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TWO STAGED COMBUSTION OF HYDROGEN-GASOLINE FUELS IN DIVIDED CHAMBER COMBUSTOR

الاحتراق ثنائي المرحلة لوقودي الهيدروجين والجازولين في غرفة احتراق مقسمة

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الخلاصة - يشتمل هذا البحث على دراسة معملية لبحث وتطوير عملية الاحتراق ثنائي المرحلة لخليط سابق التكوين من وقودي الهيدروجين والجازولين والهواء في غرفة احتراق مقسمة . وتم الحصول في هذه الدراسة على قياسات محورية وقطرية لدرجات الحرارة وتركيز نواتج الاحتراق داخل وخارج غرفة الاحتراق عند نسب مختلفة من نسب الوقود الى الهواء ودرجة الشحن الطبقي . عاملان من عوامل التصميم تم دراسة تأثيرهما هما قطر الفوهه الموصلة بين الغرفتين وقطر الحارق . ثلاثة أقطار مختلفة للفوهة تم دراستهما هما ٢٠، ٢٥، ٣٠ مم بينما قطران للحارق تم الدراسة عليها هما ٥، ٦ مم . من النتائج العملية اتضح أن خواص الاحتراق ثنائي المرحلة في غرفة الاحتراق مثل درجات الحرارة وتركيز نواتج الاحتراق وكفاءة الاحتراق تعتمد على قطري الحارق والفوهه الموصلة بين الغرفتين مثل اعتمادها على عوامل التشغيل المختلفة مثل نسبة الوقود الى الهواء ونوع الوقود ودرجة الشحن الطبقي . ومن الدراسة اتضح أن وقود الهيدروجين يحسن من عملية الاحتراق وان زيادة نسبة الهيدروجين في الوقود المستخدم تؤدي الى انخفاض كلا من أول وثاني أكسيد الكربون وزيادة كفاءة الاحتراق لجميع قيم الهواء الزائد المستخدم مع الجازولين كما اتضح أيضا أن عملية الشحن الطبقي تحسن عن عملية الاحتراق .

ABSTRACT

An experimental program to research, develop and demonstrate an axially two staged combustor with premixed gasoline/air and hydrogen/air mixtures is described. Radial and axially profiles for species concentrations and gaseous temperatures are obtained for a wide range air-fuel ratios and degree of charge stratification. Two design parameters were varied namely, the connecting orifice diameter and the burner diameter. Three different orifice diameters are used, those are 20,25 and 30 mm, and two different burner diameters are used, 5 and 6 mm. The results obtained showed that at higher values of excess air factor in the main chamber, CO does not consumed completely before the exit from the combustor. At higher values of excess air factors in the pre- and main chambers, the combustion efficiency was ensured within the combustor length. Decreasing the connecting orifice diameter improves the turbulent and decreasing the flame length. A stratified charge combustion has been studies for leaner combustion to improve emissions and fuel economy. The carbon monoxide is decreased while the combustion efficiency is increased with increasing the degree of charge stratification. The same benefits are obtained when increasing the amount of hydrogen fuel in the mixtures.

1-INTRODUCTION

One of the important goals for combustion system designers is the reduction of specific fuel consumption and pollutants emitted to the atmosphere. As we know, the keys to enhance thermal efficiency and pollutants emitted are to operate the combustion device with lean mixture. The problem associated with lean burning is the lower burning velocity. This difficulties must be overcome without any concomitant increase in noxious emissions these are already subject to quite severe legislation in the world. A number of concepts for the operation of lean burning combustion systems outlined now.

In order to achieve all the benefits of operating with lean mixtures, it is necessary to improve ignition performance and to enhance combustion rate to compensate the reduced burning velocity of lean mixture. The logical means of increasing burning rate is to enhance the degree of turbulence within the combustion device. Turbulence affect combustion through wrinkling and distortion of the flame front. This will increase the surface over which combustion reaction occurs and accelerates the burning of the charge[1]. Experimental data in the form of radial profiles of mean temperatures, gaseous composition and velocities at the combustor exit and combustion efficiency are reported and discussed for a swirling flow, continuous combustor[2]. The results were obtained for both propane and methan fuels. Combustion occurs in the region close to the combustor inlet in a thin turbulent flame sheet. Lewis and Smooth[3], reported the mixture fraction and the concentration measurements in a natural gas combustor with co-axial feed of fuel and air. El-Mahallawy et al[4] investigated turbulent mixing in a cylindrical furnace axially fired with a gases fuel (town gas).

Khalil[5] reported measurements of velocities, mean temperature and wall heat flux in a natural gas fired model furnace. He used different burner arrangement and a wide range of initial flow conditions. The results were compared with those of an isothermal model furnace. El-Mahallawy et al[6] had studied the effect of burner loading on flame structure and heat transfer characteristics of the model water tube boiler. They carried out their measurements on two flames corresponding to fuel flow rates of 74.5 Kg/hr and 114.7 Kg/hr. The air to fuel ratio was kept at (17:1) for both flames. They found that the increase in burner loading caused higher rates of fuel droplets evaporation in the up-stream region of the flame with a consequent increase in CO ,soot formation rates and a comparatively longer flame. They also found that the heat flux rate to the model walls increases with the increase in fuel flow rate. Leuckel and Fricker[7] investigated the characteristics of swirl stablized natural gas flames. Flow patterns and flame types were related to burner geometry, swirl intensity and gas air velocities. They had also investigated the effects of swirl and burner mouth geometry on the stability of industrial-scale natural gas flames.

An alternative approach to the problem of operating combustion device with a lean mixture is based on the idea of using non-homogeneous charge (stratified charge). In such a combustion system arrange rich region of mixture in the vicinity of the ignition point, the overall air/fuel ratio is maintained lean. Ignition is facilitated in the rich region, which then provides a healthy ignition source promoting rapid combustion of the remaining lean mixture. The connecting orifice size and the ratio of the prechamber volume to the main chamber volume can be selected so that the gas pushing out of the prechamber generates sufficient turbulence in the main chamber to cause the complete burning within an acceptable period.

Further approach to the problem of using lean mixture combustion device is the use of hydrogen fuel. There has recently been much more renewed interest in hydrogen, both as source of new clean energy, and as an alternative fuel enricher. With homogeneous mixture, the presence of hydrogen in the mixture increases combustion speed and reduces misfiring. As a result, the lowest specific fuel consumption point is displaced towards leaner mixtures as a whole and is reduced in amounts as the ratio of hydrogen to the total amount of fuel supplied is increased[8].

The basic idea of the present work is the stratification of hydrogen around the ignition point, in order to have primer which allows a regular combustion of lean mixtures in a simple design, high efficiency divided combustion chamber. Thus combining hydrogen enrichment and stratified charge benefits. The experiments are carried out to investigate the different factors affecting the combustion temperature, species concentration and combustion efficiency in the combustor. Parameters varied during experiments are excess air factors, connecting orifice diameter and burner diameter.

2-EXPERIMENTAL SETUP AND PROCEDURES

The general layout of the test rig is shown schematically in Fig.(1). The combustion chamber is made of a mild steel two halves cylindrical shell (220 mm diameter, 120 mm long and 26 mm thickness for the prechamber(11), and 220 mm diameter, 360 mm long and 26 mm thickness for the main chamber(8)) with unrestricted outlet. The combustion chamber is fixed horizontally on a steel table to eliminate the gravitational effect. It is equipped with the necessary auxiliaries which facilitate the operation and control of different experimental parameters. The prechamber carried out the sparking plug(12). Between the two halves there are an orifice plate which can be changed with different opening size and an (O) ring rubber seal in order that a gas-tight seal could be made when joining the two chambers. Tappings are drilled along the pre- and main chambers axis at suitable distances to insert the thermocouples and sampling probes. The pre- and main chambers surfaces are insulated. There are two similar mixing tubes(6&14) for gasoline-air and hydrogen-air mixtures respectively. Each of mixing tube is a 23 mm inner diameter, 300 mm length stainless steel one. A homogeneous flow is attained at the outlet of each tube by the turbulent flow mixing through it. The outlet of the mixing tube is fed to the burner inlet. The hydrogen is led to the mixing tube from a gas supply cylinder(21), provided with a spring regulator(20) to control the outlet pressure. A needle valve is also introduced in the gas flow line to control the up-stream pressure. The burner(13) is a simply co-axially pipe of special design

(5 or 6 mm inner diameter, 400 mm length stainless steel tube)fitting in the pre-chamber. The inlet pipes of pre- and main chambers are connected through a valves to achieve the required conditions during the experiments. A rotameter and three orifice meters are connected for measuring the gasoline, hydrogen and air mass flow rates. The air necessary for combustion is forced through a 10 mm pipe by means of an air compressor. The air mass flow rate is regulated by means of valves and metered by two orifice meters operated under two pressure control valves. A designed pressurized fuel tank is used for gasoline fuel supplied to the main chamber. The gasoline fuel mass flow rate is measured by a rotameter. There are also a pressure control valve fitted on the delivery line and a needle valves to control the mass flow rate. The hydrogen fuel is supplied through a gas bottle stored at a pressure of 180 bar. Hydrogen flowing from the bottle passing through a pressure regulator. There are a pressure gauge and temperature indicator to measure the inlet hydrogen conditions.

Gas sampling probes and thermocouples are performed at different radial and axial positions in the combustion chamber using several probes located at 6 positions for temperature measurements and 4 positions for gas analysis, Figs.(2)and(3). The thermocouples used in this experiments are of type (R platinum 13%, rhodium VS). The wires diameter are of 0.25 mm and are insulated by a fine ceramic tubes each have two holes for the two wires. The tubes were placed in a stainless steel tube of 2.5 mm diameter. The gas chromatograph Berkin Elmer model 13920 is used for species analysis and for determination of the fuel composition used in the experiments. The oxygen concentration was detected by oxygen detector type MSA Model 260. The total hydrocarbon is analyzed using flame ionization detector.

3-EXPERIMENTAL RESULTS AND DISCUSSIONS

The results of tests are collected and displayed graphically as a group families of curves. For each connecting orifice size and burner diameter, species concentration of CO2, CO, O2 and HC and gaseous temperature inside the pre- and main chambers are recorded at different excess air factor and different radial and axial positions. The experiments were carried out at a wide range of operating conditions. Hydrogen has been used as a supplementary fuel to extend lean operation limit and improve combustion performance. From the measured results, calculations were made for some combustion parameters as follows;

1-Incompleteness of combustion, $$Q_c = \frac{CO_{2max.} - CO_2}{CO_{2max.}} \times 100$$

2-Oxygen and hydrogen consumption efficiencies; which are defined as ($O_2/O_{2int.}$) and ($H_2/H_{2int.}$) respectively.

3-From the calculated results, contour mapping for temperature measurements, CO2 and CO are drawn.

The results obtained are presented and discussed now as in the following; Shown in Fig.(4) are the radial and axial temperature distribution at different stations and different excess air factors. Temperature measurements were taken for (6) stations in axial direction, Fig.(2). The measurements were carried out every 5 mms along the radial direction. The results are presented for two burner diameters 5&6 mms, and two connecting orifice diameters 25&30 mms. Shown in Fig.(5) is the effects of excess air factors $\phi 1$ and $\phi 2$ on the temperature distribution along the combustion chamber center line. From these results it can be observed that the temperature is increased as the amount of hydrogen fuel is increased (decreasing the excess air factor $\phi 1$). Since the curves are approximately parallel, it means that the temperature is mainly dependent on air/fuel ratio and energy liberated from the fuel. The maximum temperature of 1630 oC is obtained and prevails in a large area of the central zone. Moreover, at the central zone, the corporating high temperature is prolonged to station (5) with decrease in fuel quantity. This may be attributed to the increase of convective diffusion of fuel. In radial direction it may be observed that the temperature distribution is uniform. When moving down stream, the variation in temperature becomes slight, then the curves tends to flatten at higher values, if the excess air factor exceeds a certain limits the temperature falls down again. The axial station distance at which the temperature distribution becomes uniform is increased with the increase in excess air factor. This may give an indication that the flame length is increases with the increase in excess air factor. The decrease in excess air factor $\phi 1$ will increase the intensity of combustion turbulent mixing. The temperature distribution has a maximum value at the recirculation zone boundaries.

Figures (6)through(9) show the radial distribution of O2,CO2,CO and HC at different axial stations in the main chamber. As can be seen from these figures, the CO2 concentrations increases down stream positions and reaches its maximum value at station (4), near the combustor exit. At all stations, the CO2 concentrations is increases with the movement from the center line to the combustion chamber wall. At further down-stream positions, the results show that both temperatures and CO2 levels increases while both CO and HC levels are decreases. The increase of CO2 and temperature is mainly due to increased oxidation rate of CO and H2. Carbon monoxide concentration has a maximum value at the center line and decreases with the movement towards the combustion chamber wall. This may be attributed to the partial oxidation of fuel in the core of recirculation zone, due to mixing with hot recirculated gases. The presented results concluded also that increasing in connecting orifice diameter may lead to a wide spread of the ignition source into the main chamber which in turn results in increased initial frontal area of the flame and increases the burning rate. This behavior is reflected in shorter duration on main combustion phase.

Species concentrations of CO2, CO, O2, H2 and H2O at outlet from the combustor as a function of excess air factors are shown in Fig. (10). These measurements were taken at different prechamber excess air factor $\phi 1$, different main chamber excess air factor $\phi 2$ and different connecting orifice diameter. From these results it can be concluded that, when the excess air factor $\phi 1$ is increases the CO2 concentration is increased and H2O is decreased for all values of $\phi 2$. Traces of CO and H2 which are found in lean mixtures products are mainly due to incomplete combustion. The obtained results concluded that the presence of H2 fuel in the mixture increases combustion rate and reduced emissions. The maximum value of CO is presented at $\phi 2=.589$, as the excess air factor $\phi 1$ is increased the CO and CO2 are increases, while H2O is decreases.

The average hydrogen and oxygen consumption efficiencies at exit were determined and presented in Figs.(11)and(12), while the axial distribution of oxygen consumption efficiency is shown in Fig.(16). It can be noticed from these results that as the excess air factor $\phi 2$ is increases ,keeping excess air factor $\phi 1$ constant, the oxygen consumption efficiency is increases while the hydrogen consumption efficiency is decreases. When moving towards the main chamber exit, the oxygen consumption efficiency is decreases, Fig.(11). The oxygen consumption efficiency is decreases sharply up to station 2, while slight variations is occurs until station 4. The incompleteness of combustion Qc based on CO2 calculations were determined both average values at combustor exit and axial distributions as shown in Figs.(13)and (14)It is clear from these figures that as the excess air factor $\phi 2$ is increases , Qc is decreases, i.e. the reaction is improved. Investigations of the radial distribution indicates that the extension of incompleteness of reaction is confirmed at a location (20 to 25 mms) away from the center line. This is occurs at station 3 which is 240 mms down wards of inlet fuel distributor. The value of Qc is decreases when movement along the main chamber towards the exit port.

From the volumetric concentrations measurements of CO2&CO, and temperatures measurements , calculations were made and contour mapping were drawn for CO2,CO and temperature. It should be noticed that, any particular plotted point does not represent a sample location in the combustion chamber except when coincide. The points shown have been found from the isoparametric lines of radial and axial distribution plots. The contours of local distributions of CO2, CO and temperatures are shown in Figs.(15)through(17). Investigations of these contours indicated that the CO2&CO follow nearly the same trends irrespective of the value of excess air factor. It should be noted that at lower values of excess air factors CO can not be consumed before the exit section of the chamber. Comparison of these figures show that the decrease in CO with radial distance is faster for lower excess air factors than that for higher ones. This oxidation rate could be interpreted as a result of the degree of mixing and temperature level. From the results of temperature contours, Fig.(17) we may seen that the local temperature is significantly influenced by the overall excess air factor. As the overall excess air factor increases $\phi>1$ the hot zone moves axially to the main chamber exit.

Shown in Figs.(18)through(20) are the effects of degree of charge stratification and hydrogen energy added in the fuel mixtures on outlet species concentration and incompleteness of combustion Qc. The degree of charge stratification is defined as the degree of richer in the prechamber and the hydrogen energy is defined as the percentage of heat added in hydrogen fuel to the total heat added. The results presented in these figures concluded that as the degree of charge stratification is increased, CO and CO_2 concentrations are decreases while H_2O and Qc are increases.

CONCLUSIONS

Based on the experimental results, the following conclusions are drawn;

1-Decreasing the connecting orifice diameter results in; lower temperature levels, faster the completion of reaction and decreasing the radial extent of combustion zone. While increasing the connecting orifice diameter results in widening the area of minimum CO_2 concentration.

2-A maximum temperature of 1630 oC is obtained and prevail in a large area of 20 mms about the center line.

3-The CO_2&CO concentrations are decreases while each of H_2O and Qc is increases with the increasing of degree of charge stratification and hydrogen energy added.

NOMENCLATURE

Dor	The connecting orifice diameter	mms
EH2	Hydrogen energy ratio	%
O2in	Initial admitted amount of oxygen	Kg
H2in	Initial admitted amount of hydrogen	Kg
P	Pressure	bar
Qc	Incompleteness of combustion	%
T	Temperature	oC
ϕ	Excess air factor	$\phi<1$ rich mixture
$\phi 1$	Pre-chamber excess air factor	
$\phi 2$	Main chamber excess air factor	

REFERENCES

1-ANAND, M.S and GOULDIN, F. "Combustion Efficiency of a Premixed Continuous Flow Combustor"ASME, July 1985,vol.107

2-LEFEBURE, A.H "Fuel Effects on Gas Turbine Combustor Ignition, Stabilities and Combustion Efficiency" ASME,JUL. Vol.107

3-LEWIS,M.H & SMOOT,L.D"Turbulent Gaseous Combustion;Part 1 Local Species Concentrations Measurements"Comb.&Flame,vol.42

4-EL-MAHALLAY,F.M.,LOOKWOOD,F.C.and SPALDING,D.B "An Experimental and Theoretical Investigation of Turbulent Mixing in a Cylindrical Furnace"Comb.&Flame,Vol.25,pp283-295,1974

5-KHALIL, E.E. "Flow and Combustion in Axisymetric Furnace", Ph.D Thesis,London Univ.,1976

6-EL-MAHALLAWY,F.M.et al"Effect of Burner Loading on Flame Structure and Heat Transfer of a Large Cylindrical Oil Fired Flame Tube"AIAA Joint Propulsion Conf.,Cinc.,Ohio,1984

7-LECKEL,W.and FRICKER,N. "The Characteristics of Swirl- Stabilized Natural Gas Flames, part1, The Effect of Swirl and Burner Mouth Geometry on Flame Stability"J.Ins.of Fuel,vol.49,1976

8-STROBI and PESCHKO,W.W. "Liquid Hydrogen As A Fuel of the Future for Industrial Transport" 6WHEC,Vienna,July 1986

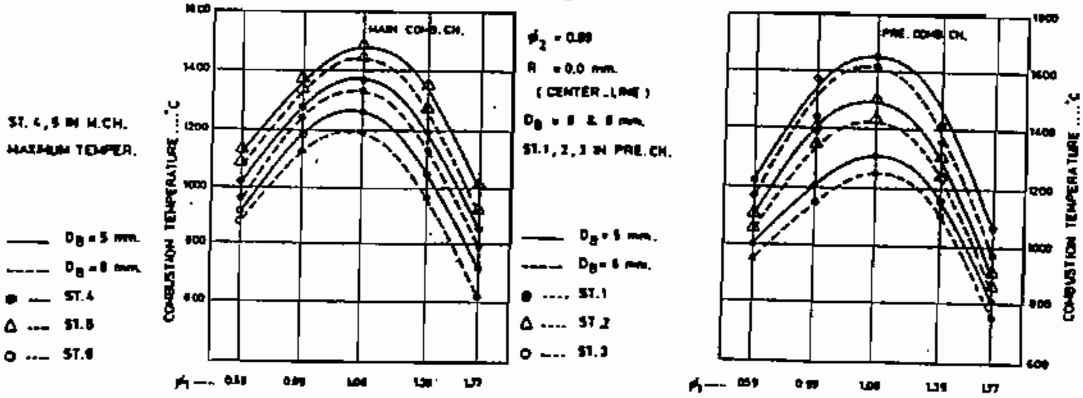


Fig.5 TEMPERATURE DISTRIBUTION VS. ϕ2 AT CENTER LINE

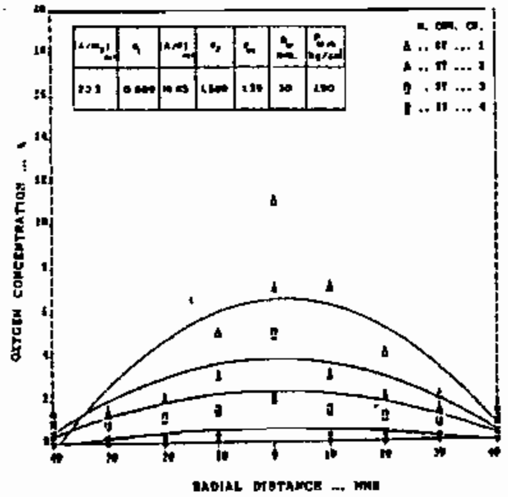


Fig.6 RADIAL OXYGEN DISTRIBUTION AT DIFFERENT AXIAL STATIONS

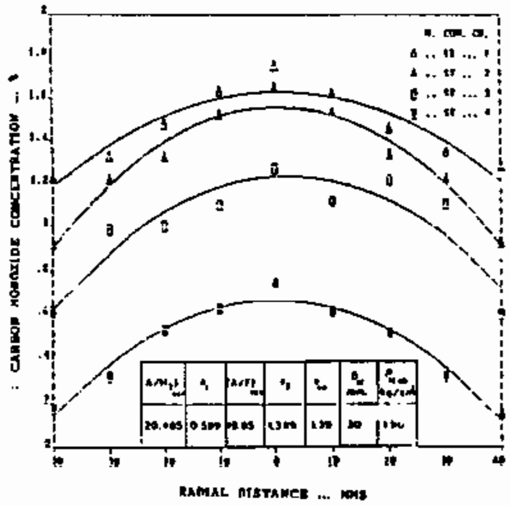


Fig.7 RADIAL CO DISTRIBUTION AT DIFFERENT AXIAL STATIONS

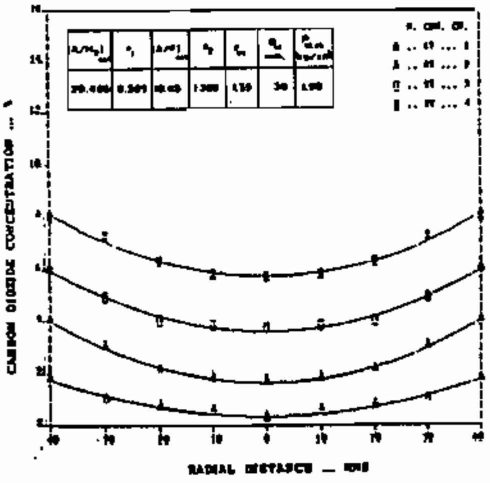


Fig.8 RADIAL CO2 DITRIBUTION AT DIFFERENT AXIAL STATIONS

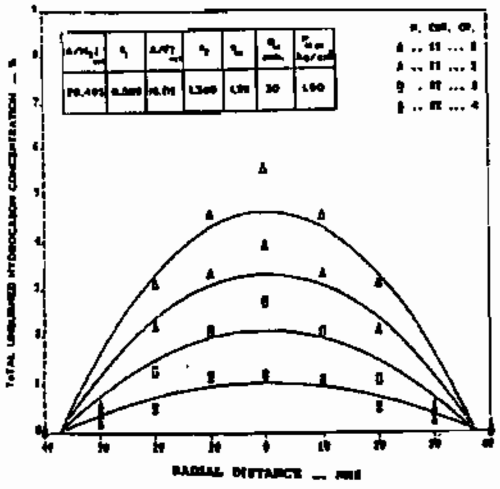


Fig.9 RADIAL HC DISTRIBUTION AT DIFFERENT AXIAL STATIONS

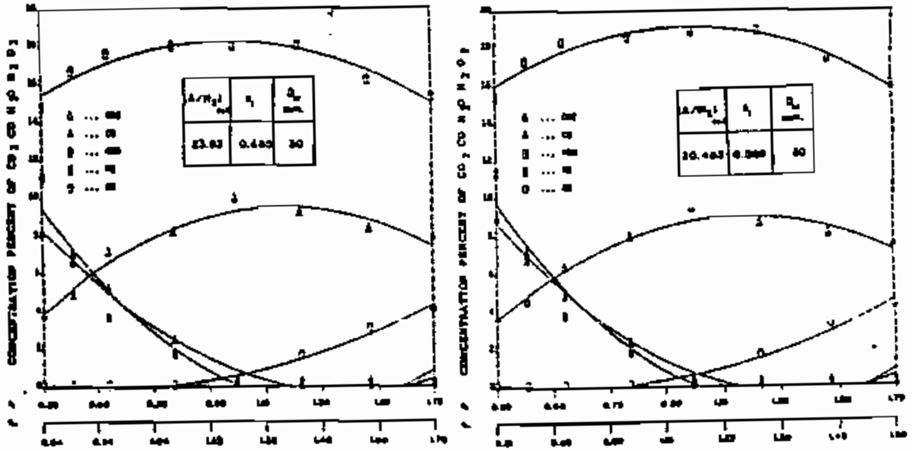


Fig.10 SPECIES CONCENTRATIONS VS. EXCESS AIR FACTORS AT OUTLET

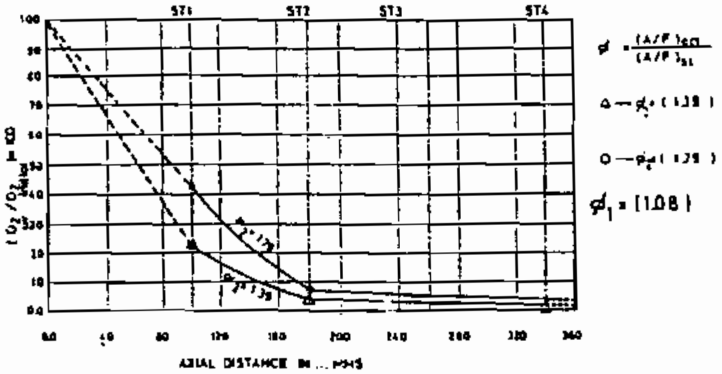


Fig.12 OXYGEN CONSUMPTION EFFICIENCY AT DIFFERENT AXIAL POSITIONS

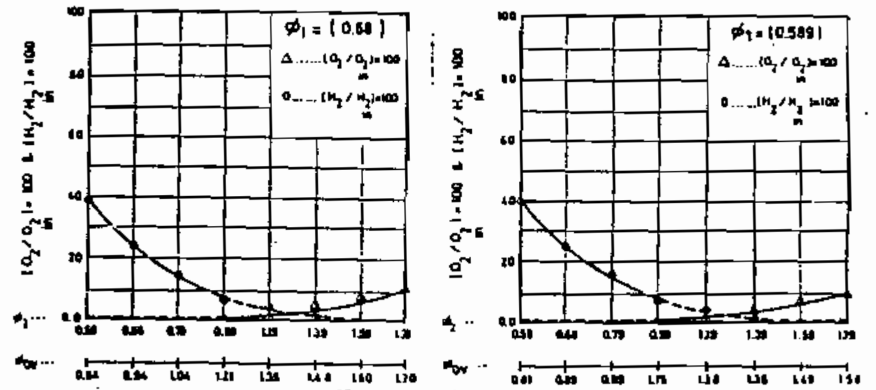


Fig.11 OXYGEN & HYDROGEN CONSUMPTION EFFICIENCIES VS. ϕ2 & ϕov

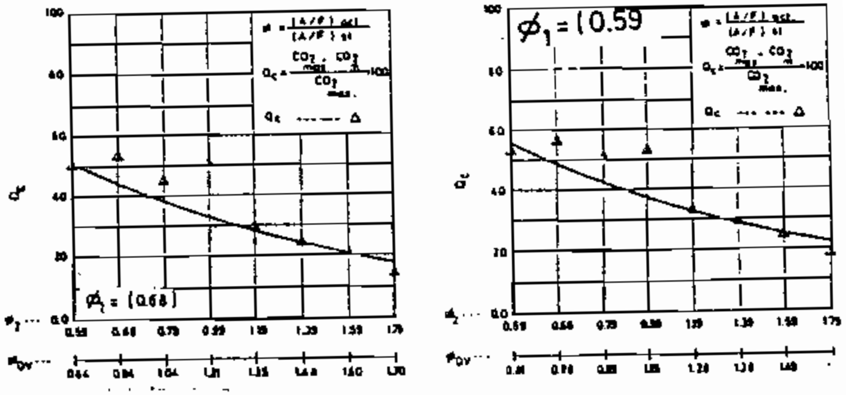
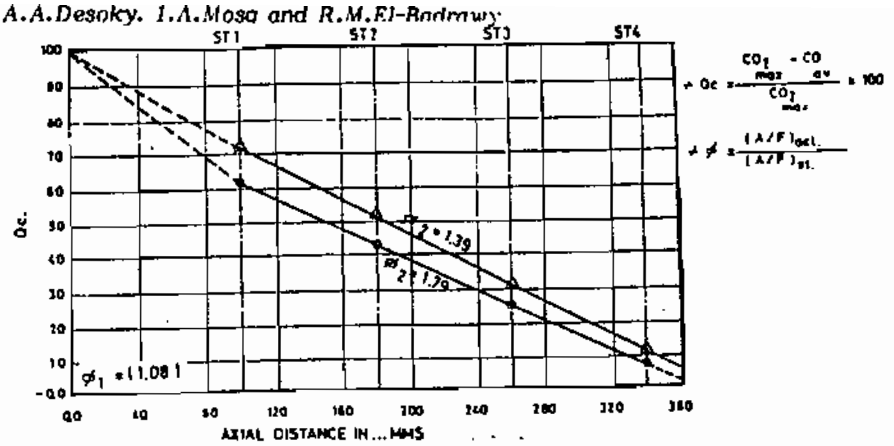


Fig.13 INCOMPLETNESS OF COMBUSTION (Qc) VS. ϕ2 & ϕov



$$* \ Qc = \frac{CO_{2_{max}} - CO_{av}}{CO_{2_{max}}} \times 100$$

$$* \ \phi = \frac{(A/F)_{act.}}{(A/F)_{st.}}$$

Fig.14 INCOMPLETNESS OF COMBUSTION,Qc AT DIFFERENT AXIAL POSITIONS

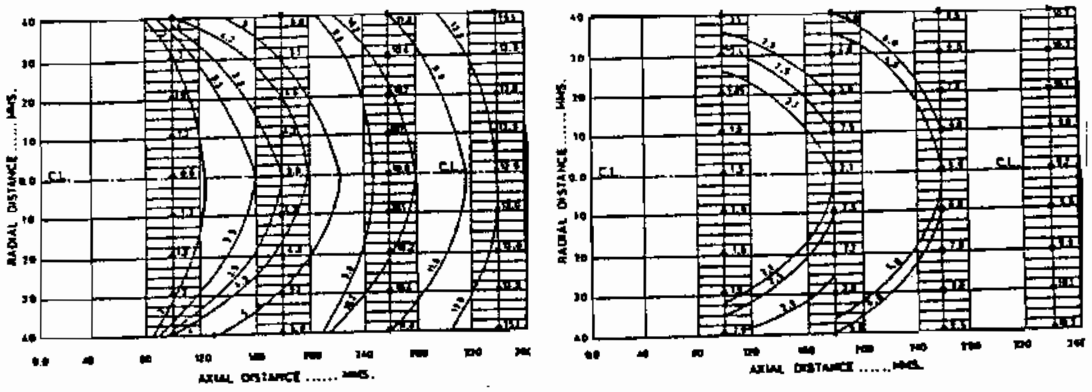


Fig.15 CO2 CONTOURS, φ1=1.08 & φ2=0.999   φ1=1.08 & φ2=1.385

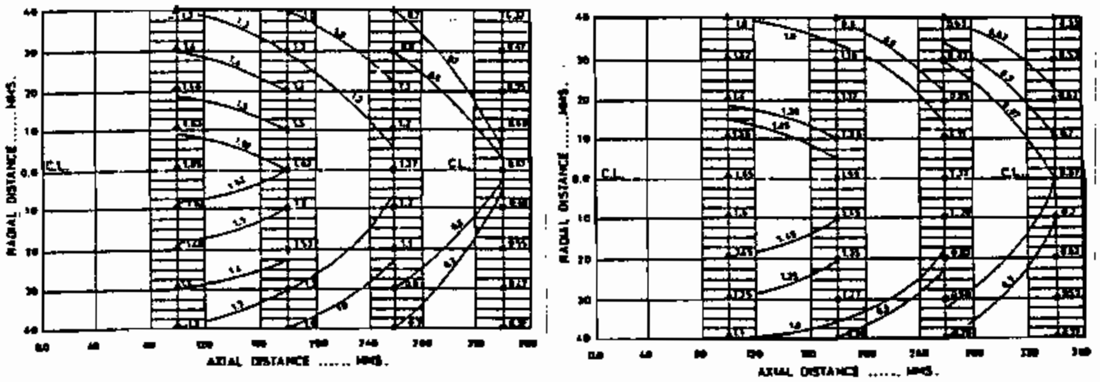


Fig.16 CO CONTOURS, φ1=1.08 & φ2=0.999   φ1=1.77 & φ2=0.999

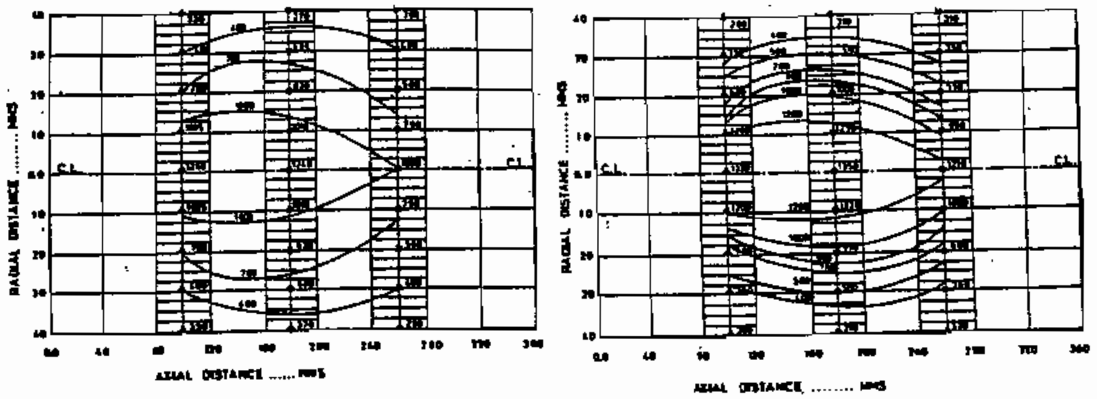


Fig.17 TEMPERATURE CONTOURS φ1=.589&φ2=1.798   φ1=1.77&φ2=.589

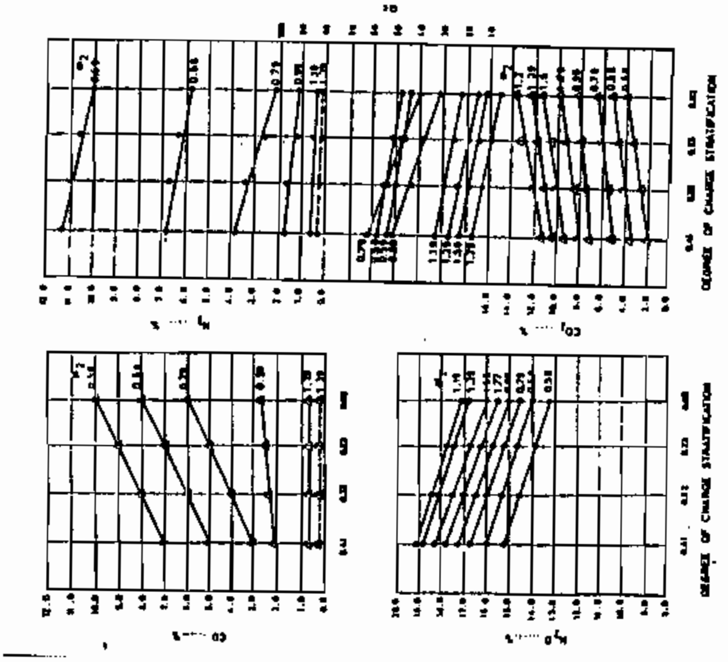


Fig.19 SPECIES CONCENTRATION & Qc VS. DEGREE OF CHARGE STRATIFICATION

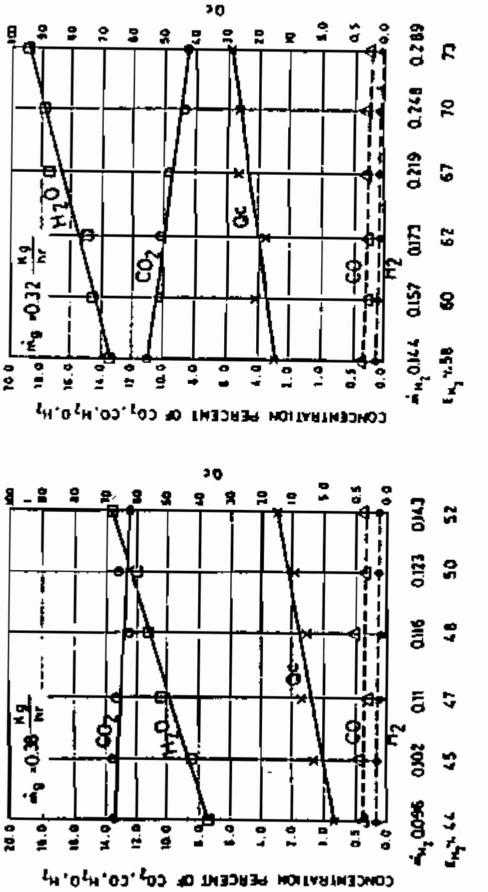


Fig.20 SPECIES CONCENTRATION VS. EH2

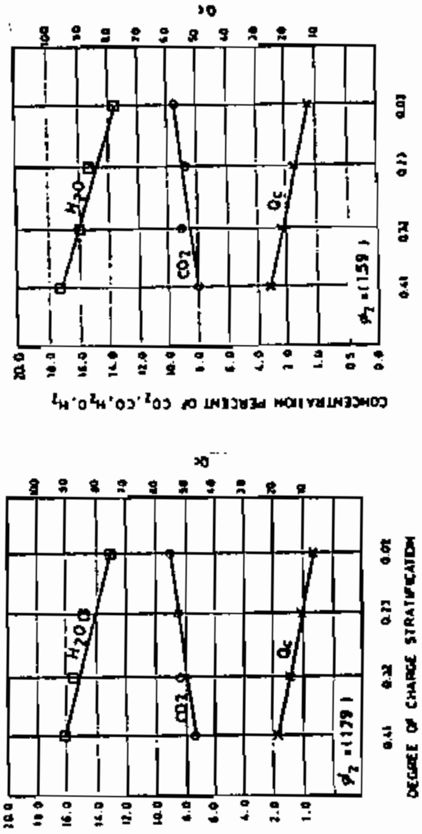
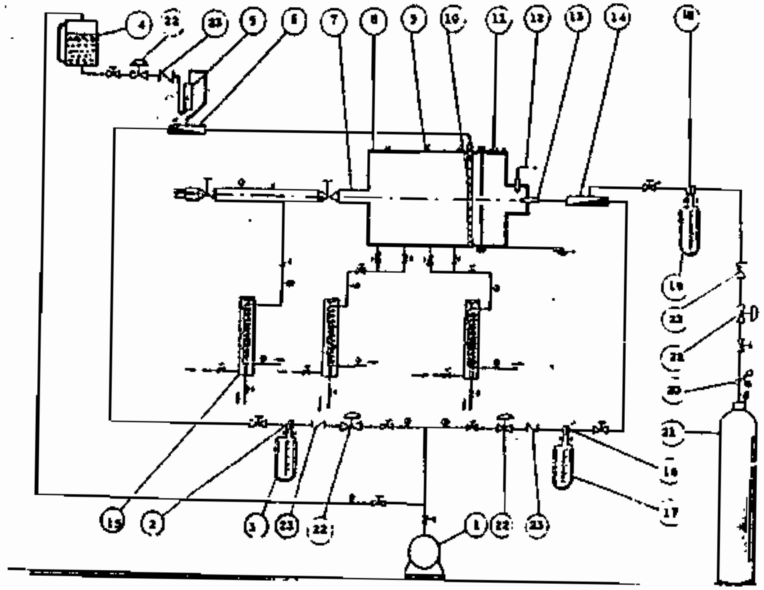


Fig.18 SPECIES CONCENTRATION & Qc VS. φ2& DEGREE OF CHARGE STRATIFICATION



(1) Air compressor.
(2) Air orifice-meter.
(3) Water-U-tube manometer.
(4) Gasoline-fuel tank.
(5) Gasoline-rota-meter.
(6) Air-Gasoline mixing tube.
(7) Exhaust-line
(8) Main combustion chamber.
(9) Thermo-couple.
10) Inlet fuel distributer.
11) Pre-combustion chamber.
12) Spark-plug.
13) Burner.
14) Air-hydrogen mixing tube.
15) Three-water coolers.
16) Air-orifice-meter.
17) Water-U-tube-manometer.
18) Hydrogen-orifice-meter.
19) Water-U-tube-manometer.
20) Hydrogen pressure regulator.
21) Hydrogen vessel.
22) (P.C.V) Pressure control valve.
23) Check valve(nonreturn valve).

Fig.1 LAYOUT OF THE APPARATUS AND MEASURING INSTRUMENTS

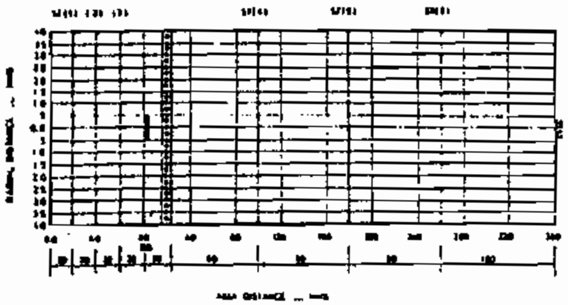


Fig.2 TEMPERATURE MEASUREMENTS STATIONS

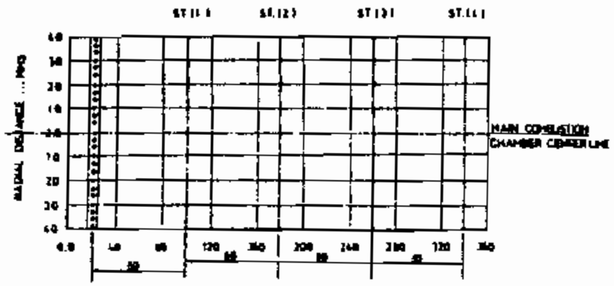


Fig.3 SAMPLING PROBE STATIONS

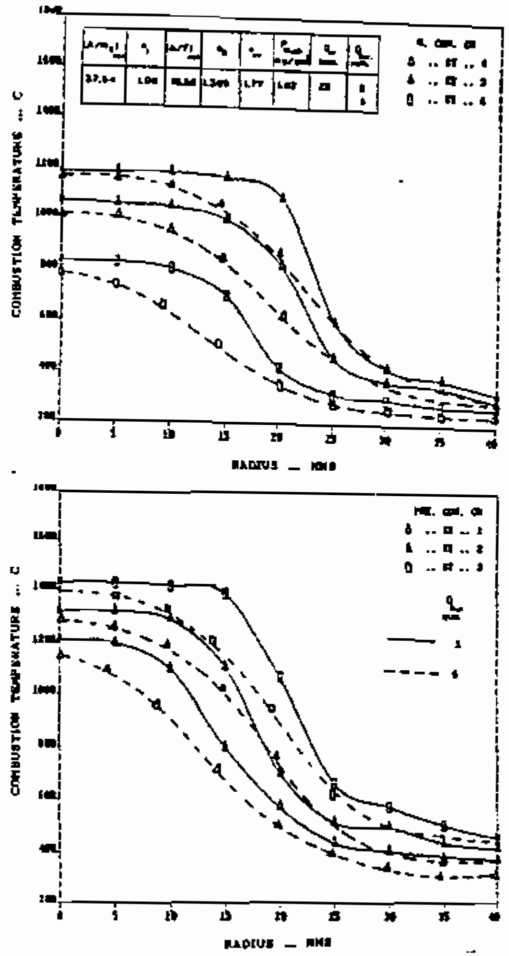


Fig.4 RADIAL TEMPERATURE DISTRIBUTION AT DIFFERENT AXIAL STATIONS