. The purpose of this filter was to safeguard the engine in case of failures in the other filters.

8.3 METHOD OF AIR/FUEL MIXTURE

The set up used for gas producer and engine interconnection is shown in Figure 8.3. The air and gas were mixed in a simple mixer at a T-joint some distance from the engine inlet. The amount

- 1 - Manometer
- 2 - Air Metering Device (supplied with engine) used for leaning air-fuel mixture
- 3 - Butterfly
- 4 - Gas Flow
- 5 - Air Flow
- 6 - Engine
- 7 - Air Metering Device for Air-gas mixture

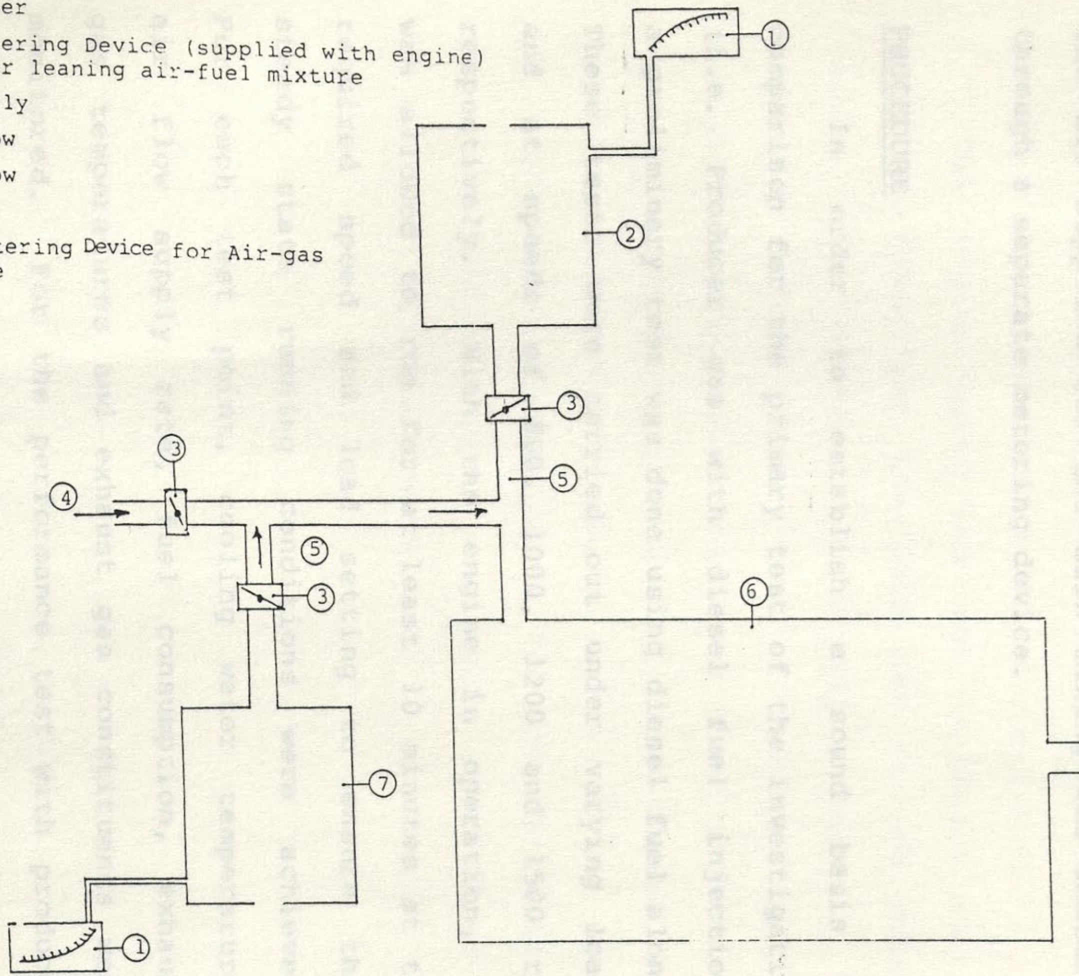


FIGURE 8.3 - AIR-GAS MIXING ARRANGEMENT

of air used by the engine was measured by an orifice meter. Butterfly valves were used to regulate the air flow rate. The air metering system supplied with the engine was used as a leaning device for the air-gas mixture. This was positioned after the point where the main air-gas mixing took place. The air supplied for the main mixing was measured through a separate metering device.

8.4 PROCEDURE

In order to establish a sound basis of comparison for the primary test of the investigation (i.e. Producer gas with diesel fuel injection) a preliminary test was done using diesel fuel alone. These tests were carried out under varying loads and at speeds of 800, 1000, 1200 and 1500 rpm respectively. With the engine in operation, it was allowed to run for at least 10 minutes at the required speed and load setting to ensure that steady state running conditions were achieved. For each test point, cooling water temperature, air flow supply rate, fuel consumption, exhaust gas temperatures and exhaust gas constituents were monitored. For the performance test with producer gas and diesel fuel injection, additional parameters including producer gas supply rate, air-gas mixture ratio, gas producer temperature, water vapour content along with impurities in the gas and gas inlet temperature to the engine were monitored.

The gasifier at its operating point produced about 0.55 Nm^3/min and was capable of generating about 12 KW of power. The engine's maximum demand however at 1500 rpm was $2x10^{-3}$ Nm^3/min and the excess produced was bypassed and burnt at the flare.

The engine speed was set initially at the required value and the load set at its maximum value. The diesel fuel injection quantity was gradually reduced while that of the gas supplied was gradually increased until the point was reached where any further reduction in the diesel fuel injection resulted in unstable running of the engine as evidenced by knocking. For the duration of the main investigation, the point is referred to as the point of stable operation.

CHAPTER 9

ENGINE TESTS WITH PRODUCER GAS

9.0 SUMMARY

A C.I. engine normally aspirated and rated at 9KW at 1800 rpm, was run on producer gas generated from charcoal in a fixed bed downdraft gasifier. The gas was cooled and cleaned before engine use. The producer gas was found to supply up to 80% of the total energy at between low and intermediate torque levels and provided a wider operating torque range for the engine.

During producer gas use, the levels of pollutants at low engine load were higher than with normal diesel operation but as the torque increased, the pollutant level fell to levels comparable with that of the diesel operation.

9.1 OBSERVATION

In a given speed, the diesel fuel pump was set at the point that just allowed the engine to operate at no load condition so that when the engine was loaded slightly, instability developed and the engine tended to stall. With this fuel pump setting, the load and gas supply were increased step by step until the required load conditions were attained with the engine stalling.

For the general operation throughout the investigation, it was observed that on the admission of the producer gas to the engine, the engine started to accelerate. Further increase in the gas admitted caused the operation to become unstable. This was highlighted by a knocking sound. On increasing the load however, the engine operation became more stable. When operating under the same low load condition, a further increase in the gas admitted resulted in a more intense knocking sound. Conditions were made stable by increasing the diesel fuel input to the engine. However the noise level of the engine was lower to some extent when operating under dual fuel condition than when under normal diesel operation.

9.2 RESULTS

9.2.1 Fuel Economy

Figures 9.1(a) - 9.1(d) shows the plots of fuel consumption of diesel fuel and of charcoal in kg/hr against Brake Power in kilowatts for both modes of operations at speeds of 800, 1000, 1200 and 1500 rpm. Under dual fuel operation at the lower loading range at all speeds, the quantity of diesel fuel supplied remained almost constant. At 800 rpm (See Figure 9.1(a)), the diesel fuel consumption quantity remains almost constant at about 0.07 kg/hr for almost 70% of the loading range after which it increased fairly rapidly for a further increase in the engine load. With the other speeds, for about 40% of the loading range the diesel fuel consumption was almost steady and beyond this point, the consumption increased with a further increase in load; for speeds of 1000, 1200 and 1500 rpm, the diesel fuel consumption remained steady at about 0.05, 0.225 and 0.325 kg/hr respectively.

For all four operating speeds in the dual fuel mode, it appears that the lowest diesel fuel injection used for the test were much lower than that which was necessary for stable operation. This is quite noticeable from the plots since although the power output was increasing gradually in the lower range, the quantity of diesel fuel injected remained steady as the quantity of producer gas was increased. Approaching intermediate and full load setting for all four operating speeds, as the diesel fuel injection quantity increased, the quantity of producer gas consumed by the engine reached a maximum value and then started to decrease. It is also interesting to note that for all speeds, the highest power generated under dual fuel operation was greater than that which was available under normal diesel operation. For 800 rpm the difference

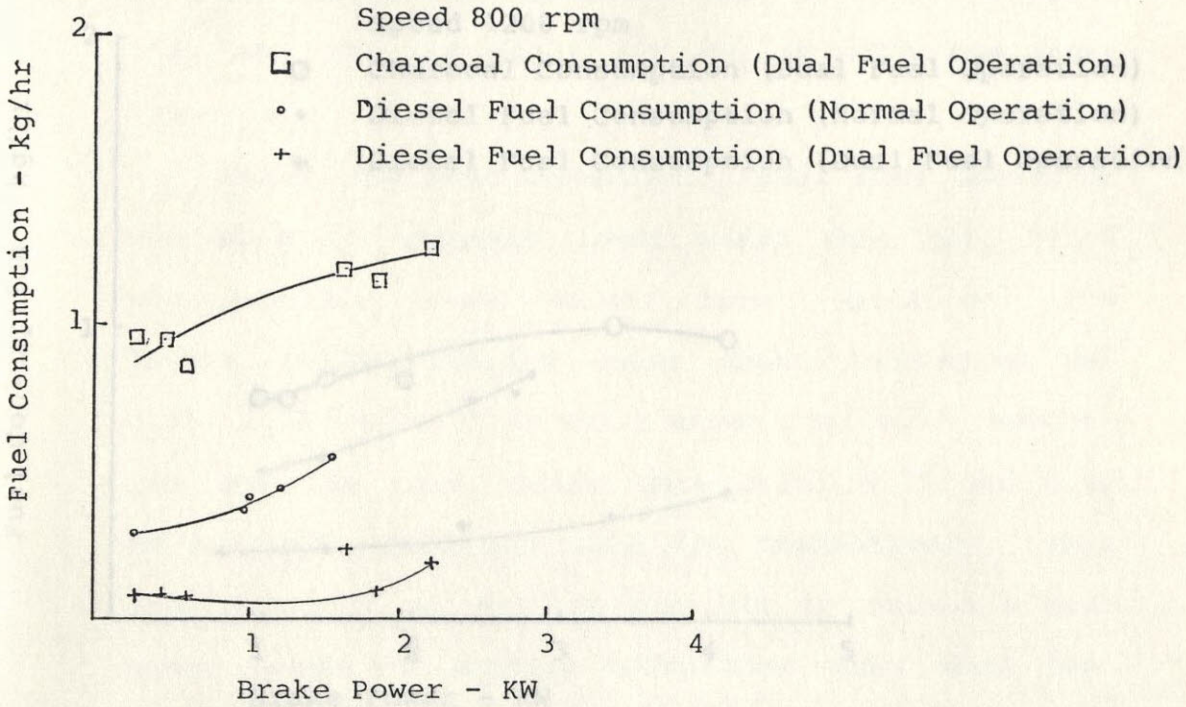


FIGURE 9.1(a) - FUEL CONSUMPTION AT VARIOUS LOADS (800 rpm)

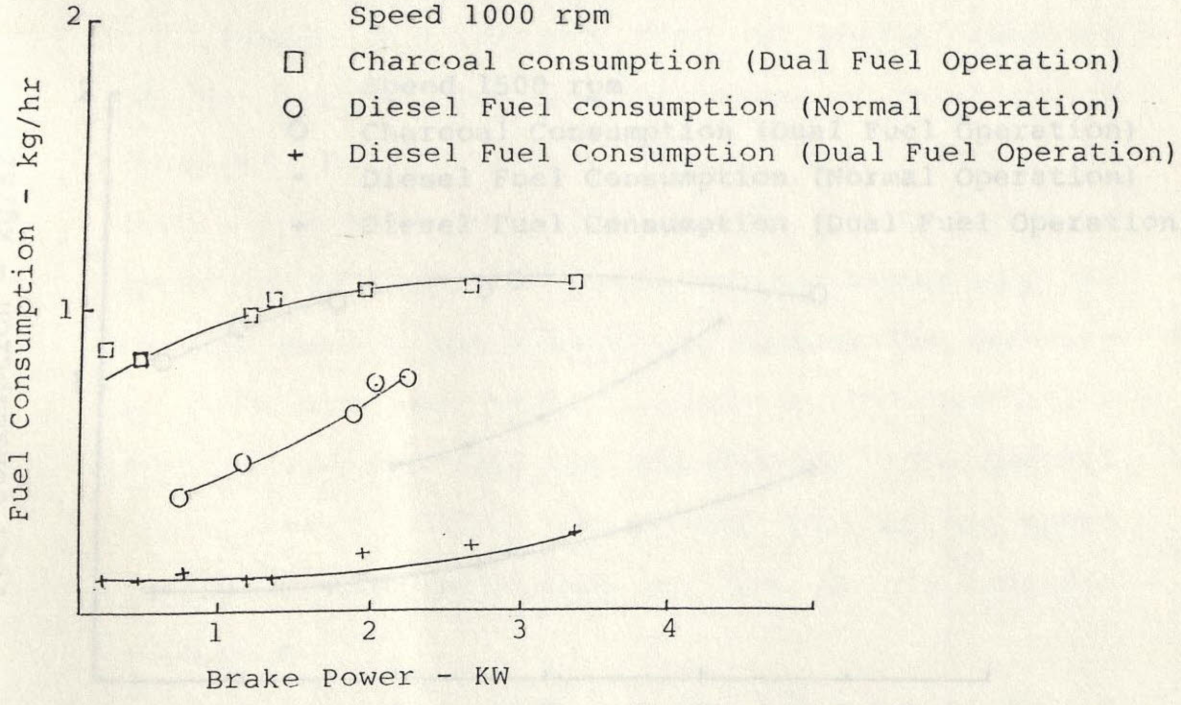


FIGURE 9.1(b) - FUEL CONSUMPTION AT VARIOUS LOADS (1000 rpm)

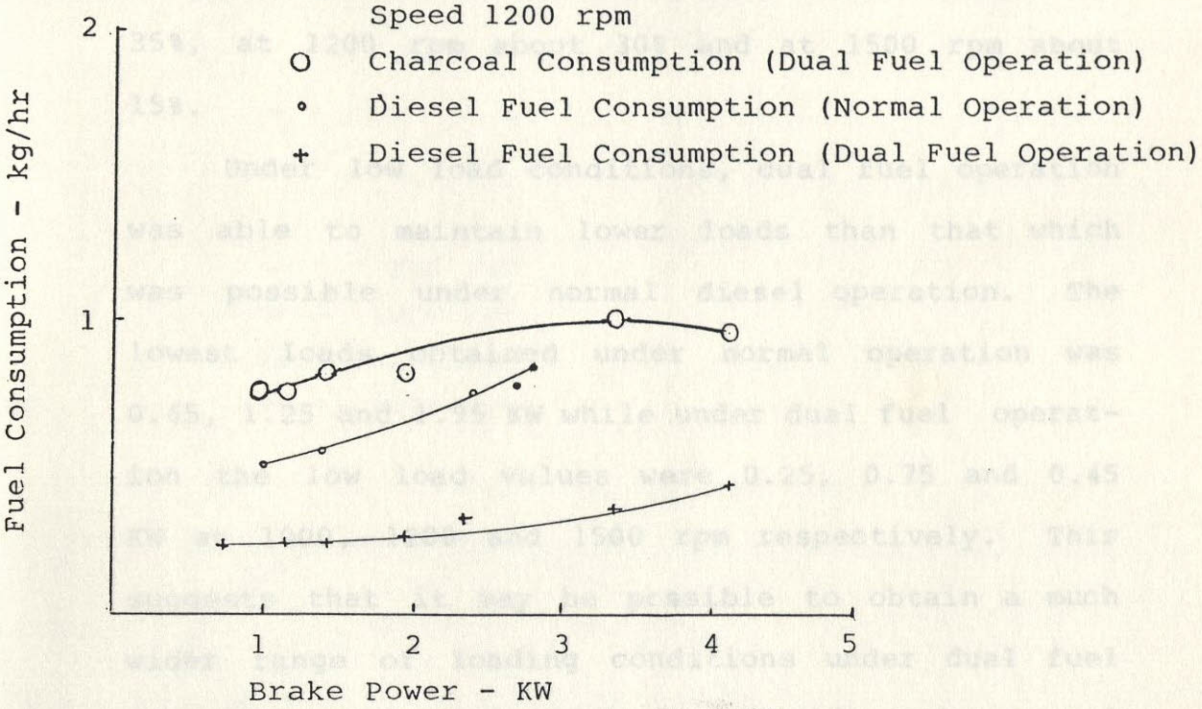


FIGURE 9.1(c) - FUEL CONSUMPTION AT VARIOUS LOADS (1200 rpm)

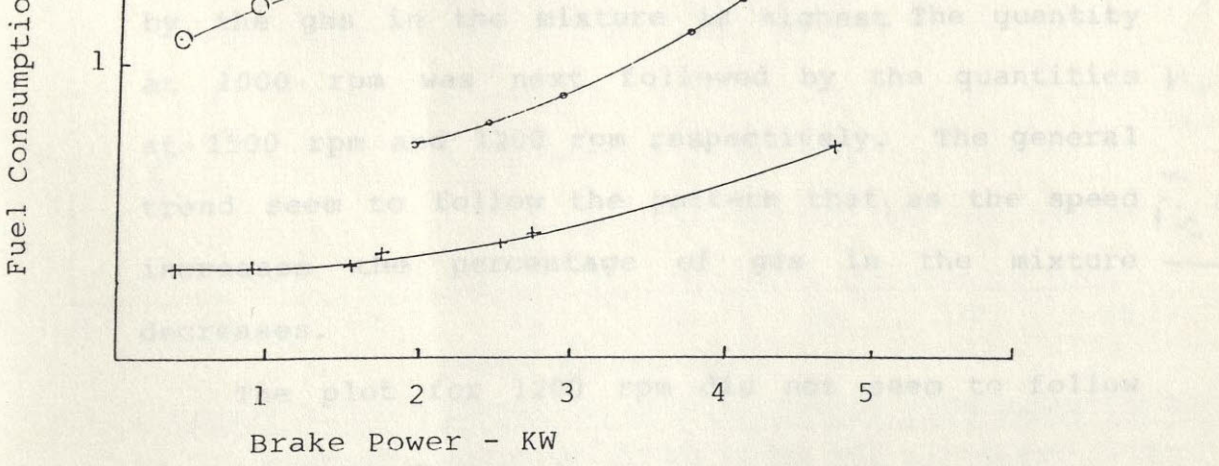


FIGURE 9.1(d) - FUEL CONSUMPTION AT VARIOUS LOADS (1500 rpm)

in power generated was about 30%, at 1000 rpm about 35%, at 1200 rpm about 30% and at 1500 rpm about 15%.

Under low load conditions, dual fuel operation was able to maintain lower loads than that which was possible under normal diesel operation. The lowest loads obtained under normal operation was 0.65, 1.25 and 1.95 KW while under dual fuel operation the low load values were 0.25, 0.75 and 0.45 KW at 1000, 1200 and 1500 rpm respectively. This suggests that it may be possible to obtain a much wider range of loading conditions under dual fuel operation than that which is possible under normal diesel operation.

Figure 9.2 is the plot of energy supplied by the producer gas as a percentage of total energy supplied to the engine against Brake Torque in N-M. The plot shows that at the lowest operating speed of 800 rpm, the percentage of energy supplied by the gas in the mixture is highest. The quantity at 1000 rpm was next followed by the quantities at 1500 rpm and 1200 rpm respectively. The general trend seem to follow the pattern that as the speed increases the percentage of gas in the mixture decreases.

Not so in Fig 9.2

The plot for 1200 rpm did not seem to follow

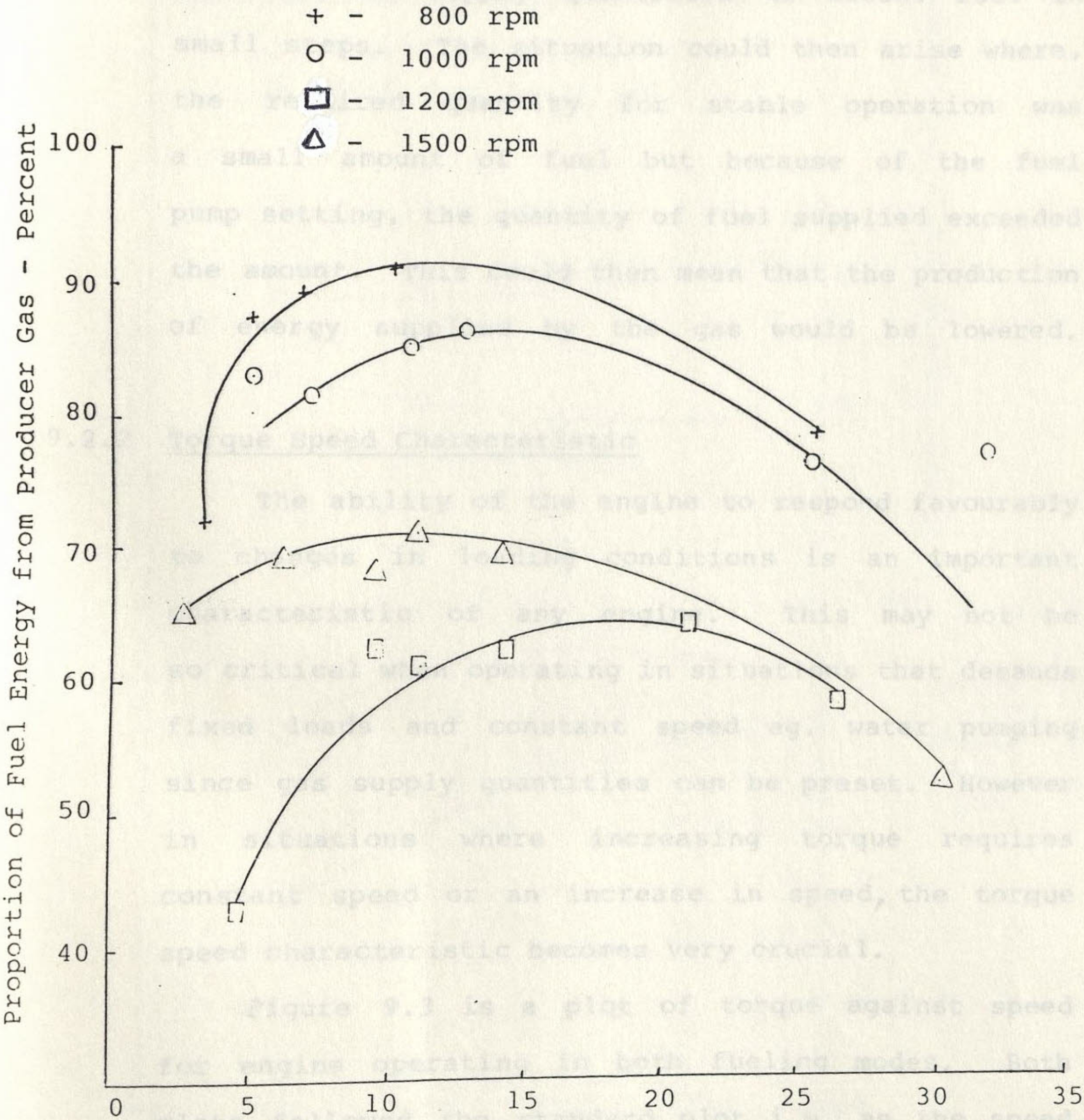


FIGURE 9.2 - PROPORTION OF FUEL ENERGY FROM PRODUCER GAS AT VARIOUS LEVELS OF BRAKE POWER FOR DIFFERENT SPEED

the general trend and had a lower percentage of producer gas than that of the 1500 rpm plot. The possible reason for this may lie in the engine fuel supply system. The fuel pump setting was not able to supply quantities of diesel fuel in small steps. The situation could then arise where, the required quantity for stable operation was a small amount of fuel but because of the fuel pump setting, the quantity of fuel supplied exceeded the amount. This could then mean that the production of energy supplied by the gas would be lowered.

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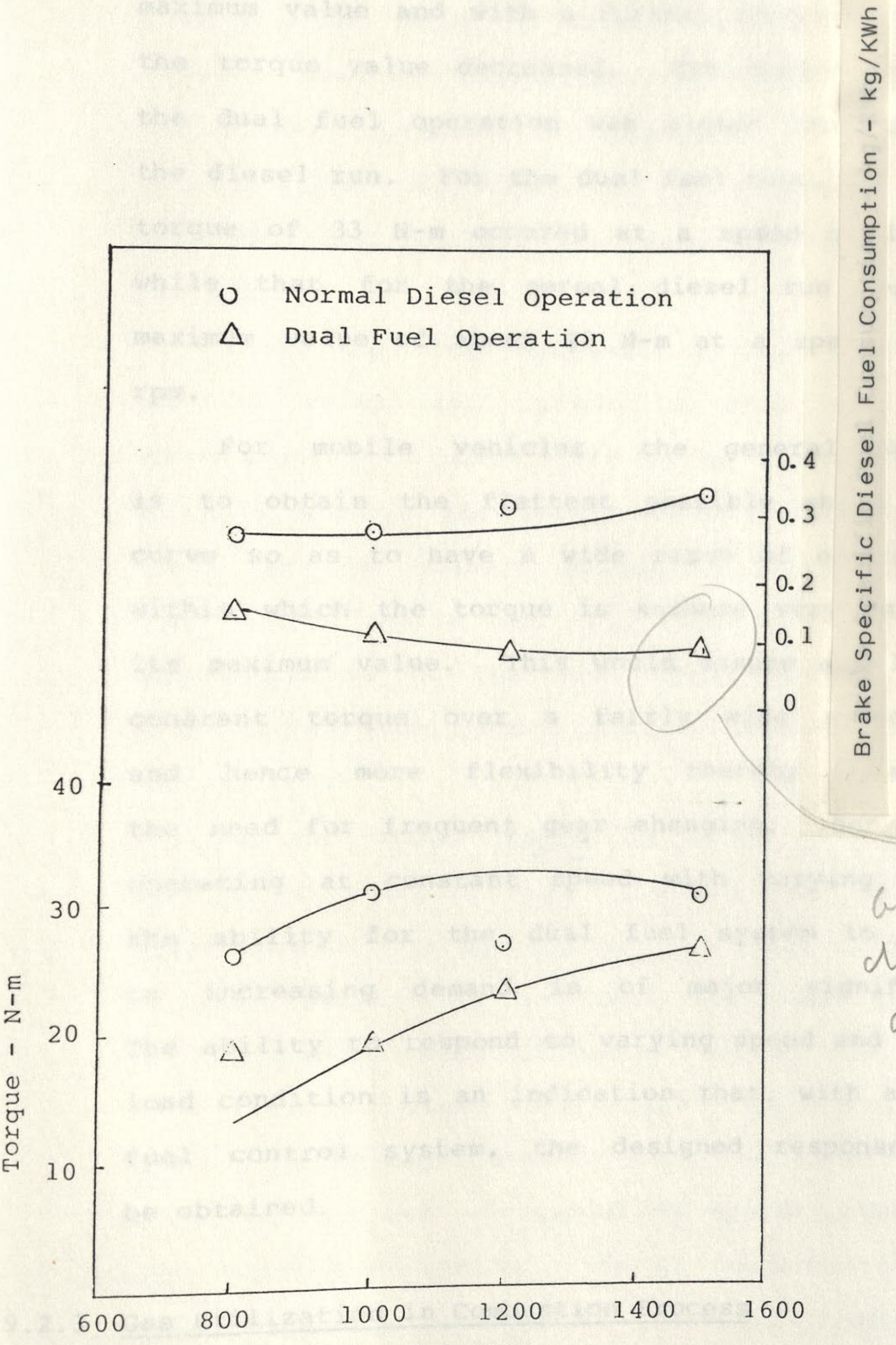
9.2

9.2.2 Torque Speed Characteristic

The ability of the engine to respond favourably to changes in loading conditions is an important characteristic of any engine. This may not be so critical when operating in situations that demands fixed loads and constant speed eg. water pumping since gas supply quantities can be preset. However in situations where increasing torque requires constant speed or an increase in speed, the torque speed characteristic becomes very crucial.

Figure 9.3 is a plot of torque against speed for engine operating in both fueling modes. Both plots followed the standard plot i.e. as the speed increased, the torque value increased towards a



so this based on diesel fuel only ??

FIGURE 9.3 - TORQUE SPEED VARIATION FOR NORMAL DIESEL OPERATION AND DUAL FUEL OPERATION

maximum value and with a further increase in speed the torque value decreased. The torque level for the dual fuel operation was higher than that for the diesel run. For the dual fuel test, the maximum torque of 33 N-m occured at a speed of 1200 rpm while that for the normal diesel run reached a maximum value of about 25 N-m at a speed of 1500 rpm.

For mobile vehicles, the general objective is to obtain the flattest possible shape in the curve so as to have a wide range of engine speed within which the torque is nowhere very far below its maximum value. This would ensure a relatively constant torque over a fairly wide speed range and hence more flexibility thereby eliminating the need for frequent gear changing. For systems operating at constant speed with varying torque, the ability for the dual fuel system to respond to increasing demand is of major significance. The ability to respond to varying speed and varying load condition is an indication that, with a proper fuel control system, the designed response could be obtained.

9.2.3 Gas Utilization in Combustion Process

The dual fuel engine has the ability to operate over a wide range of mixture strength and would involve various combustion reactions. Some of the primary products of combustion for both modes of operation were monitored at engine speeds of 800 and 1500 rpm and are shown in Figure 9.4(a) - 9.4(d).

Under dual fuel operation at the lower speed, the CO level fell gradually from its highest concentration of about 7.5% at an operating torque of 3.25 N-m to its lowest concentration of about 1.25% at the highest operating torque of 26.25 N-m. This value was significantly higher than that obtained at the same speed operating fully with diesel fuel which varied between 1000 ppm and 300 ppm.

At the higher operating speed of 1500 rpm, the CO concentration with producer gas maintained lower levels. It had its highest value of 5% again at the lowest load and then decreased gradually to its lowest value of about 1.5% at the highest torque levels. These values again were significantly higher than those obtained from the normal diesel operation at the corresponding speed although at high loading conditions, the CO concentration were approaching typical values obtained from normal diesel operation.

The high CO concentration in the exhaust gas at low load conditions under dual fuel operation, seems to suggest that poor gas utilization occured in the combustion chamber at this point and its decrease in concentration as the load increases, suggests that the gas utilization in the combustion process was improving with increasing load. Approaching full load condition for the diesel operation at both speeds, the CO concentration decreased to minimum values and then started to show an increase. This could be an indication that the maximum combustion efficiency possible under the operating condition was reached and then started to decrease. For the dual fuel operation and approaching full load condition, the CO concentration continued to fall. The slope then was not as significant as seen at low load conditon and seems to suggest that the combustion efficiency and gas utilization was approaching its maximum value.

The levels of formaldehyde in the exhaust was higher under dual fuel operation than with the normal diesel operation. At 800 rpm with producer gas, as the diesel injection quantity was increased, the formaldehyde concentration fell from 30 ppm to 15 ppm while that of the normal diesel operation fell from 10 ppm to about 4 ppm. At 1500 RPM the

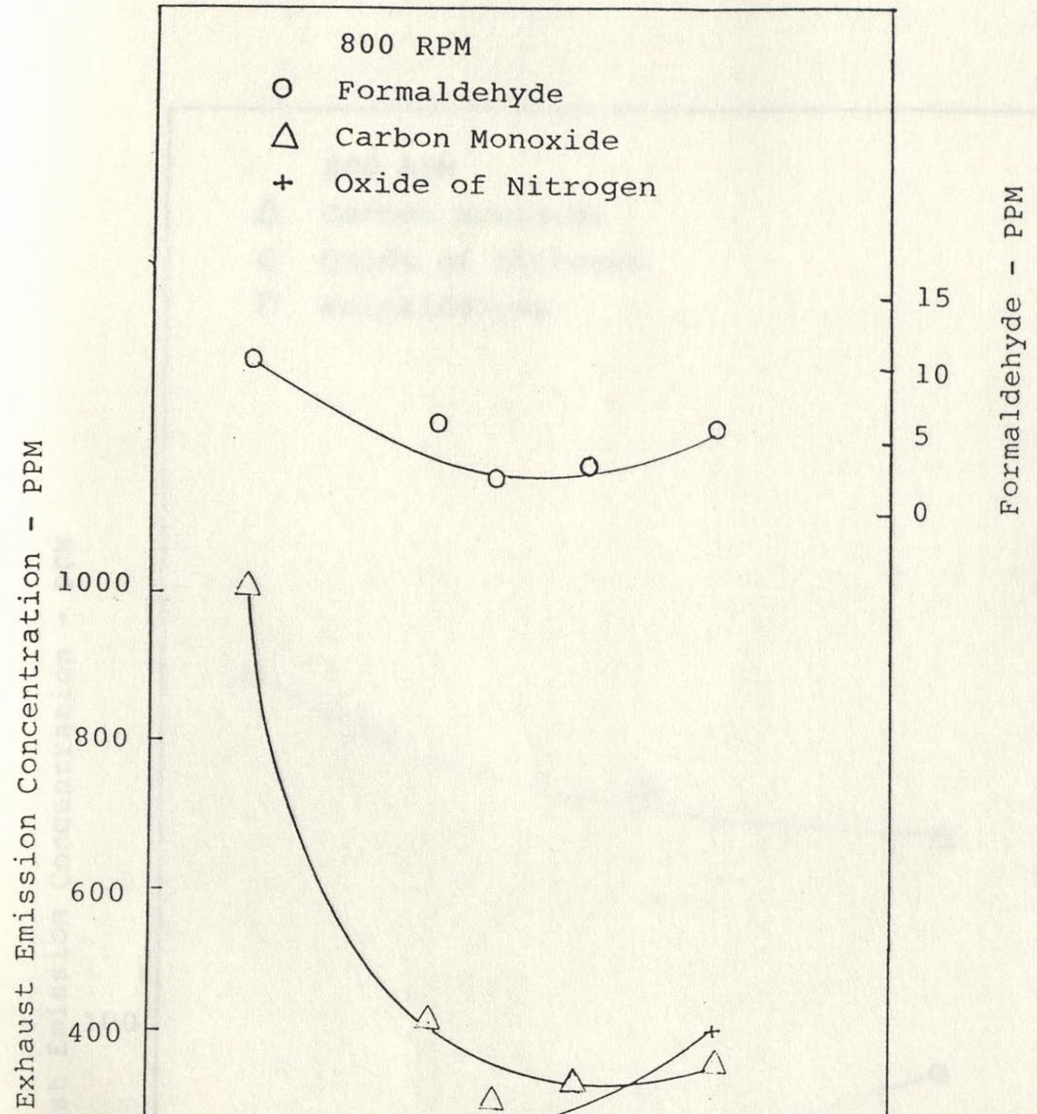


FIGURE 9.4(a) - POLLUTANT EMISSION IN EXHAUST FOR DIESEL FUEL OPERATION AND VARIOUS LEVELS OF BRAKE TORQUE

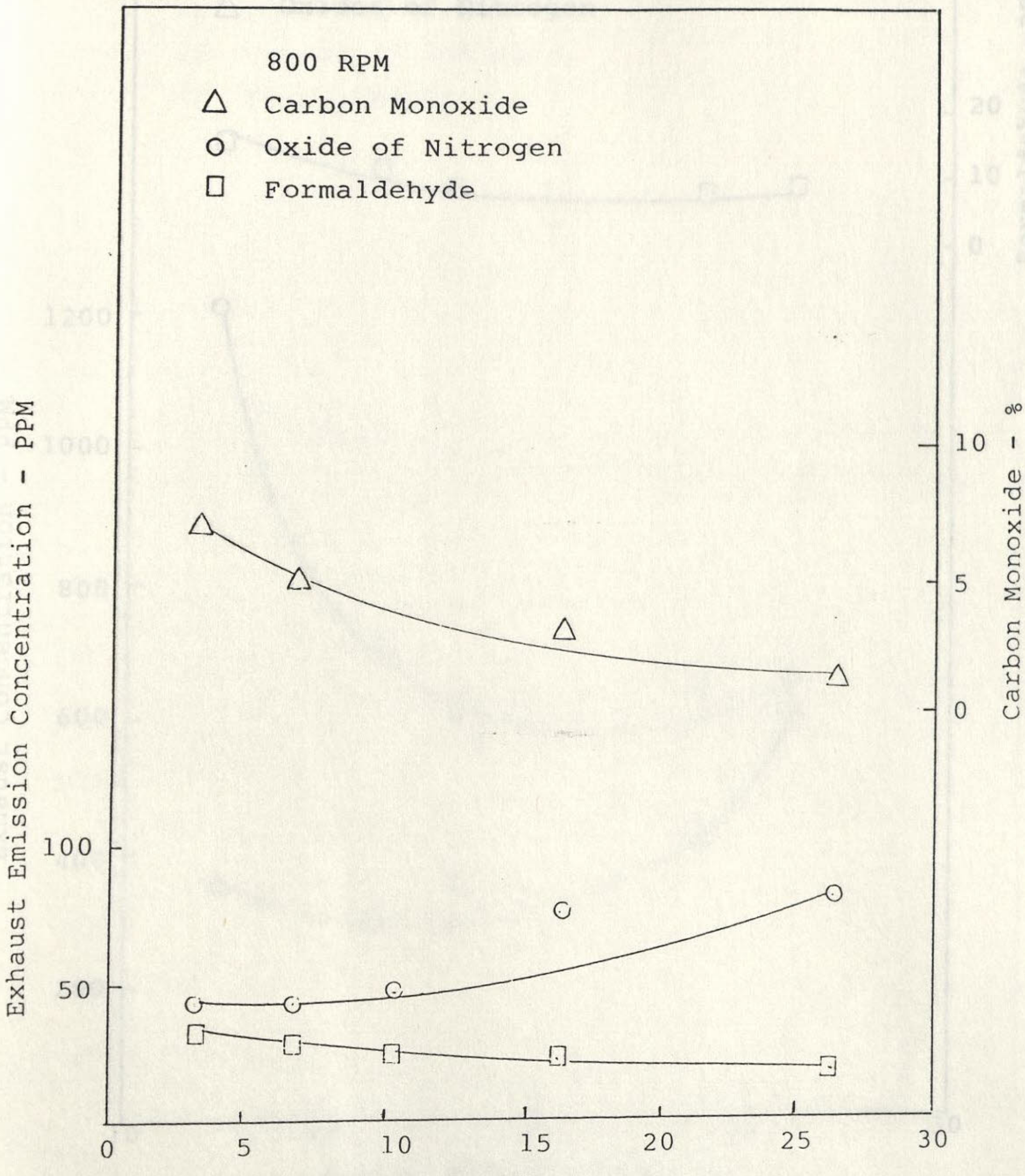


FIGURE 9.4(b) - POLLUTANT EMISSION IN EXHAUST FOR DUAL FUEL OPERATION AND VARIOUS BRAKE TORQUE

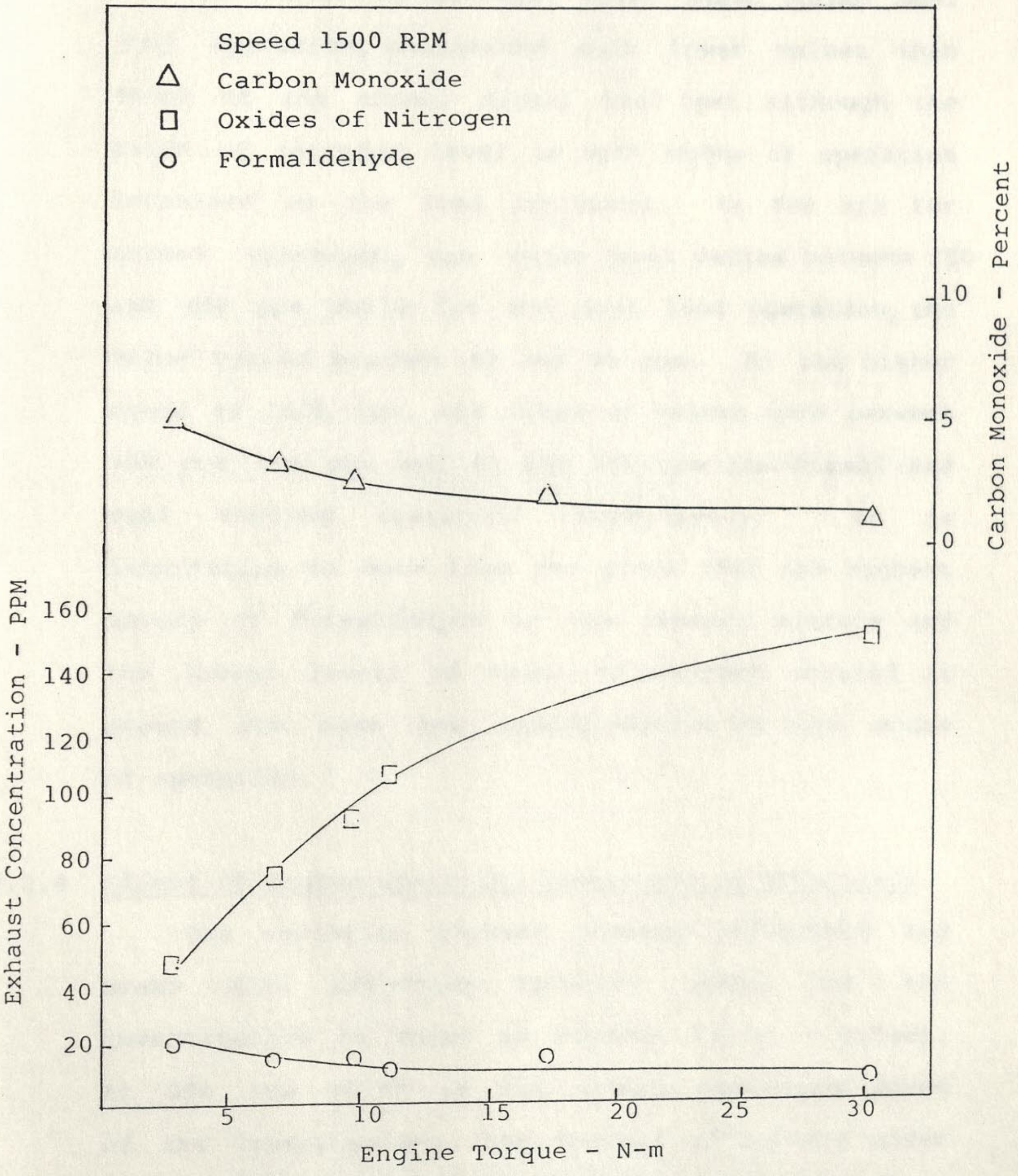


FIGURE 9.4(d) - POLLUTANTS EMISSION IN EXHAUST FOR DUAL FUEL OPERATION AT VARIOUS BRAKE TORQUE

concentration fell from about 20 ppm to about 8 ppm and from about 15 ppm to about 8 ppm for dual fuel and normal diesel operation respectively.

The oxide of nitrogen level under normal dual fuel operation, maintained much lower values than those of the normal diesel fuel test although the oxide of nitrogen level in both modes of operation increased as the load increased. At 800 rpm for normal operation, the oxide level varied between 240 and 400 ppm while for the dual fuel operation, the value varied between 40 and 80 ppm. At the higher speed of 1500 rpm, the range of values were between 300 and 600 ppm and 43 and 144 ppm for diesel and dual fueling operation respectively. It is interesting to note from the plots that the highest levels of formaldehyde in the exhaust mixture and the lowest levels of oxide of nitrogen occured at around the same low load condition for both modes of operation.

9.2.4 Effect of Engine Operating Conditions on Efficiency

The variation between thermal efficiency and Brake Mean Effective Pressure (BMEP) for the investigation is shown in Figures 9.5(a) - 9.5(d). At 800 rpm which is the lowest operating speed of the investigation, the thermal efficiency under

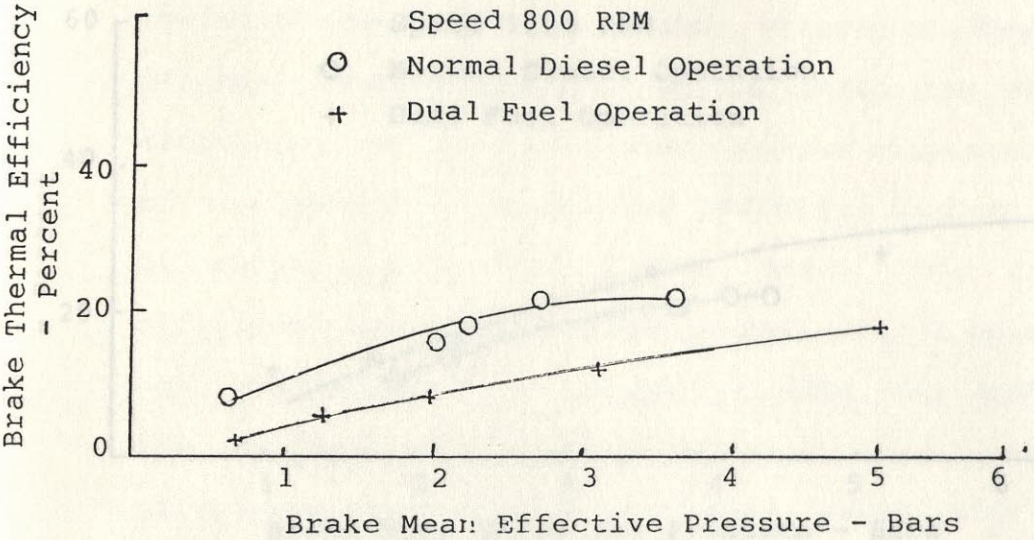


FIGURE 9.5(a) - EFFECT OF MEAN CYLINDER PRESSURES ON THERMAL EFFICIENCY

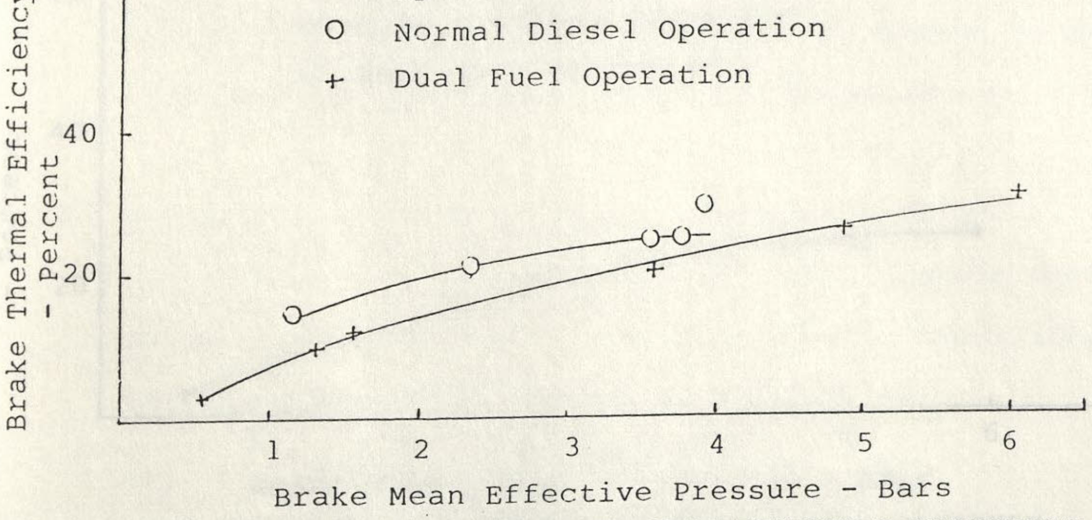


FIGURE 9.5(b) - EFFECT OF MEAN CYLINDER PRESSURES ON THERMAL EFFICIENCY

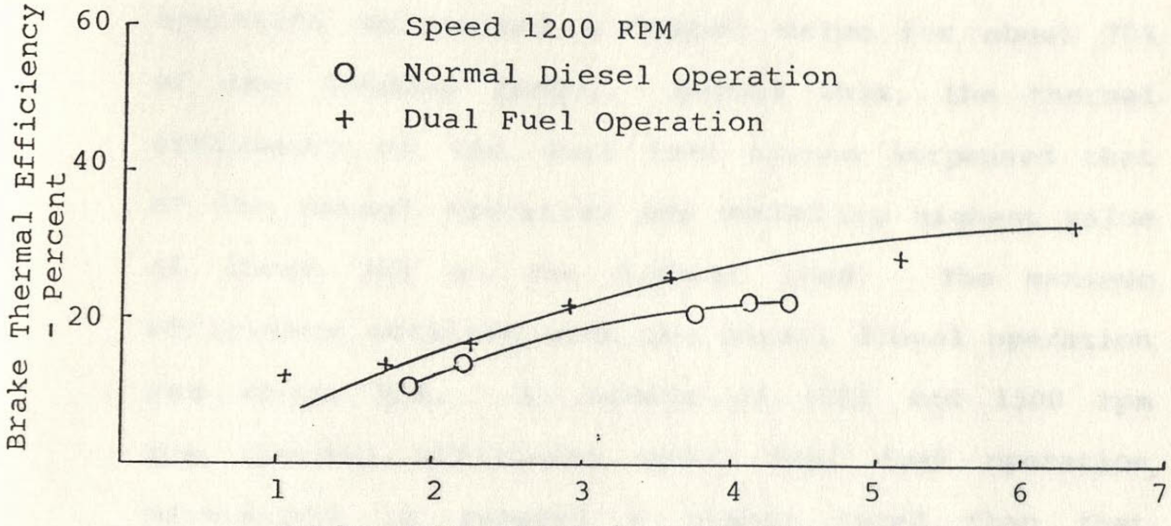


FIGURE 9.5(c) - EFFECT OF MEAN CYLINDER PRESSURE ON THERMAL EFFICIENCY

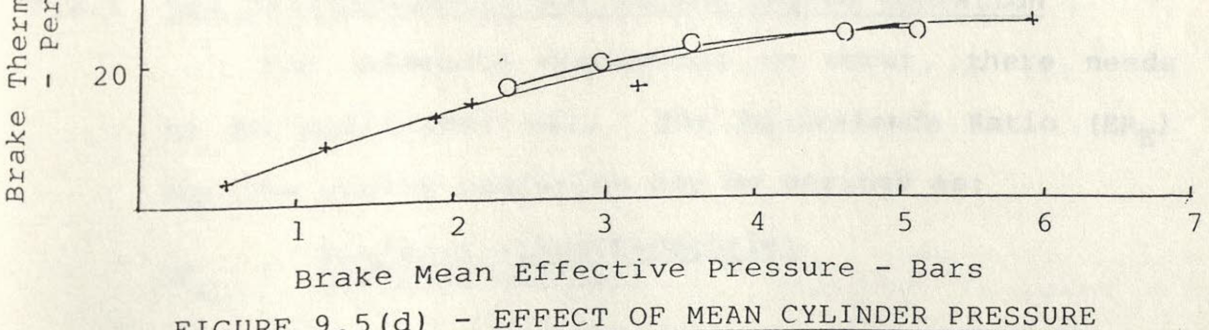


FIGURE 9.5(d) - EFFECT OF MEAN CYLINDER PRESSURE ON THERMAL EFFICIENCY

diesel operation was higher than the values obtained under the dual fuel test. At an increased speed of 1000 rpm, the efficiency value under normal operation maintained a higher value for about 70% of the loading range. Beyond this, the thermal efficiency of the dual fuel system surpassed that of the normal operation and reached its highest value of about 30% at the highest load. The maximum efficiency obtained with the normal diesel operation was about 25%. At speeds of 1200 and 1500 rpm the thermal efficiency under dual fuel operation, maintained in general a higher level than that of the normal diesel run. Low BMEP (Low Load) and associated cylinder temperature seems to be linked with much lower thermal efficiency with producer gas use than with the other mode of operation since, as the load and speed increases and the operating temperature increases, the thermal efficiency with producer gas reaches higher values than that of the normal operating condition.

9.2.5 The Utilization of Air During Engine Operation

For adequate combustion to occur, there needs to be sufficient air. The Equivalence Ratio (ER_E) for the engine operation may be defined as:

$$ER_E = \frac{\text{Air/Fuel (Stoichiometric)}}{\text{Air/Fuel (Actual)}}$$

where values below 1.0 indicate leaner their stoichiometric Air/Fuel ratio and values above 1.0 indicate a rich mixture. For the investigation, the stoichiometric air/fuel ratio for diesel fuel combustion is taken to be 14.88:1 and that for producer gas taken to be 1:1 (See Appendix 1(IV).

Figures 9.6(a) - 9.6(c) are plots of equivalence ratio against BMEP. For the first plot at a speed of 800 rpm, it was observed that the equivalence ratio for dual fuel* operation was greater than that for the diesel operation. For this particular speed there was a significant difference in levels between both modes of operation. Beyond about 80% of the dual fuel loading range, the air fuel mixture became rich and resulted in equivalence ratios above 1.0. This could be attributed to the fact that at the lower speeds, the proportion of total energy supplied by the gas was higher than the diesel fraction (See Figure 9.2). As the speed increased to 1000 rpm and the BMEP increased, the equivalence ratio for both modes of operation became much closer. In fact beyond 60% of the loading range the equivalence ratio of the dual fuel operation fell below that for the normal diesel operation.

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* Equivalence Ratio for dual fuel operation is based on the composite fuel mixture.

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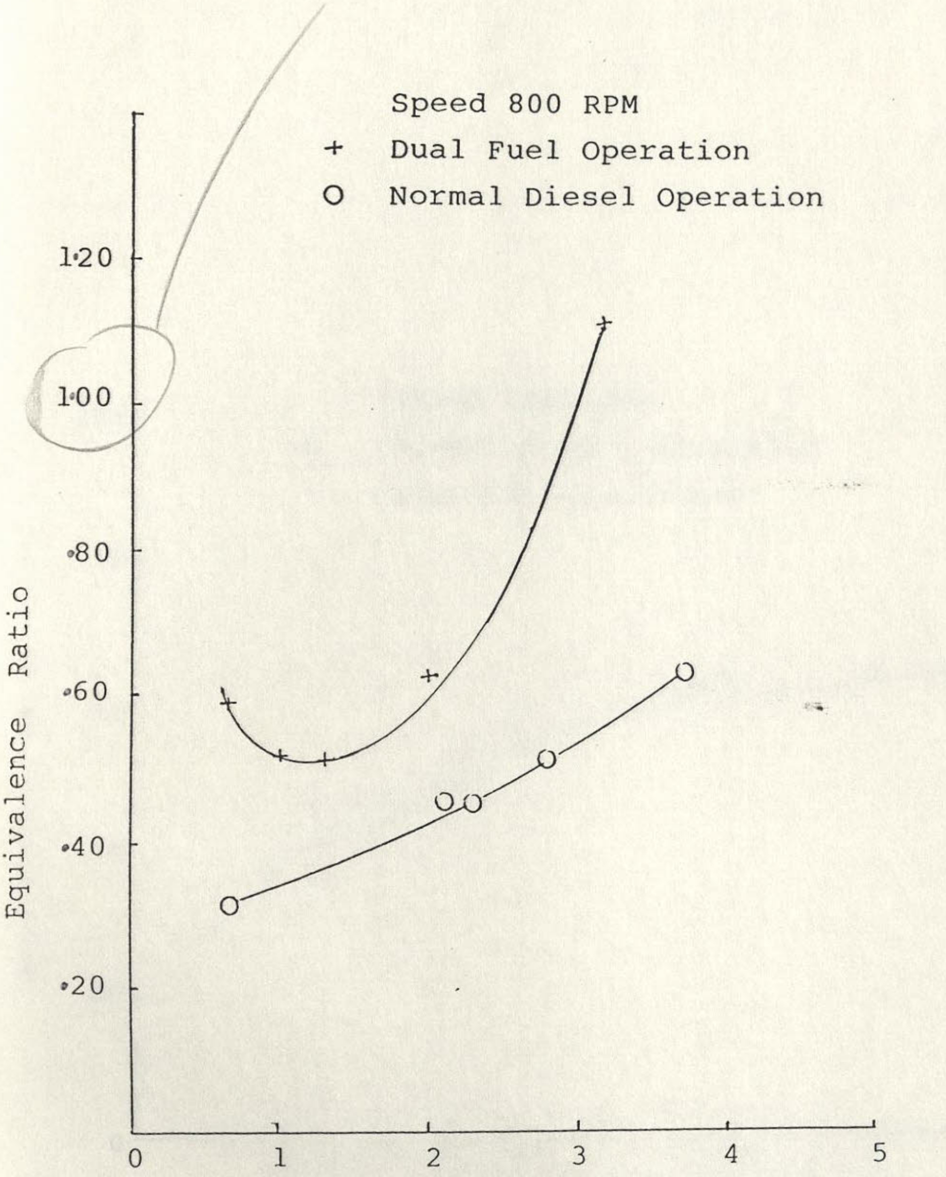

FIGURE 9.6(a) - EFFECT OF MEAN CYLINDER PRESSURE ON EQUIVALENCE RATIO

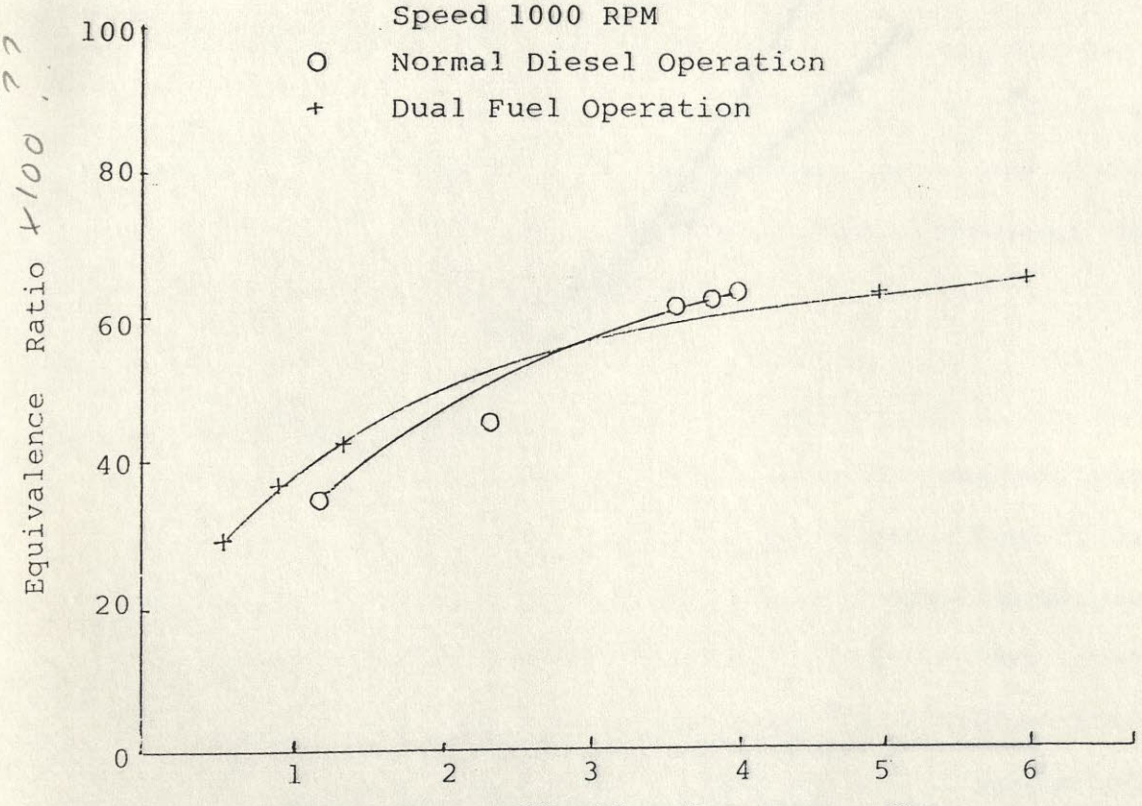

FIGURE 9.6(b) - EFFECT OF MEAN CYLINDER PRESSURE ON EQUIVALENCE RATIO

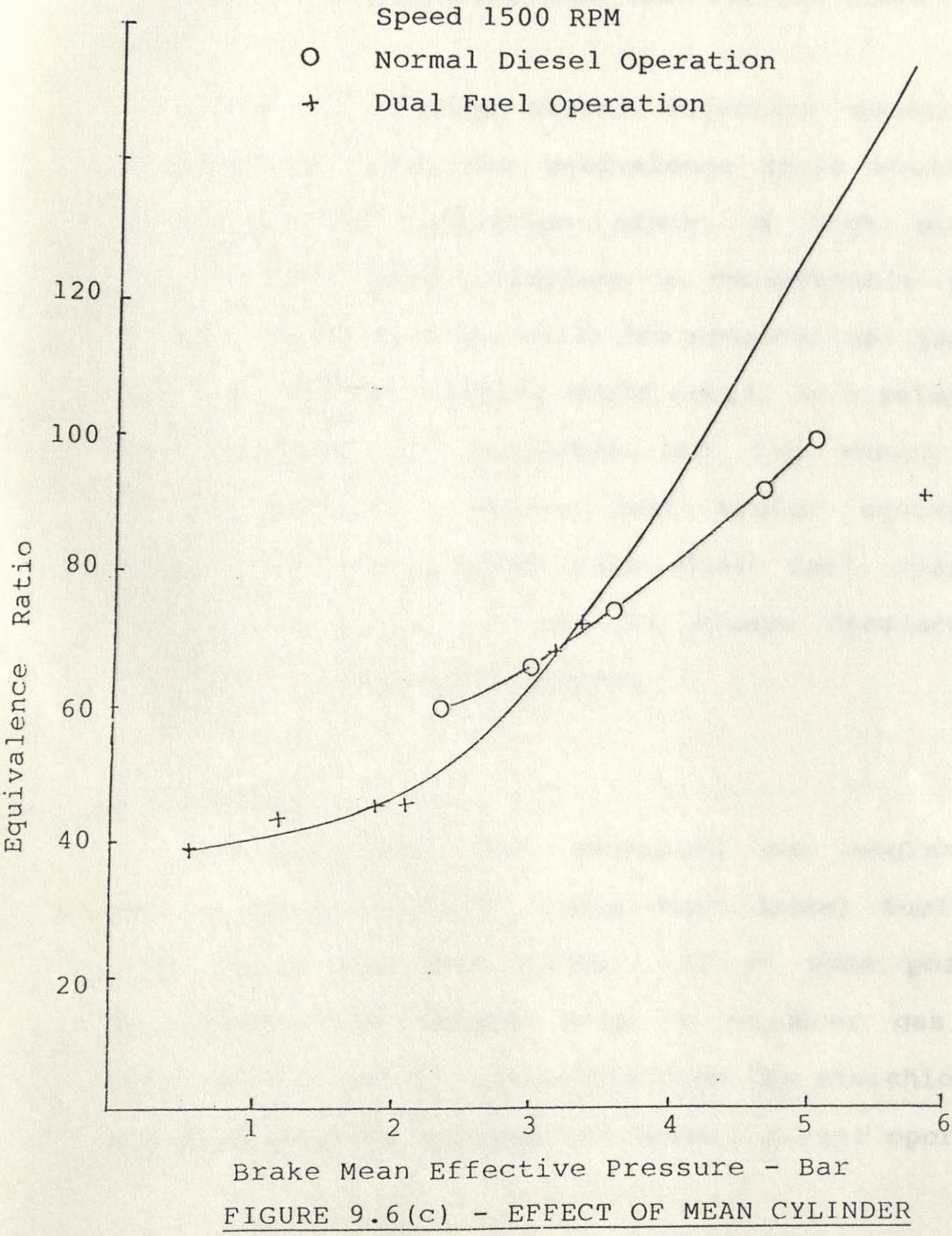

FIGURE 9.6(c) - EFFECT OF MEAN CYLINDER PRESSURE ON EQUIVALENCE RATIO

At 1500 rpm and at low load conditions, the equivalence ratio for the dual fuel operation was lower than that for the diesel operation. As the load increased to about 70% of the loading range, the equivalence ratio for the dual fuel operation attained higher values than that for the other operating mode.

With a varying diesel injection quantity it is expected that the equivalence ratio would show a significant variation since, a high producer gas content would displace a considerable amount of the air aspirated, while low producer gas quantity and high diesel quantity would result in a relatively large amount of available air for engine use. It is apparent however that higher equivalence ratios are associated with dual fuel operation since a quantity of air is always displaced by the gas allowed in the system.

9.3 DISCUSSION

The producer gas generated for engine use has a lower calorific value than diesel fuel i.e. 4.15 MJ/kg and 45.8 MJ/kg. If it were possible to operate the engine only on producer gas, the ratio of the energy obtainable from the stoichiometric air fuel mixture between the normal diesel operation and the producer gas operation would be about 1:0.65. This obviously would mean a significant difference in the level of power generation possible between the two modes of operation.

From the plots in Figure 9.2 it can be seen that as the engine speed increases, the contribution by the producer gas to the total energy supplied to the engine fuel decreased. The resulting increase in diesel fuel requires a corresponding increase in air quantity for combustion. When the producer gas was being supplied to the engine in the air intake, a quantity of air was displaced. Increasing gas supply further would result in a gradual reduction in the air being available for diesel combustion in the engine. With too high a producer gas content usually led to excessive knocking in the engine. This knocking may be due to the uncontrolled combustion occuring when at the instant of ignition, the cylinder is filled with a combustible mixture. It was also observed, as to be expected that under such conditions, there was a significant reduction in the power output combined with a significant increase in the specific energy consumption of the engine.

At all four operating speeds of 800, 1000, 1200 and 1500 rpm, the quantity of producer gas

quantity or proportion ??

supplied to the engine rose to a maximum value and then fell off. This was the situation as the load increased and the quantity of diesel fuel increased.

Pre-ignition is one of the undesirable phenomenon that can occur at high loads under duel fuel operation and can limit the output of the engine. Pre-ignition is taken to be the early ignition of the gas-air mixture by some means other than the piolot injection. This could have originated from:

(1) Ignition at a hot surface.
(2) Ignition by hot deposits.
(3) Ignition by compression.
(4) Ignition by the mixing of fresh charge with hot residual gases.

Hydrogen has a relatively low level of pre-ignition resistance when compared to other gaseous fuels. This makes producer gas quite vulnerable to this effect.

King (1948) (62) found that pre-ignition by the mixing of fresh charge with hot residual gases was highly probable in dual fuel engine. This was because active carbon species present in the residual gases are quite capable of promoting spontaneous ignition of fuel with a significant amount of hydrogen. This phenomenon could have partly contributed to the decrease in energy supply by the producer gas to the engine for increasing load.

Dual fueling operation as seen in Figure 9.1 seems to have the ability to generate a wide range of engine torque. It was able to exceed the maximum torque value for the normal diesel operation in most cases and likewise generate torque at levels below where stalling would probably occur under normal conditions. Its high overall fuel consumption however does not make it attractive and economically viable at these low load conditions. In situations where there is an abundance of the gaseous fuel, this mode of operation could be considered.

From the engine tests, it was found that the minimum quantity of diesel fuel injected at low loading condition was more than that required for stable operation. The fuel economy in the lower loading range however was not explored although it appeared that better fuel economy could have been obtained.

The main reason for not exploring the fuel economy at low load condition was because the fuel pump did not have provisions for variation by small steps for fuel feed. Dual fuel engines have been known to perform unsatisfactorily at low load (33) (40) (62) and hence during its operation the following may be adopted:

(1) Operate near full load condition.

(2) Operate at low load condition using normal diesel operation and at higher loads revert to dual fuel operation.

The quantity of diesel fuel consumed under normal diesel operation as was expected was much more than the quantity consumed under dual fuel operation at corresponding loads. The diesel fuel consumed under both modes of operation can be expressed as a ratio, the Diesel Fuel Consumption Ratio (DFCR). This ratio may be defined as:

$$\text{DFCR} = \frac{\text{Diesel fuel consumption rate under normal operating condition}}{\text{Diesel fuel consumption rate under dual fuel operation}}$$

DFCR of about 10:1 were possible within the investigation although the average value obtained was about 5:1. Higher DFCR were obtained at higher loading throughout the investigation and seems to suggest that under dual-fuel operation, the fuel economy at higher load is much better than that for low load conditions.

The problem associated with the dual fuel operation at low load conditions seems to be partly as a result of the increase in the ignition delay of the diesel fuel with the addition of the gaseous fuel (40) (42) (60). At very light loads, when a small amount of producer gas is added to the air intake, it may not necessarily burn despite the presence of excess air and the piolot injection but may pass out in the engine exhaust (42). This was because the small quantity of producer gas added even at the existing high temperatures reached near the peak of compression and the effective temperature after the diesel fuel had released its energy to the gas mixture, the gas concentration was still too low to propogate a flame. The fuel mixture could then be quenched and a quantity pass through unreacted to the exhaust. The high levels of CO in the exhaust at low load conditions, could have been as a result of this phenomenon See Figures 9.4(a) - 9.4 (d). The possible causes were discussed by Lyn (38) and Mehler (61) who associated the occurence to the chemical inhibition of the gaseous mixture. The extent of this ignition delay can in fact necessitate an advance in the diesel injection timing settings.

Producer gas operation when compared to the normal diesel operation throughout the investigation, was seen to have lower levels of formaldehyde. The formation of formaldehyde is as a result of the incomplete combustion of the diesel fuel and its presence in the exhaust indicates that the intermediate reactions in the combustion chamber may have been chilled (59) (64). With dual fuel operation, cooling of the reaction chamber can occur. This could have been the case, since along with the relatively low heating value of the gas, inert and non combustible gas fractions are also present in the gas mixture. This can result in relatively high formaldehyde concentration and could have been the reason for the difference in levels between both operations.

The oxides of nitrogen formation could have been as a result of the high temperature and pressure obtained during combustion and the reaction between the oxygen and nitrogen of the air charge in the cylinder (58) (59). The lower levels of oxides of nitrogen present in dual fueling exhaust emission when compared to normal operation could partly be as a result of the reduced quantity of excess air available for the combustion process and could also be an indication of the lower cylinder pressures and temperatures that are present under this mode of operation.

The thermal efficiencies obtained throughout the investigation under dual fuel operation appears to have higher levels than those of the normal diesel test above speeds of 1000 rpm (See Figures 9.5(a) - 9.5(d)).

Ver
mrg

The fact that under dual fuel operation the air-gas mixture is homogenous and that for greater part load at higher speeds, the air gas mixture will be above the inflamability limit and flame propagation is assured throughout the combustion zone, the rate of combustion would be more rapid i.e. similar to that occuring in a S.I. engine and hence, the combustion process would be closer to completion in the cycle than with the other mode of operation. Maximum utilization of the air supply would be ensured and higher mean effective pressures than that occuring in the normal diesel operation becomes possible.

For normal diesel operation, the combustion process is usually more gradual and proceeds while the fuel is still being injected into the combustion chamber. This could then mean that the combustion process could be extended into the expansion process thereby lowering the potential available power and quite possibly allowing exhaust emission to leave the engine cylinder at relatively higher temperatures.

9.4 CONCLUSION

From the foregoing investigation using producer gas to dual fuel a C.I. engine several conclusions were drawn. They may be summarised as follows:-

(i) Producer gas generated from charcoal may be used successfully to fuel an I.C. engine.

(ii) The engine system operated throughout its loading range when dual fueled with producer gas.

(iii) The proportion by which the diesel fuel was replaced by the producer gas depended on the engine load and speed.

(iv) Producer gas may constitute over 70% of the total energy input to the engine.

(v) Approaching intermediate and full-load conditions the utilization of the producer gas supplied in the fuel mixture for dual fuel operation gradually improved.

(vi) When operating under dual fuel operation, higher levels of CO existed in the exhaust throughout the low to intermediate loading range than that obtained under normal diesel operation. Approaching full load conditions, the CO concentration became comparable with that of normal diesel operation. The formaldehyde concentration was higher than that occuring in the normal diesel operation while the oxide of nitrogen was less.

(vii) The maximum limiting torque under dual fuel operation was greater than that which was obtained under normal diesel operation.

(viii) Diesel fuel replacement of over 55% of the total energy supplied to a C.I. engine will make the cost of shaft power very attractive for low to medium cost gasifier systems.

CHAPTER 10

ECONOMICS OF SHAFT POWER

10.0 SUMMARY

The life cycle method of costing is used to evaluate the cost of shaft power from a diesel engine using diesel fuel and the engine dual fueled with producer gas using charcoal as the primary fuel.

The basis of comparison for the costing was to consider the economics at full load for both modes of operation and a period of 2000 hours/year. The initial capital cost proved to be the most significant parameter in determining the cost of shaft power.

10.1 INTRODUCTION

10.1.1 Method of Costing

The life cycle method which is used in the present analysis, considers an economical evaluation of the system under various operating conditions ranging from aquisition right through to use. This includes operation and maintenance of the system to its ultimate retirement or disposal (62).

10.1.2 Gasifier System Life Cycle Cost

(i) Initial Cost (Cost of Ownership)

Some of the initial costs relating to a gasifier system are:-

(a) Gas generator - including delivery, installation and special site infrastructure.

(b) Blower, pipe, valves,

Gas cleaner,

Gas cooler,

Controls and distribution system, insulation

(c) Value of space occupied by system

(d) Testing and commissioning

(e) Labour.

(ii) Future Cost

The life cycle cost occuring during the life of the system are called future cost and can include:

(a) Maintenance - personnel, material.

(b) Repairs - personnel, material.

(c) Power cost for operating blower, supplying feedstock, controls etc.

(d) Insurance.

(e) Taxes.

Discounting has not been considered in the analysis essentially because the costing was done with a view to provide possible estimate for investment appraisal. Discounting however can be considered in other instances.

10.1.3 Sensitivity Analysis

A sensitivity analysis was done on the system by considering a range of values for the diesel fuel cost, the charcoal cost and the quantity of diesel fuel replaced by the producer gas. This was done by considering values obtained from the life cycle costing method.

The actual costing for the analysis was based in some instances on information obtained from local surveys done with people from various territories in the region and current costing from equipment catalogue.

10.1.4 Annualized System Cost

The total cost C_y of the systems operation on an annual basis, is the total of the amortized cost and distributed cost expresed on a present worth basis (63) See Eq. 10.1.

$$\begin{aligned} C_y = {} & C_{G,tot} \; [CRF\,(i^1,t)] \text{ initial investment} \\ & + C_{G,sal} \; [RWF(i^1,t)][CRF(i^1,t)] \text{ salvage value} \\ & + \sum_{k=1}^{t} R_K \; [PWF(i^1,t_k)][CRF(i^1,t)] \text{ replacements} \\ & + C_e \frac{[CRF(i^1,t)]}{[CRF(i^{11},t)]} \text{ energy cost} \\ & + T_{prop} \; C_{G,ass} \text{ property tax} \end{aligned}$$

$+ T_{inc} - T_{prop} C_{G,ass}$ Property tax, tax deduction

$- T_{inc} i_m [{}_K \frac{P_K}{(1+i^1)^K}] [CRF(i^1, t)]$ interest tax deduction

$+ M$ Maintenance

$+ I$ Insurance charges

$- T_{inc} [CRF(i^1, t)] {}_K \frac{D_K}{(i+i^1)^K}$ - depreciation tax deduction

$+ C_L$ Lubrication cost

$+ C_{FS}$ Feed stock cost

$+ C_{FF}$ Fossil fuel cost ...(10.1)

there

$C_{G,tot}$ = Total initial gasifier system investment including sales tax

$C_{G,sal}$ = gas generator salvage value at end of period

$C_{G,ass}$ = assessed value of gasifier system

C_e = energy cost to operate gasifier system in year 1

$i^1 = \frac{i-j}{1+j}$ effective discount rate

$i^{11} = \frac{i-j_e}{i-j_e}$ effective discount rate for energy

i = discount rate

j = general inflation rate

M = maintenance cost \$/year

i_m = market mortgage rate

j_e = energy inflation rate

K = years at which replacement or repairs are made

I = insurance charges

R_K = replacement or repair cost in year K

P_K = outstanding principal (unpaid balance) of $C_{G\ tot}$ in year K

t = life cycle time or period of analysis

T_{prop} = property tax-rate

T_{inc} = income tax rate (marginal)

C_L = lubricant cost \$/year

C_{FS} = feed stock cost \$/year

C_{FF} = fossil fuel cost \$/year

and

$$P_K = C_{G,tot}\left[(1+i_m)^{K-1} + \frac{(1+i_m)^{K-1}-1}{(1+i_m)^{-t}-1}\right] \qquad \ldots(10.2)$$

and

$$i_m \sum_K \frac{P_K}{(1+i^1)^K} = C_{G,tot}\left[\frac{CRF(i_m,t)}{CRF(i^1,t)} \frac{1}{1+i_m} \cdot \frac{1}{[CRF(i^1-i_m,t)]} \cdot [1_m-[CRF(i_m,t)]]\right] \qquad \ldots(10.3)$$

The main parameters considered in the analysis are listed in Table 10-1 and all cost considered in the study are in U.S. Dollars.

10.2 PARAMETERS CONSIDERED AND ASSUMPTIONS MADE FOR GASIFIER SYSTEM AND ENGINE COSTING

With regards to gasification plants in the region, commercial experience is limited and hence an actual manufacturing cost could not be readily placed on similar systems manufactured for similar applications. Experience in Brazil and the Philippines, is that systems can be made commercially available for as little as 50-$100/KW (10). These systems however were not considered suitable since it was the general feeling that they were not quite capable of handling the purification of the gas produced. Hence a cost for the cleaning system has to be added. To cover a representative value of possible system cost, a range of 300-$2000 was considered. A cost of $2000 could represent a system containing semi-automatic capabilities while a system for $300, could represent a system with relatively small fuel storage capabilities, permanently fixed and fully manual. This range would enable the economically viable system cost to be determined under the different assumed conditions.

ASSUMPTIONS USED IN ECONOMIC ANALYSIS

TABLE 10-1

Variables	Base Values	Range of Values
Power output	4.5 KW	-
Discount Rate	10%	-
System life	6 years	-
Annual operating hours	2000	-
Diesel cost	$1.00/gal	80¢-$1.20
Charcoal cost	$40.00/ton	0-$80.00/ton
Diesel System		
Diesel engine & alternator cost	$200.00/KW	-
Annual maintenance cost	5% capital cost	-
Lubricant cost	5% Diesel fuel cost	-
Diesel consumption	0.414 gal/hr	-
Gasifier System		
Cost of gasifier	$700	$300, $700, $2000
Annual maintenance cost	10% total capital cost	-
Lubricant cost	2 x cost for diesel system	-
Diesel substitution	52%	20-80%
Diesel consumption	0.20 gal/hr	-
Charcoal consumption at 90% generator efficiency	1.5 kg/hr	-

All cost in US$

The system was assumed to run at full power output for 2000 hours per year with a replacement after 6 years. This was equivalent to eight hours operation per week day and a total working life of 12000 hours. This working period is one that would be expected from a system supplying motive power or for electrical power generation in a small processing industry.

10.2.1 Diesel Fuel Consumption and Cost

For the normal diesel fuel operation, the quantity of fuel demanded by the engine was 0.414 gal/hr at 4.5 KW. This was from the experimental data at 1500 RPM. With the producer gas operation, the quantity of diesel fuel demanded by the engine was 0.20 gal/hr. This represented a substitution of about 52% by the gas. This quantity was used as the base value for the analysis. To see the effect of the degree of substitution by the producer gas on the Gasifier Economics, a range of 20-80% was considered.

The cost of diesel fuel used in the investigation was assumed to be $1.00/gallon. This cost was determined after evaluating the relative cost of diesel fuel in some of the territories in the region. It should be noted that for locations where there are major transportation and distribution problems the fuel prices can be substantially higher. To see the effect of varying prices on the gasifier's economics, a range of cost between 0.80 - $1.20/gallon was considered.

10.2.2 Maintenance

Annual maintenance cost of the dual fuel system was taken to be 10% of the capital cost of the gasifier system and the diesel engine together. For the normal diesel operation the cost was taken to be 5% of the engine capital cost. The value of 5% is a typical value used in maintenance allocation for engine operation. However for the dual fuel operation, filter changes and general repair to the gasifier quite obviously required higher maintenance cost and hence the 10% value was chosen.

10.2.3 Lubrication

For the straight diesel operation this was taken to be 5% of the cost of the diesel fuel. Double this amount was assumed for the dual fuel system. This was to allow for more frequent engine oil changes.

10.2.4 Charcoal Cost

A charcoal cost of $40.00/ton was found to be a representative value for the primary fuel in the Caribbean. This figure was chosen after considering its relative cost in the territories where large quantities are normally produced at very low cost. However it should be noted that the major contributor to its cost can be the transportation and distribution input. If these factors were obviated the fuel cost would have been very low. Hence the charcoal considered for the analysis was assumed to be available firstly at no cost and then at a high rate of $80/ton.

10.2.5 Discount Rate

A discount rate of 10% was used in the analysis. This was not a subsidised rate. This took into consideration the rate of inflation and the general rate used for loan repayment (See Section 10.1.2). The general expression i.e. equation 10.1 that was introduced to evaluate the total cost of the system's operation on an annual basis included several variables that were not directly related to the present investigation. These parameters were then neglected in the analysis. For other situations however where these variables are integrally involved in the system's operational cost, their inclusion can significantly affect the overall cost.

By using the related parameters and under the assumptions made, the annual cost of the system operating under both conditions were determined.

10.3 RESULTS

Table 10-2 gives the result of the analysis using the base values given in Table 10-1, the assumptions made and the general equation 10.1 for annualizing the system's cost.

The results show that Case 1 which is the low cost gasifier, provided shaft power at a cheaper rate than that of the conventional diesel system. The power cost worked out to be 11.04¢/KW-h which represents as saving of 11% of the diesel power of 12.4¢/KW-h. Considering the pay back period, the low cost system could achieve this in about 5 months.

Power from the medium and high cost systems in contrast was more expensive than that for the conventional diesel system. The medium cost system however was only marginally more expensive. The cost for the power generation were 12.5¢/KW-h and 17.3¢/KW-h. These were 0.8% and 39% more than the corresponding diesel cost.

The main reason for the higher operational cost for the medium and high cost system were as a result of the high initial capital cost and the higher levels of maintenance cost required. The increase in operating cost for the higher cost system was $436. This was much greater than the savings incured in the low cost system.

TABLE 10-2

ANNUAL CAPITAL CHARGE FOR 4.5 KW SHAFT POWER PRODUCTION

Cost Component	Diesel System $	Gasifier System Case 1 $	Case 2 $	Case 3 $
Engine	207	207	207	207
Gasifier	-	69	161	460
Maintenance	45	120	160	290
Lubricants	39	78	78	78
Diesel fuel cost	828	400	400	400
Charcoal	-	120	120	120
Total annual cost	1119	994	1126	1555
Overall power cost cents/KWh	12.4	11.04	12.5	17.3
Savings compared to diesel system	-	11.0%	-0.8%	-39%

Cost in US $

Notes:

(1) Costs are estimated based on the assumptions listed in Table 1.

(2) Annual capital charges are calculated using equation (1)

Case 1 - Low Cost Gasifier $300.00

Case 2 - Medium Cost Gasifier $700.00

Case 3 - High Cost Gasifier $2,000.00

From the assumptions made then, it would appear that for the system to save money the capital cost of the gasifier system has to be below $650.00. An initial conclusion drawn here is that gasifier systems can be profitable if low cost systems are employed and their operating periods are maximized.

10.3.1 Sensitivity Analysis

Using the three base line cases a series of calculation were performed in which each of the main assumptions were varied in turn. The result is shown in Table 10-3. For the variables considered the range of values tested are shown together with the corresponding power cost under each set of assumptions. These are compared with the result previously calculated i.e. Table 10-2.

The analysis done reveals clearly the significance of the initial capital cost on the systems's operation. From Table 10-3 we can see clearly that the cost of power from a high cost system is more expensive than that of the diesel system under all the variations tested. The medium cost system in some cases were more expensive than the diesel system while the low cost system for most of the conditions considered was cheaper.

TABLE 10-3

RESULT OF SENSITIVITY ANLAYSIS FOR SHAFT POWER SYSTEM

		Gasifier System Overall Post Cost Cents/KWh			
Variable	Value of Variable	Diesel System	Case A	Case B	Case C
(1) Diesel cost ($/gallon)	$0.80/gal	10.5	10.15	11.6	16.3
	$1.00/gal (B)	12.4	11.04	12.5	17.3
	$1.20/gal	14.2	11.9	13.4	18.1
(2) Charcoal cost ($/ton)	$0/ton	12.4	9.7	11.1	15.9
	$40/ton (B)	12.4	11.04	12.5	17.3
	$80/ton	12.4	12.3	13.7	18.5
(3) Diesel substitution quantity (percentage %)	20%	12.4	13.9	15.4	20.2
	52% (B)	12.4	11.04	12.5	17.3
	80%	12.4	8.3	9.8	14.6

Notes:

B - base values

The effect of diesel fuel price can be considerable on the savings that would be desired from using a gasifier system. The economic attractiveness of the gasifier system at varying diesel prices are shown in Figure 10-1. The plot shows that a low cost gasifier system would be cheaper than the diesel system at any diesel price above 75¢/gal. A medium cost gasifier system would be cheaper above $1.00/gal whilst the diesel cost for the high cost gasifier system would have to be above $2.00/gal for the system to be economical. These figures assume a charcoal cost of $40/ton. Figure 10-2 shows that even if the charcoal was obtained free of cost the high cost gasifier system still would not be economical. The medium cost system would be economical if the charcoal price was anywhere below $35/ton and for the low cost system anywhere below $80/ton. This was assuming a diesel cost of $1.00/gal.

The amount by which the diesel fuel is replaced by the producer gas has a marked effect on the system economics. In applications where frequent load changes occur, the economics of the system can be severely affected. Systems running at full and continuous load are ideally desired for this operation since under these conditions, the

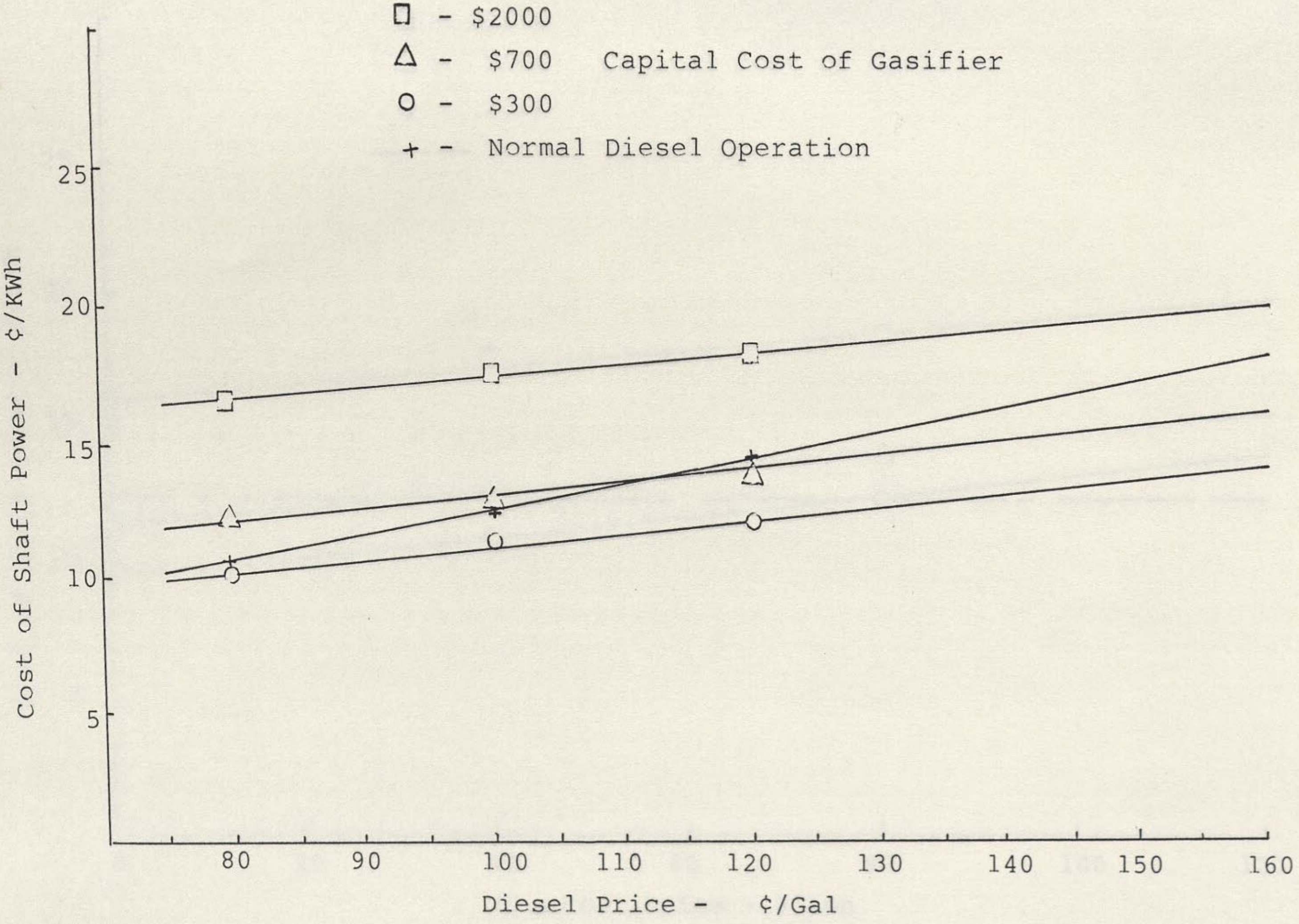

FIGURE 10.1 - EFFECT OF DIESEL PRICE ON GASIFIER ECONOMICS

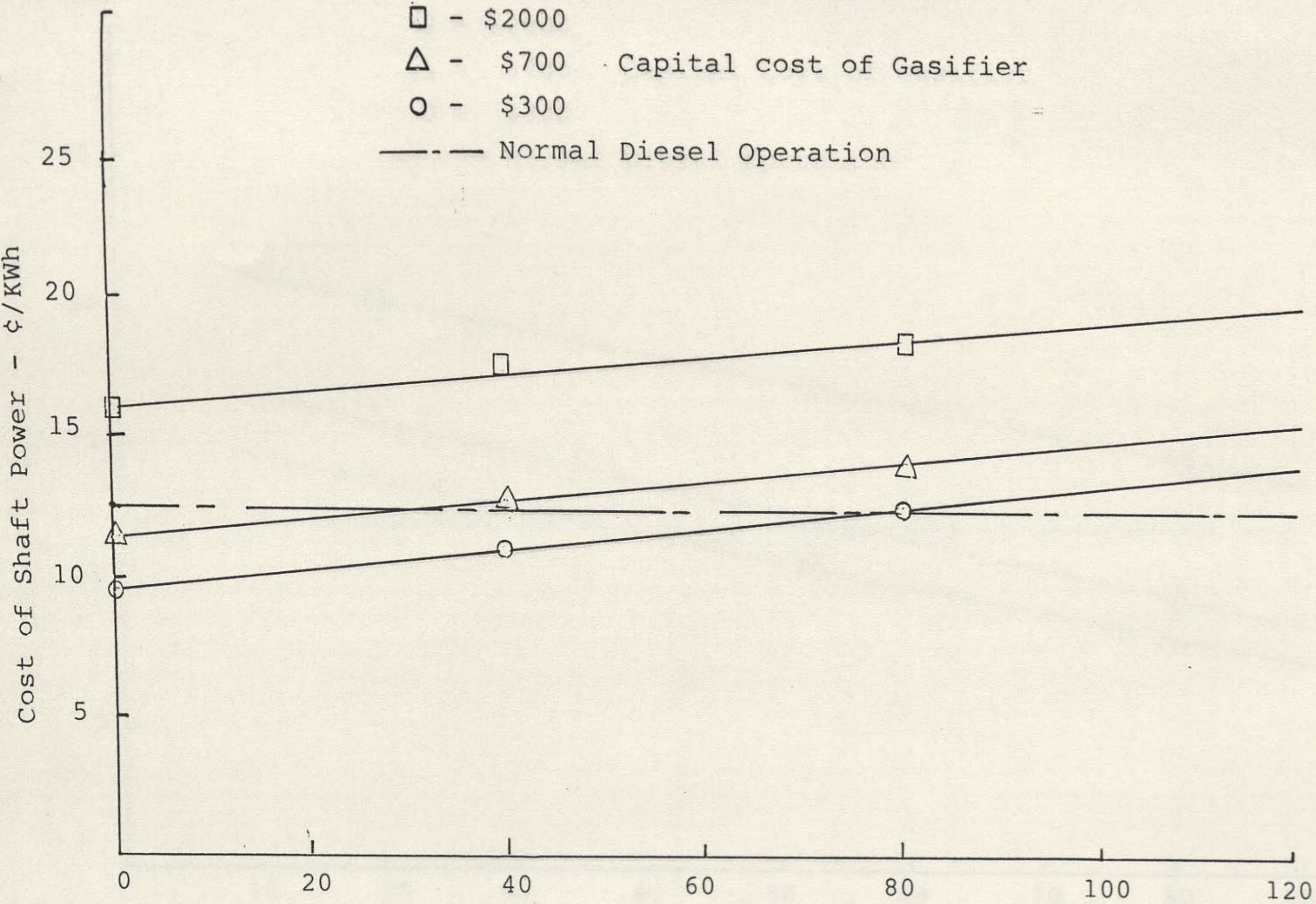

FIGURE 10.2 - EFFECT OF CHARCOAL PRICE ON GASIFIER ECONOMICS

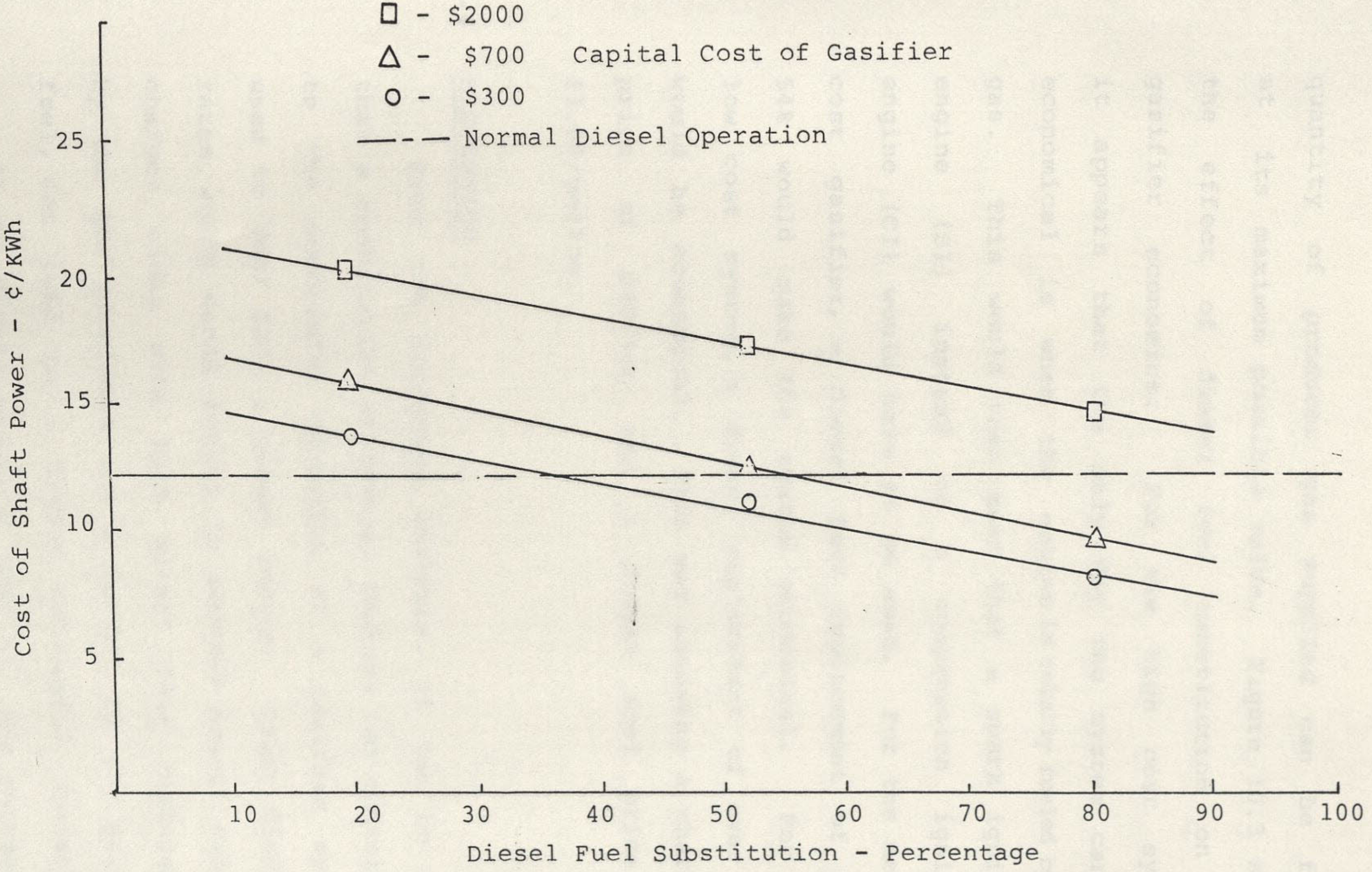

FIGURE 10.3 - EFFECT OF DIESEL FUEL SUBSTITUTION GASIFIER ECONOMICS

quantity of producer gas supplied can be fixed at its maximum possible value. Figure 10.3 shows the effect of diesel fuel substitution on the gasifier economics. For the high cost system, it appears that the only way the system can be economical is when the engine is totally fueled by the gas. This would then mean that a spark ignition engine (SI) instead of a compression ignition engine (CI) would have to be used. For the medium cost gasifier, a diesel fuel replacement of over 54% would make the system economical. For the low cost system, a diesel replacement of over 36% would be economical. This was assuming a charcoal price of $40/ton and a diesel fuel price of $1.00/gallon.

10.4 DISCUSSION

From the foregoing analysis, it can be seen that a combination of several factors can contribute to the successful operation of a gasifier system used to dual fuel a diesel engine. Lower discount rates, which would result in reduced annual capital charges, along with high diesel fuel replacement by the gas generated and a low cost of the primary fuel, can lead to a highly successful operation.

It is highly unlikely that all the parameters discussed earlier would reach the desired acceptable level that would make the system operate at a minimum cost. For example, for the cost of the primary fuel to be minimal, it would necessitate the gasifier system being located in close proximity to the charcoal production site. It is then quite possible that two operating systems depending on their respective proximity to the fuel source, could operate under favourable or unfavourable economic condition.

Since the diesel fuel is one of the major cost contributor, a significant reduction in the quantity used is most desirable. From the 20-80% replacement range considered, the lower limit was totally undesirable. With a 20% replacement, it meant that 80% of the fuel energy was supplied by the diesel fuel. This would definately make the operation uneconomical. Replacement values above 55% are desirable. This difference in fuel cost can be seen in Figure 10.3.

The economics of dual fuel operation with producer gas can be viewed from another perspective. In situations where fossil fuel has to be imported, usually a substantial amount of foreign exchange has to be used for its purchase. In developing countries where balance of payment problems usually exists, high operational cost that utilizes local currency can be tolerated. This would then mean that the amount of foreign exchange originally allocated to purchasing fossil fuel, could be reduced and channeled into other areas. Another fact that could largely affect the operational cost is the local availability of low cost construction and gas purification materials. For fixed stationary operations, construction could be done partially with refractory cement and bricks. This would be utilizing local raw material and would result in reduced dependence on imported materials.

Recirculation of exhaust emission through the gasifier may be another means of improving the overall cost of operation. With this process, it may be possible to supplement the charcoal fuel with the exhaust emission. This could then mean that less biomass fuel would be required and could result in a reduction in fuel consumption rate. With a batch type system, the frequency of reloading could be reduced. During recirculation, in addition to the possiblity of supplementing the charcoal fuel, the reaction temperatures can be maintained at levels lower than when air was used as the gasifying agent (See Section 7.4) which would result in lower frequency of reactor burnout and hence a greater useful life and a lower repair cost.

In concluding, it can be said that with favourable operating conditions, it is possible to operate a diesel engine dual fueled with producer gas at a lower cost per unit kilowatt-hour than for the normal diesel operation. The major cost contributors for the dual fuel operation were found to be the capital cost of the gasifier and the overall diesel fuel cost. A diesel fuel replacement above 55% by producer gas will definitely make the operating condition more attractive under most conditions using a low to medium cost gasifier system.

CHAPTER 11

CONCLUSIONS AND LINE FOR FUTURE STUDY

11.0 CONCLUSION

A downdraft gasifier capable of producing about 0.55 Nm³/min of producer gas with a heating value of about 170 MJ/hr from charcoal has been designed and fabricated. The producer gas generated can be used for process heat generation or for fueling I.C. engine.

11.1 Process Heat Generation

For process heat generation the hot raw gas can be burned directly and used for steam generation, kiln firing or providing heat for drying. When used directly, the sensible energy generated adds significantly to the energy generation capability of the gas. In evaluating the gasifier's performance, the following are the main findings:-

(i) A gas with a total heating value of about 5.2 MJ/Nm³ is possible when air is used as the gasifying medium.

(ii) A gas with comparable heating value can be obtained at lower reaction temperatures when a mixture of air and steam or air, steam and CO_2 are used as the gasifying medium.

(iii) A gas with a CO concentration of 32%

and a H_2 concentration of 8% is possible when air is used as the gasifying medium.

(iv) The cold gas efficiency (i.e. efficiency based on calorific value of gas) of the generator when using a mixture of air, steam and CO_2 is higher than that obtained when using air and a mixture of air and steam as the gasifying medium. Their values were about 85, 76 and 75% respectively. The higher levels of efficiencies obtained when using the air, steam and CO_2 mixture may be attributed to the additional carbon supplied to the system in the CO_2.

(v) Slagging of ash is reduced when a mixture of air and steam and a mixture of air, steam and CO_2 are used as the gasifying medium.

(vi) It is possible to recirculate I.C. engine exhaust gas up to a total quantity of about 10% in the gas supplied to the gasifier and obtain a gas with a heating value comparable to that obtained by direct generation.

(vii) Fuel savings of up to about 4.5% can be obtained in a gasifier when recirculation is utilized.

11.2 I.C. Engine Operation

From the investigation using producer gas to dual fuel a C.I., engine several conclusions were drawn:-

(i) Producer gas generated from charcoal may be used successfully to fuel an I.C. engine.

(ii) The engine system operated throughout its loading range when dual fueled with producer gas.

(iii) The proportion by which the diesel fuel was replaced by the producer gas depended on the engine load and speed.

(iv) Producer gas may constitute over 70% of the total energy input to the engine.

(v) Approaching intermediate and full load conditions, the utilization of the producer gas supplied in the fuel mixture for dual fuel operation gradually improved.

(vi) When operating under dual fuel operation, higher levels of CO existed in the exhaust throughout the low to intermediate loading range than that obtained under normal diesel operation. Approaching full load conditions, the CO concentration became comparable with that of normal diesel operation. The formaldehyde concentration was higher than that occuring in the normal diesel operation while the oxide of nitrogen was less.

(vii) The maximum limiting torque under dual fuel operation, was greater than that which was obtained under normal diesel operation.

(viii) Diesel fuel replacement of over 55% of the total energy supplied to a C.I. engine will make the cost of shaft power very attractive for low to medium cost gasifier systems.

11.3 POSSIBLE LINES OF FUTURE WORK

From the foregoing investigation, it is seen that there are several areas that could be explored for future development. Chapters 2 to 7 described the gasifiers characteristic using charcoal as the feedstock. It may be possible at a later stage to explore the following areas:-

(1) The utilization of other feedstocks like peat, sawdust, rice husk and coir.

(2) The development of suitable equipment for densifying the feedstock with low bulk density.

(3) The adaptation of the gasifier system to accept products of combustion from I.C. engine and other systems for useful combustible gas regeneration.

With regards to Chapters 8 to 10 of the investigation which dealt with the dual fueling of the C.I. engine with producer gas generated, the following areas could be explored and developed:-

(1) Means of improving engine economy and reducing pollutant levels under dual fuel condition with producer gas under light load operation.

(2) The potential capacity to generate greater loading than that possible under normal diesel operation.

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APPENDIX 1

(i) To convert Gas Volume to Standard Volumes at 70°F and 760 mm (1 Atm).

?

$$V_o = V \cdot \frac{P}{760} \cdot \frac{273}{273 + t}$$

273 K = 0°C = 32

P = Absolute pressure of gas (mmHg)

t = Temperature of gas (°C)

V = Volume of gas (m³)

V_o = Standard Volume (Nm³)

(ii) To calculate Rate of Charcoal Consumption from the gas quality obtained (57).

$$\frac{-dm}{dt} = \frac{12Po_2 \text{ X } F}{22400 \text{ x } 100} \text{ x } \left[\frac{CO + CO_2}{CO_2 + O_2 + \frac{1}{2}CO} \right]$$

F = rate of flow of gas in cc per minute (at standard temperature & pressure)

Po_2 = percentage oxygen in gasifying agent

CO = percentage CO in gas mixture

CO_2 = percentage CO_2 in gas mixture

O_2 = percentage O_2 in gas mixture

$\frac{dm}{dt}$ = rate of charcoal consumption in gram/minute

(iii) Stoichiometric air/fuel ratio for producer gas and diesel fuel consumption.

Producer gas composition by volume.

Constituents		% Range
Carbon Monoxide	- (CO)	26.54 - 31.4
Carbon Dioxide	- (CO_2)	1.27 - 2.08
Hydrogen	- (H_2)	3.9 - 7.63
Methane	- (CH_4)	0.03 - 0.06
Oxygen	- (O_2)	1.9 - 2.85
Nitrogen	- (N_2)	58.08 - 64.24

Traces of other gases were neglected.

For representative percentage constituent of producer gas manufactured we take average values.

Average Composition	% Volume	Volume Fraction
CO	29.0	0.290
CO_2	1.675	0.01675
H_2	5.765	0.05765
CH_4	0.045	0.00045
O_2	2.370	0.0237
N_2	61.135	0.6113
	100.00%	1.000

Step 1

To use the average volumetric analysis data found in the investigation and convert to a weight basis.

Component	M_i	V_i	V_iM_i	$M_i = \frac{V_iM_i}{\sum V_iM_i}$
CO	28	0.29	8.12	0.3023
CO_2	44	0.01675	0.732	0.0274
H_2	2	0.05765	0.1153	0.0043
CH_4	16	0.00045	0.0072	0.000268
O_2	32	0.0237	0.7584	0.0282
N_2	28	0.6113	17.12	0.637
		1.000	26.86	1.00

$$\frac{M_i}{M} = \frac{N_iM_i}{\sum N_iM_i} = \frac{V_iM_i}{\sum V_iM_i}$$

Step 2

Oxygen required to burn completely carbon monoxide (CO), hydrogen (H_2) and methane (CH_4).

Chemical equation for reaction.

(i) $2CO + O_2 \rightarrow 2CO_2$

(ii) $2H_2 + O_2 \rightarrow 2H_2O$

(iii) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Step 3

Using molecular weights for chemical equations.

Compounds	Molecular Weight Ratios	kg of oxygen required column 1 x 2
CO - 0.3023	32/56	0.1727
H_2 - 0.0043	32/4	0.0344
CH_4 - 0.000268	64/16	0.00107
Total		0.208

Step 4

Calculating mass of air required.

$$\text{Mass of air required} = \frac{0.208}{0.23} = 0.91$$

For complete combustion of 1kg of gas produced, 0.91 kg of air is required.

For the purpose of this investigation, it will be assumed that the stoichiometric air-fuel ratio is 1:1 by mass.

(iv) Equivalence Ratio (ER_E)

The equivalence ratio was computed by finding the total quantity of air required for the total combustion of diesel fuel $C_{16}H_{34}$ and producer gas. The sum of the air required for total combustion was divided by the actual weight of air supplied for combustion by the engine.

$$\text{Equivalence Ratio} = \frac{\text{Air required (Producer gas \& disel)}}{\text{Air supplied (from investigation)}}$$

Combustion equation for diesel $C_{16}H_{34}$.

$$C_{16}H_{34} + 24.5O_2 + 24.5 \times 3.76N_2 \rightarrow 16CO_2 + 17H_2O + 3.76 \times 24.5N_2$$

Stoichiometric air/fuel ratio by mass is:

$$\frac{3356.36}{226} = 14.8$$

For complete combustion of diesel, 1kg fuel requires 14.8kg air.

(v) To Calculate Calorific Value of Gas

Analysis by Volume		Effective Heating Value Kcal/Nm³	
CO	0.29	0.29 x 3020	= 875.8
CO_2	0.0167	–	
H_2	0.057	0.057 x 2570	= 146.49
CH_4	0.00045	0.00045 x 8550 =	3.84
O_2	0.0237	–	
N_2	0.6113	–	
Total			1026.13 Kcal/Nm³

Effective heating value of gas mixture

is 1026.13 Kcal/Nm³

or 4.29 MJ/Nm³

Range of heating value of gas:

3.78 - 4.81 MJ/Nm³