

COMBUSTION RESEARCH PROGRAM

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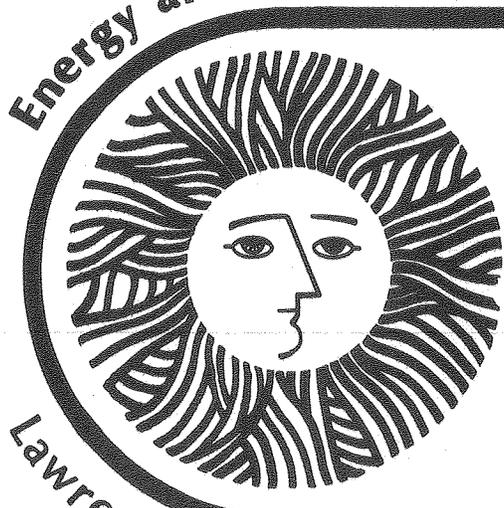
Energy & Environment Annual Report 1977

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COMBUSTION RESEARCH PROGRAM

chapter from
Energy & Environment Division
Annual Report 1977

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Combustion Research

INTRODUCTION

Combustion of fossil fuels is our primary source of energy and is likely to remain so for quite some time. Two important factors in using this valuable, non-renewable resource are the efficiency of utilization of the fuel and the generation of pollutants which contaminate our environment. The combustion system used to burn the fuel and transfer the heat to either a working medium or the ultimate source is one of the most important steps in the long chain of processes which convert the fuel to energy from its original state. The aim of combustion research and development is to improve the overall efficiency of combustion systems while minimizing the pollution generated and the cost.

A combustion system typically involves a complex interaction of chemical and fluid mechanical phenomena. It is a fertile field for sophisticated research and development which draw on the academic disciplines of high temperature chemical kinetics and turbulent fluid mechanics. A number of the most recent experimental and theoretical research techniques, such as laser based instrumentation, molecular beam techniques, and powerful computational and numerical analysis techniques in fluid

mechanics can be fully exploited in well planned programs of combustion research.

The initiation of research on problems associated with coal combustion is discussed in the first two articles. Coal is by far our largest fossil fuel research and we believe that its utilization can be significantly improved by a vigorous and farsighted research program. The first article describes a study of the combustion of solid coal and coal related fuels under conditions of slow heating rates. The research summarized in the second article is aimed at understanding and controlling the formation of submicron particulates in pulverized coal combustion.

The subsequent twelve articles summarize research projects covering a wide variety of combustion problems. Several are directly related to pollution problems; in particular there is a coordinated program aimed at developing clean burning internal combustion engines. Another important general area being studied (in three experimental and two theoretical projects) is the complex interaction of fluid mechanical turbulence with combustion heat release.

THE COMBUSTION OF COAL AND COAL RELATED FUELS IN AN OPPOSED FLOW DIFFUSION FLAME

W. K. Chin and R. F. Sawyer

INTRODUCTION

The utility of the opposed flow diffusion flame (OFDF) apparatus for the laboratory study of the combustion of gaseous, liquid, and polymer fuels has been demonstrated by a number of researchers. We have employed this configuration to study the steady state of combustion of graphite, pulverized coal, and solvent refined coal in an opposed flow of oxygen/nitrogen or oxygen/argon. The advantages of this geometry lie primarily in the ability to observe the combustion of coal and coal related or derived fuels in a particularly well controlled, steady state environment. While the heating rates, which are known to be important to the pyrolysis and combustion of coal, are considerably less than is typical of the burning of pulverized coal, they are in the range of applicability to the *in situ*, fluidized bed, and possibly stoker fed combustion of coal. Unlike most other experimental methods, the technique appears to be suitable for the study of a number of coal derived or coal related fuels such as coal, pressed pulverized coal, char, coke, solvent refined coal, and coal liquid--thereby providing a means of observing the combustion of these fuels under comparable combustion conditions.

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The fuel holder and oxidizer nozzle are contained in a 10 cm diameter pyrex cross to eliminate external disturbances, to aid in the collection of product gases, and to allow operation at below atmospheric pressure if desired. One horizontal side of the cross serves as a viewing port, and the other provides access for temperature and gas sampling probes. The oxidizer enters through the top port and the fuel feed mechanism through the lower port. The sample feed system provides accurate placement and control of the location of the fuel surface to within ten micrometers. A laser beam and photodiode detector are used to sense the burning fuel surface, providing a signal to a stepping motor which automatically positions to the 12.7 mm diameter fuel rods. Linear regression rate measurements are obtained directly from a counter driven by the stepping motor feeding sample. Due to the substantial radiation loss from most surface burning fuels, including coal, it is not possible to burn some samples in air and an oxygen enriched flow is required.

Graphite, pressed pulverized coal, and solvent refined coal were selected for study

to demonstrate the suitability of the method to this family of fuels and to provide a comparison among related solid fuels. Pressed pulverized coal was selected because of the chemical and physical homogeneity which such a material exhibits, especially in contrast to coal itself which is highly anisotropic and presents difficulty in insuring constancy from sample to sample. The pressed pulverized coal samples were prepared from Pittsburgh seam pulverized coal under 35 mesh (417 micrometer) sieve. The pulverized coal has significant ash content, about 6%. Rods were prepared in a plunger and die apparatus with and without the addition of a binder. Varying sample water content was obtained through dessication. Density, void volume, and pore size distribution of the pressed coal samples were found by porosimetry using a 400 MPa mercury intrusion porosimeter capable of measuring pore size from 70 down to 0.003 micrometers.

Burning rates were measured as linear regression rates for several sample compositions and under a range of oxidizer flow rates and oxygen concentrations. A typical record of the regression rate history of a pressed-pulverized coal sample is shown in Fig. 1. The irregularities are caused by the buildup and removal of an ash layer. Burning rate reproducibility was within eight percent, demonstrating the consistency of the sample preparation method. The effect of oxygen concentration was investigated by burning samples under a constant oxidizer flow velocity of 380 cm/sec and a varying oxygen fraction. The regression rate shows oxygen mole fraction or concentration dependency of the 0.74 power. Some selected burning rates for graphite, coal, and comparison materials are presented in Table I.

Temperature distribution within the solid phase during steady state combustion was obtained by an imbedded fine thermocouple. In this

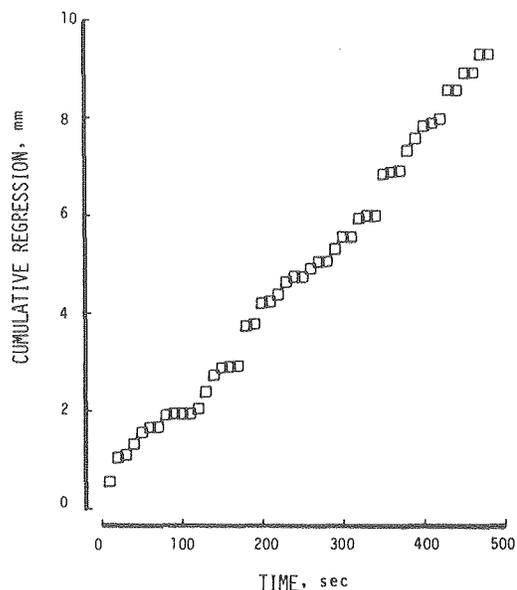


Fig. 1. Experimental regression curve for pressed pulverized coal burning in a mixture of .30 O₂ + .70 N₂; oxidizer blowing velocity, 380 cm/sec; sample density, 0.92 gm/cm³. (XBL 782-7390)

steady state burning, the measured temperature variation with time is equivalent to the instantaneous spatial temperature variation. It was found as expected, that the surface temperature increases with oxygen concentration in the oxidizer flow. Thermal diffusivities of the burning coal were extracted from the temperature measurements.

Table 1. Burning rate data for selected solid fuels.

Material	Density (gm/cm ³)	O ₂ Velocity (cm/sec)	Burning Rate (gm/sec)	Burning Rate (mm/sec)
Polymethyl Methacrylate	1.176	253	0.0137	0.0922
Maple Wood	0.731	253	0.0059	0.0640
Graphite I	1.528	589	0.0083	0.0427
Graphite II	1.334	479	0.0047	0.0279
Coal C-2 ^a	1.097	253	0.0047	0.0340
Coal B-4-1 ^b	0.950	253	0.0040	0.0330
Coal B-3-2 ^c	0.902	253	0.0043	0.0279

^aPressed pulverized coal, no binder.

^bPressed pulverized coal, with binder, unsieved.

^cPressed pulverized coal, with binder, sieved.

CONDENSATION OF ASH AND TRACE
METALS FROM PULVERIZED COAL COMBUSTION

P. Sherman and F. Robben

INTRODUCTION

Particulate emissions from sources burning coal have long been a health and environmental problem. Although much progress has been made in the development of devices for cleaning the effluent (such as electrostatic precipitators), there is considerable evidence that the collection of submicron particles formed from the combustion of coal is very inefficient. There is also evidence that the trace metals present in the coal are concentrated in the fly ash; in particular there appears to be an increase in the concentration of some metals with the decrease of particle size. These small particles which enter the atmosphere are the ones which are most easily ingested into the lungs and thus are more of a health hazard. The intelligent control of such particulate emissions by either modifications in the design of coal burning equipment or in the design of exhaust clean-up equipment requires as a first step an understanding of the mechanisms of formation of the particulates. Such understanding is also necessary in the consideration of environmental restrictions which should be placed on the burning of coal in the future.

At present, there is no good way of predicting the formation of the submicron particulates or any of their characteristics. Much more new information is necessary in order to obtain any predictive model for the generation of submicron particles. In particular, information is necessary relating the formation and growth of particles to the many combustion parameters. The condensation of vaporized ash, along with trace metals, is one suggested model for the formation of these submicron particles. The increase in concentration of the trace metals in these small particles is consistent with the formation and growth of these particles by condensation; further, rudimentary calculations using estimated combustion conditions support a condensation model.

ACCOMPLISHMENTS DURING 1977

In order to investigate the formation of particulates generated by the combustion of pulverized coal and to study the controlling parameters, a laboratory arrangement where appropriate measurements can be made was chosen as the first step. A simple system consisting of

- 1) an air-pulverized coal injection-conveyor system;
- 2) a burner for turbulent pre-mixed flow of pulverized coal, air and gaseous fuel;
- 3) a sampler for the collection of submicron particulates on a substrate appropriate for electron microscope analysis has been designed and constructed.

Controlled variations in flow rates and fuel/air ratios can be made in the laboratory arrangement to change residence times, temperatures and temperature gradients, velocities and velocity gradients. A schematic of the present experimental arrangement is shown in Fig. 1. A jet ejector using air as a carrier gas entrains the pulverized coal from a hopper and blows the air-powder mixture through 3 mm diameter tubing into the 12 mm diameter vertical tube-burner. Gaseous fuel and air are metered, mixed in the vertical tube-burner, and burned with the flame stabilized at the tube exit. Oxygen enriched air may be used to facilitate burning the coal without gaseous fuels.

The sampler is evacuated with a vacuum pump so that a supersonic jet impinges on the collector surface. A cleaved mica surface with a thin evaporated carbon layer will be used as the collecting surface in the initial experiments. Transmission electron microscopy will be used to measure the particle sizes. A very sensitive spectroscopic technique known as Zeeman shifted atomic absorption, developed at Lawrence Berkeley Laboratory, will be used to measure the trace metal concentrations.

PLANNED ACTIVITIES FOR 1978

The apparatus described above will be used to evaluate the measurement techniques and then to try to obtain some information on the formation of submicron particles in this particular burner. Collection of samples from industrialized pulverized coal combustors may also be carried out in order to obtain more data on the emission of small particulates from commercial combustors.

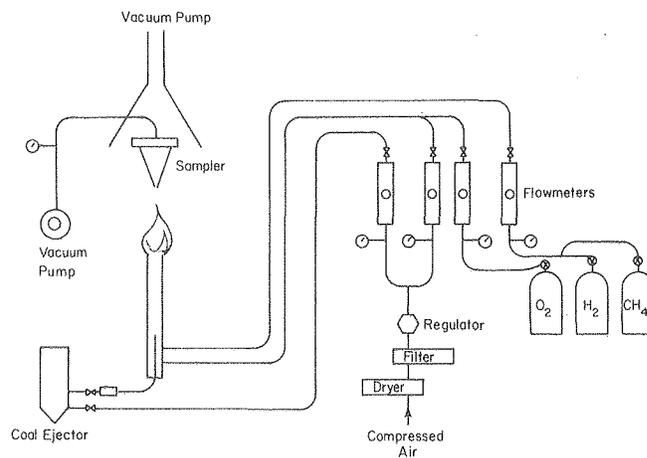


Fig. 1. Schematic of a pulverized-coal-burning experimental arrangement. (XBL 781-2380)

SECONDARY POLLUTANTS FROM AMMONIA INJECTION
NO_x CONTROL PROCESSES

N. J. Brown, R. F. Sawyer, and A. K. Gordon

INTRODUCTION

Consideration of odd-nitrogen compounds (essentially all nitrogen containing compounds other than N₂) as air pollutants has been primarily focused upon the nitrogen oxides, NO and NO₂, with occasional interest in ammonia. The oxides of nitrogen result either directly or indirectly in atmospheric nitrogen dioxide, photochemical smog, nitrate compounds, and probably other compounds whose role in air pollution is less well defined.

Combustion sources both of the mobile and stationary types are recognized as the primary sources of the oxides of nitrogen. The two principal sources of nitrogen oxides in the combustion of conventional fuels are oxidation of atmospheric molecular nitrogen (thermal NO_x) and oxidation of nitrogen containing compounds in the fuel (fuel nitrogen NO_x). Until recently, the former has been the dominant source of NO_x; however, in combustion processes using crude oil, coal and shale derived fuels, and some refinery gases, fuel nitrogen can be a significant and even dominant source of NO_x. The amount of fuel nitrogen contained in fossil fuel can vary considerably with negligible amounts in natural gas, significant amounts found in distillate fuels, and amounts from 0.5 to 3 percent in heavier fuels (residual oil, coal, coal derived, and shale derived fuels). The amount of fuel nitrogen NO_x produced in combustion processes increases with the fuel nitrogen content of the fuel. Fuel nitrogen nitric oxides may account for more than half of the nitric oxides emitted from the combustion of high nitrogen content oil or coal in power plants.

The mechanism of fuel NO_x production, although not understood, appears favored under conditions different from those which enhance thermal NO_x production. Consequently, the various control strategies used in the United States to meet NO_x emission standards, namely the modification of the combustion processes to reduce thermal production, are ineffective in reducing fuel NO_x.

A new NO_x control technology has been patented by Exxon Research and Engineering Company which selectively removes NO from combustion effluents through homogeneous reaction with ammonia and oxygen. This process is distinctly different from other technologies in that it removes NO_x after its formation rather than attempting to prevent its formation. Thus, the process offers the possibility of removing both thermal and fuel NO_x. This process has been demonstrated commercially in Japan and is likely to be proposed for use in California for the control of oxides of nitrogen from stationary sources. The major question regarding this process is its potential for formation of secondary pollutants, especially at operating conditions

different from those which are optimal for the reduction of oxides of nitrogen.

In recognition that NO_x removal through NH₃ addition now appears to be a viable control process for stationary combustion sources, a new research program sponsored by the California Air Resources Board has been initiated at Lawrence Berkeley Laboratory which is directed toward identification and quantification of the nitrogen containing products formed from the addition of ammonia. This research will be performed in a laboratory scale combustion tunnel with a well-controlled experimental environment. A test sequence is planned to examine product formation associated with 1) optimum ammonia addition conditions, 2) off-design ammonia addition conditions, 3) optimum and off-design ammonia addition conditions with an oil fuel rather than the propane of the first two test series, and 4) the effect of fuel additives and impurities on the nitrogen-containing products formed. The overall objective of this research is to provide a framework to assist the California Air Resources Board in assessing potential pollution hazards associated with application of the ammonia addition control process to reduce stationary source emissions.

ACCOMPLISHMENTS DURING 1977

A premixed, laminar flat flame is being used to provide a prototype combustion environment for developing and testing gas analysis procedures. A new burner which was designed and fabricated at Lawrence Berkeley Laboratory has been characterized, and its ability to support a stable, reproducible one-dimensional flame has been ascertained. Radial and axial temperatures and velocity profiles have been determined for a series of propane/air flames. An analytical scheme for N₂ and NO has been developed. A laboratory combustion tunnel has been designed utilizing a propane/air burner followed by a reaction duct, including a temperature controller, ammonia injector and sampling ports.

PLANNED ACTIVITIES FOR 1978

A continuing review of developments in the field of ammonia addition control technology will be conducted through examination of the open technical literature and direct contact with individuals and groups working in this field. This information is essential to the study of the secondary pollutant potential of the process. The combustion tunnel will be constructed and its performance will be characterized. A series of experiments varying fuel nitrogen additive type and concentration and equivalence ratio will be conducted to assess the ammonia addition process. N₂, NO and NH₃ concentrations will be measured as a function of time following the ammonia addition. Other nitrogen compounds which are products of the control process will be determined. The effect of operating at off-design conditions of temperature and mixture ratio will be determined.

CATALYZED COMBUSTION IN A BOUNDARY LAYER

R. Schefer, F. Robben, R. K. Cheng, and I. Namer

INTRODUCTION

Studies have indicated that considerable promise exists in the use of surface catalysis in the combustion process to reduce the associated pollution.¹ Results have shown that catalytically supported combustion makes possible the efficient burning of a variety of fuels under fuel lean pre-mixed conditions with a substantial reduction in thermal NO_x levels. Surface catalysis is very effective in this application by initiating and speeding up the combustion reactions so that complete combustion can be attained under conditions where stable combustion is difficult or impossible to achieve using conventional combustors.

The principal objective of the present research is to improve the understanding of high temperature heterogeneous catalysis of combustion reactions and the coupling with the homogeneous reactions and the fluid mechanics. Combustion in the laminar boundary layer of a heated flat plate with a free stream flow of premixed fuel and air involves most of the important physical and chemical processes of catalytic combustion systems while providing a geometry which facilitates experimental study and numerical modeling. The experimental configuration used in the present study consists of a thin quartz plate with vacuum deposited platinum heating strips mounted over an open, atmospheric pressure jet of premixed hydrogen and air. Electrical heating of the platinum strips is used to heat the plate surface to temperatures approaching 1400°K. The plate may be used to study catalysis of combustion by a platinum surface, or may be coated with various other catalytic and noncatalytic materials. Current diagnostic techniques include laser-Doppler velocimetry for measurement of velocity, Rayleigh scattering for the measurement of density, and optical pyrometry for measurement of temperature. In addition, a variant of the Schlieren technique known as deflection mapping has given considerable insight into the boundary layer behavior under combustion conditions. Future measurements may include species concentration profiles utilizing Raman scattering of laser light and gas sample probing in conjunction with a gas chromatograph-mass spectrometer system.

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Detailed density measurements were obtained over SiO and SiO_2 "noncatalytic" surfaces and with a platinum catalytic surface for equivalence ratios from 0.0 to 0.3 and plate temperatures up to 1250°K.² Measurements with the silicon dioxide surface indicated no gas phase combustion of lean hydrogen-air mixtures at surface temperatures up to 1250°K. This was determined by comparison of experimental and calculated thermal boundary layer profiles and boundary layer thicknesses. The numerical results show a very marked thickening of the thermal boundary layer in the zone of maximum energy release rate, as

well as a peak in the temperature profile. Neither of these was present in the experimental results. In Fig. 1 thermal boundary layer thickness is plotted as a function of distance from the plate leading edge for equivalence ratios from 0 to 0.1. As shown, the measurements agree well with numerical calculations for no combustion, and thus it is concluded that no gas phase reactions were occurring under these conditions.

Similar results were found with a catalytic platinum plate where no gas phase reaction was apparent up to a surface temperature of 1200°K. However, significant surface combustion was measured at plate temperatures less than 900°K. Preliminary measurements indicate that surface heat release rates can be determined from the change in power input to the plate heating strips as fuel is added. Such measurements will be useful in evaluating the effectiveness of various catalytic surfaces.

The numerical calculations were carried out based on a numerical finite difference solution of the governing differential equations for laminar boundary layer flow and combustion over a heated flat plate.³ A detailed hydrogen-air reaction mechanism with 13 reactions and 8 chemical species was used. Results for a lean ($\phi = 0.1$) H_2 /air mixture over a heated constant temperature ($T = 1100^\circ\text{K}$) noncatalytic plate indicate the existence of several stages of combustion. These include an initial induction period during which

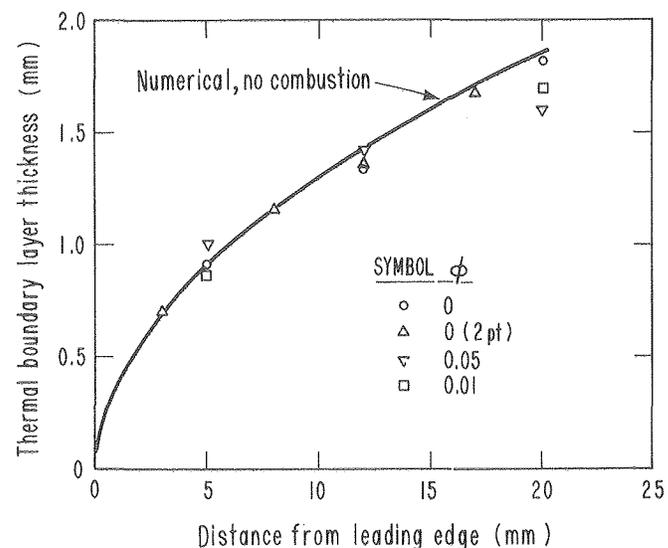


Fig. 1. Comparison of measured thermal boundary layer thickness ($T/T_\infty = 2.0$) at hydrogen-air equivalence ratios of 0.0, 0.05, and 0.10. Silicon dioxide coated plate with surface temperature of 1250°K and free stream velocity 3.17 m/s. Also shown is the numerical result for combustion. (XBL 779-2011)

radical concentrations increase with little associated heat release and a downstream region of rapid heat release during which the boundary layer rapidly thickens. Typical species concentration profiles for this case are shown in Fig. 2 as a function of nondimensional distance above the plate. The results shown are for a distance of 1.98 mm from the plate leading edge.

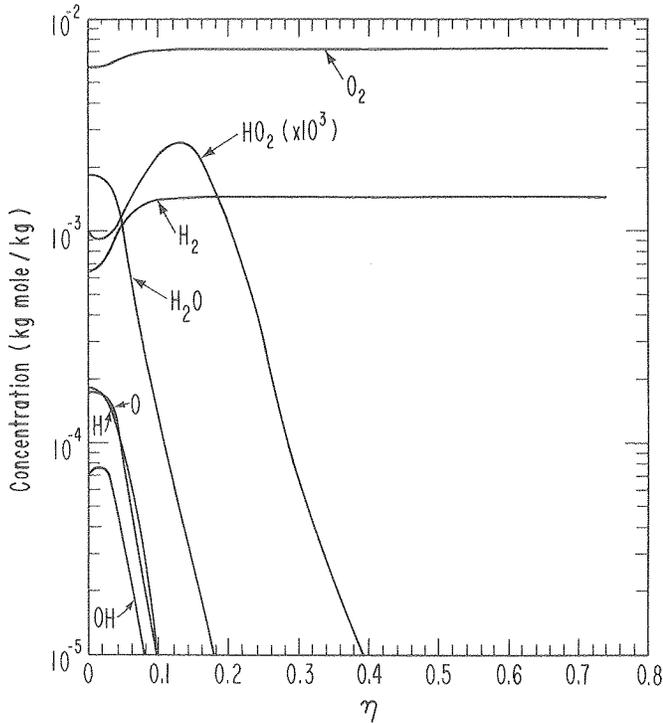


Fig. 2. Concentration profiles as a function of nondimensional distance above plate noncatalytic plate. $X = 1.89$ mm from leading edge. H_2 /air combustion. $\phi = 0.1$, $T_{wall} = 1100K$, $U_\infty = 3.17$ m/s. (XBL 779-2006)

A simplified model was formulated for a catalytic surface based on equilibrium conditions for species diffusing from the surface, and calculations were carried out for the same conditions as with the noncatalytic surface. The equilibrium wall was found to act as a source of radicals very near the plate leading edge. Further downstream it behaves as a sink for radicals and results in a delay of the onset of homogeneous combustion.

PLANNED ACTIVITIES FOR 1978

More extensive data will be taken over platinum and SiO_2 plates. This data will include measurements over a greater range of equivalence ratios and plate temperatures under conditions in which gas phase and surface reactions occur simultaneously. Alternate catalytic and non-catalytic surfaces and additional fuels such as methane and propane will be studied. Further development of data reduction techniques should allow accurate determination of the relative importance of surface as opposed to gas phase reactions and heat release. A more realistic model for surface reaction will also be developed.

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TECHNIQUES FOR THE STABILIZATION OF LEAN COMBUSTION SYSTEMS

J. W. Daily, A. K. Oppenheim, and R. F. Sawyer

INTRODUCTION

A program has been underway for the past three years to study problems associated with stabilizing lean pre-mixed, pre-vaporized gas turbine combustors. The work has focused on the development and utilization of a two-dimensional model gas turbine combustor fitted with quartz side windows which allow optical studies of the combustion phenomena. The combustor itself has a variable fuel inlet system to allow study of separate fuel-air addition and combustion characterizing pre-mixed, pre-vaporized fuel-air

addition. Air preheat of up to 600° Kelvin is also possible to simulate compressor heating. The combustion of lean pre-mixed fuel-air mixtures is of special interest for simultaneous emissions reduction and maintenance of combustion efficiency.

ACCOMPLISHMENTS DURING 1977

A number of experiments have been run using the two-dimensional burner. Initial work involved the mapping of temperature, velocity and composition fields within the burner using conventional probe techniques, flow visualization through

high-speed schlieren motion pictures, establishment of blow-out characteristics, and observation of transient behavior at blow-out. More recent work involves the application of advanced laser-based spectroscopic diagnostics, especially that of Rayleigh scattering density measurements.

The gas turbine combustor test section is constructed so that fuel and air are mixed and passed through a flow straightener. The mixture is then accelerated over a rearward facing step, and a flame is stabilized in the recirculation zone which exists behind the step. Recent work on large scale eddy structures and turbulent shear flows has given a new direction to our understanding of such flow fields. One of the basic findings of this research program has been the firm establishment of experimental evidence for such large scale motion. Analysis of still photographs and high-speed schlieren motion pictures reveals several results, some of which were not expected:

1. Long exposure time schlieren pictures, 20 milliseconds or longer, show a well-defined region immediately behind the step which is commonly referred to as the recirculation zone.

2. Shorter exposure schlieren pictures, 1 millisecond, show a pattern of large eddies which grow downstream to a size of the order of the chamber height and intrude into the recirculation zone.
3. The color high-speed schlieren motion pictures confirm the pattern of the large scale structure observed in the still pictures, and reveal additional details, both qualitative and quantitative, including the formation of the eddies, their shedding frequency spectrum, growth rate, coalescence and intermittent intrusion into the recirculation zone. Flow patterns for both non-reacting and reacting flows have been observed and compared.

PLANNED ACTIVITIES FOR 1978

The study of transient phenomena within the burner is underway. It is anticipated that the information gathered in studying more steady flows will be of help in understanding such transient behavior.

PERTURBATION OF A FLAME FRONT BY A VORTEX SHEET

R. K. Cheng, I. Namer, F. Robben, R. Schefer, and L. Talbot

INTRODUCTION

The propagation of flames in premixed fuel-oxidizer gas in the presence of fluid mechanical turbulence is an important feature of many practical combustion systems. This problem has been studied at some length; however, there is no satisfactory theoretical model for such a flame front, nor is there much experimental data which are able to differentiate between the various theoretical models, or suggest alternative models. The research program summarized here is intended to give greater insight into the interaction of a flame front with a turbulent flow.

Turbulent flow consists of fluctuations in the velocity. The small scale fluctuations may be random and uncorrelated, but, at least in many situations, the larger scale fluctuations consist of vortices which are often well correlated. It is presently popular to refer to this aspect of turbulent flows as "coherent structures." It is also presently believed that combustion and flame propagation in turbulent fluids may be dominated by these larger scale coherent structures. In the present research these vortices are simulated by the Karman vortex sheet shed by a cylinder, which is located upstream of a stabilized flame front in an otherwise laminar flow. Time and space resolved density and velocity measurements are made by laser light Rayleigh scattering and laser Doppler velocimetry, respectively. A phase locked signal averaging technique will be used

to obtain the density and flow fields associated with the disturbance of the flow and flame front by the vortices shed from the cylinder.

Although the experimental data are measured point by point, plotting of these data at a given phase time related to the original and repetitive vortex structure will give a series of "pictures" of the vortex as the flame propagates through it. Such pictures will most likely consist of contour plots of density and velocity at various phase times. Such a complete picture should help evaluate the validity of the wrinkled laminar flame theory as well as lead to a better quantitative understanding of flame generated turbulence and the dilation of eddies as they pass through an oblique plane flame.

ACCOMPLISHMENTS DURING 1977

Most of the experimental facility has been completed and preliminary measurements have been made on two flow configurations.¹ Measurements on a flame stabilized on a heated 0.25 mm platinum wire in a 5 cm open jet showed rather large fluctuations in flame position due to the turbulent mixing eddies at the interface between the jet and the surrounding air. We concluded that this flow configuration would not be suitable for the proposed study. By enclosing the flow in a 5 cm square channel with pyrex walls, the flame stability was greatly increased. In this case, a 3.2 mm rod was used to create a Karman vortex sheet, generated at a frequency of 22 Hz, and measurements of the turbulent density fluctuations

through the flame front were made. Perturbations of the flame front outside and upstream of the region of the vortices in the wake of the rod were found. To our knowledge, such perturbations have not been discussed in the literature. We have attributed them to the overall disturbance of the flow field by the fluctuating flame front.

PLANNED ACTIVITIES FOR 1978

In order to implement the phase locked signal averaging technique, a PDP-11 computer will be used to correlate and signal average the measurements. A hot wire will sense the vortex shedding frequency and phase, and thus give a

time reference for the computer controlled measurements. This hot wire will be located in the wake of the cylinder, upstream of the flame front, and will give minimal disturbance to the flow.

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TURBULENT COMBUSTION IN A BOUNDARY LAYER

R. K. Cheng, F. Robben, R. Schefer, H. Dwyer and L. Talbot

INTRODUCTION

This report presents the status of and the future plans for the study of turbulent combustion in a boundary layer over a flat heated surface. The main objective of this program is to further the understanding of the complex mechanisms involved in combustion in turbulent environments. Our present goal is to look for correlations between the parameters of the coherent turbulent structures and the thermodynamic as well as chemical properties associated with combustion reactions through experimental measurements of density and flow velocity. For this purpose, turbulence will be initiated by controlled sources placed in the stream ahead of or within the boundary layer. These sources will be a vibrating rod or obstacle of some sort. The results should help establish an experimental foundation for the development of numerical models of turbulent combustion processes.

ACCOMPLISHMENTS DURING 1977

The present experimental facility is similar to the one used for the surface catalyzed combustion study. The range of Reynolds numbers possible with a platinum coated quartz plate is too low to approach the transition to turbulence in a viscous boundary layer. We have designed and are constructing a vertical wind tunnel with a 2.5 cm square modular test section where one of the walls will be lined with heating elements to heat the boundary layer. This modular design allows a much greater length for growth of the boundary layer than the flat plate configuration, resulting in larger Reynolds numbers approaching that necessary for transition to turbulence.

Diagnostics involve measurement of flow velocity by hot wire anemometry, laser Doppler velocimetry and laser particle tracking of gas density by Rayleigh scattering of laser light, and of the temperature of the heated surface by optical pyrometry. The measurements will be phase-locked to the disturbance frequency so that the details of the coherent disturbances can be measured.

Some measurements of the velocity fluctuations in a non-reacting turbulent boundary layer have been carried out. Results were obtained using a quartz plate placed in an open air jet of 16 m/sec velocity. A stainless steel wire mesh was attached to the exit of the nozzle to disturb the flow. Velocity profiles of the boundary layer and the fluctuation intensities at different locations along the quartz plate were measured by a hot wire probe. Attention was paid to the growth of the fluctuation intensity as a function of location in the flow field.

A novel diagnostic technique involving photographic particle tracking combined with laser fringe anemometry has been tested in a nonreacting open jet flow as well as in a v-shaped flame stabilized on a heated wire. It was conceived by F. J. Weinberg of Imperial College, University of London, and may be applied to this study. This method is based on using a light sheet from a laser to illuminate light scattering particles seeded in the flow. The light sheet is both separated into fringes and interrupted at a known frequency so that the system can utilize both Doppler fringe anemometry and photographic particle tracking. Particle tracking gives the spatial distribution of velocities at one instant of time, and this type of information complements that obtained simultaneously from laser Doppler anemometry. Results of particle tracking in a v-shaped natural gas-air flame stabilized on a heated platinum wire is shown in Fig. 1.

PLANNED ACTIVITY FOR 1978

The vertical 2.5 cm square wind tunnel will be completed in the early part of 1978. Detailed velocity and density data will be obtained in the disturbed boundary layer over a non-heated, heated, and heated-with-combustion surface. These data will be checked for similarities in well-known dimensionless variables and analyzed to seek correlation with parameters such as disturbance frequency and combustion heat release.

A larger horizontal combustion wind tunnel will be designed with a channel about 12 cm square and one heated wall. This configuration will result in

boundary layer Reynolds numbers greater than 10^5 , so that measurements on coherent disturbances can be made in the range of transition to turbulence.

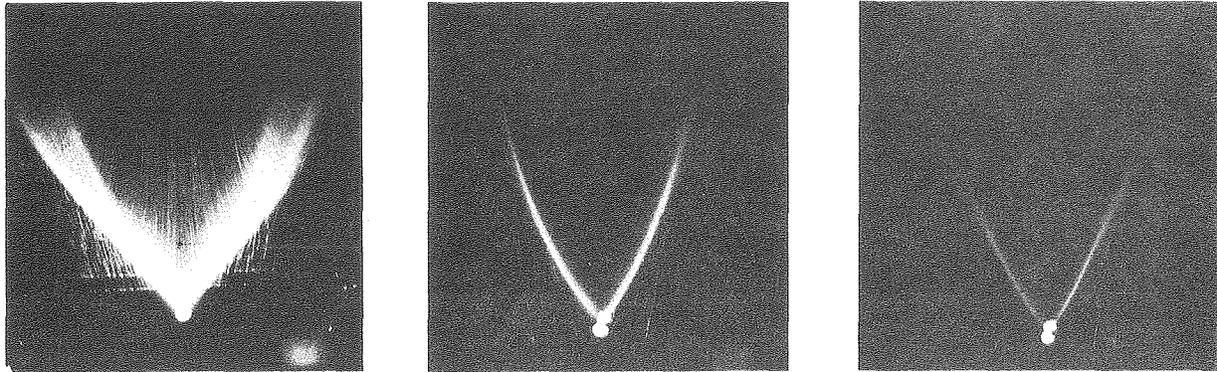


Fig. 1. Records of particle tracking in a V-shaped flame taken at three different exposure times (from left to right 1/2, 1/10, 1/25 sec) to vary particle track density. (XBB 782-2364)

NUMERICAL STUDIES OF LAMINAR AND TURBULENT COMBUSTION

A. J. Chorin, P. Concus, and P. Bernard

INTRODUCTION

In these studies we are developing computational techniques for analyzing turbulent combustion phenomena, such as those that occur in an internal combustion engine. Our goal is the construction of realistic models that are suitable for comparison with experiment and are capable of being used for design purposes. The specific features of the methods we are developing are (1) the use of sampling and random choice procedures and (2) the use of "dictionaries" of known phenomena as building blocks in the numerical schemes. These features allow us to overcome the major difficulties that have hindered the application of other numerical techniques to the study of physical combustion phenomena. Our methods, unlike others, have little or no numerical diffusion (and thus no cell Reynolds number restrictions), i.e., they can deal realistically with high Reynolds number flow. Because they are based on sampling rather than averaging, they can take into account the effect of organized structures (coherent eddies) in a flow. This feature is very important because real chemical phenomena are greatly affected, perhaps even determined, by the existence of coherent eddies and will not be accurately modelled if these coherent eddies are not taken into account.

ACCOMPLISHMENTS DURING 1977

We have continued to work on the development of random choice and random vortex methods for the analysis of turbulent and/or combusting flow. A coarse graining method, which represents a substantial advance over previously available methods, has been developed.¹ A new version of the vortex method, more accurate and computationally more

efficient than previous versions, has been developed and analyzed.^{2,3} These two methods have been combined in a computer program that analyzes turbulent boundary layers and bursting sequences for flow in a model cylinder-piston assembly. This is the first such program ever written capable of performing these calculations. It was observed that the bursting sequences dominate the turbulence and are the probable origin of intermittency in the flow.

PLANNED ACTIVITIES FOR 1978

Computer programs are being written for studying turbulent and laminar fluid transport based on the methods we have developed which do away with the introduction of artificial numerical diffusion. We plan to incorporate into these programs the means for solving numerically the ordinary differential equations of chemical kinetics so that chemically reacting flows can be treated. We expect to initiate a substantial and coordinated effort to model flows of practical interest, e.g., flow in the interior of a motored internal combustion engine and flow induced during a jet ignition process. We expect to work closely in this effort with experimentalists and engineers.

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NUMERICAL ANALYSIS OF FLOW FIELDS GENERATED BY ACCELERATING FLAMES

J. Kurylo, H. A. Dwyer, and A. K. Oppenheim

INTRODUCTION

The specific problem with which we are concerned is: steady flame propagates in an essentially unconfined combustible gas mixture. At a given moment its speed changes abruptly. The question is what happens then? The disturbances associated with this process may trigger the transition to detonation or they may die down leading eventually to the establishment of another steady state solution. Since the outcome depends on the law governing the flame propagation speed, while the experiments are relatively easy to perform, and a good deal of data on the transition to detonation in gaseous media is available in the literature, the numerical technique we are presenting should be instrumental in revealing such laws under a variety of conditions of practical interest. The phenomenon of a relatively rapid change in the flame propagation speed is well established in combustion literature. It is due to the effects of turbulence, and it has been exploited for many years in the form of the so-called Shchelkin turbulizers used in detonation research. More recently it has been employed by Wagner and his associates¹ for the study of unconfined explosions.

ACCOMPLISHMENTS DURING 1977

A new computational technique has been developed taking into account sharp discontinuities and their interactions, since their existence has been so prominently established by optically recorded experiments pertaining to this field of study.²⁻⁴ For this reason the algorithm is set in Eulerian coordinates and is based on the use of a floating shock fitting technique⁵ that has been generalized to treat all the discontinuous wave processes that can occur in the flow field. The basic algorithm used in this connection is that of MacCormack,⁶ a non-centered difference scheme applied to conservation equations expressed in divergence form. The technique consists of predictor and corrector steps made, respectively, on a simple forward and backward difference scheme of first order accuracy, while the combined two-step process has a second order accuracy.

The computational scheme is capable of treating four types of discontinuities: shock waves, contact surfaces, deflagrations, and detonations. If these discontinuities propagate without interacting with each other nor with a plane, line, or point of symmetry, they are considered to be well separated and their position in the flow field established by the floating discontinuity technique. According to our algorithm, a discontinuity requires six to

eight spatial grid points for its handling. This set of points defines its zone of influence. For each type of discontinuity, the computations handle such a zone with subroutine.

Of particular importance in the computational scheme is proper handling of deflagrations since the differentiating algorithm of the conservation equations cannot be applied across them. Through preliminary studies we have found that most of the difficulties are obviated by making sure that deflagration fronts are treated as discontinuities that always pass through computational grid points. This principle has been adopted as one of the keys of our technique: at each time interval the Eulerian computational grid is shifted throughout the whole flow field so that it moves with the velocity of the deflagration.

When the discontinuities are not well separated and their zones of influence tend to overlap, more elaborate differentiating algorithms are required in order to make sure that differentiation, applicable only to continuous portions of the flow field, are not carried out across a discontinuity.

The strategy adopted for the application of our technique is as follows. First the time-step is computed by the Courant-Friedrichs-Lewy stability condition, assuring that the numerical domain of dependence at every point in the flow field includes that of the set of hyperbolic partial differential equations governing the solution. Gas-dynamic parameters for all grid points of the flow field at the next time interval are then computed by applying the MacCormack predictor-corrector scheme as if there were no discontinuities involved in the problem. The types of discontinuities present in the flow field are then identified and located. By the use of appropriate subroutines the motion of the discontinuities and the flow fields around them are thereupon determined.

When the discontinuities tend to interact, subroutines for treating multi-discontinuity systems are invoked. After the interaction has terminated and the discontinuities become well separated, their positions are properly reordered and the computations continued in a routine manner.

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STRONG IGNITION LIMITS FOR METHANE-HYDROGEN MIXTURES

R. K. Cheng and A. K. Oppenheim

INTRODUCTION

This program pertains to dynamic properties of combustion in a homogeneous gas mixture. When such mixtures are brought uniformly and rapidly to a state of high temperature by a shock wave, they can either generate a blast wave or burn without exhibiting any gas-dynamics effects. The strong ignition limit is a line of demarcation between the two cases. It is usually expressed in terms of a curve on the plane of pressure and temperature of states at which the induction process takes place. The limit is determined experimentally by the use of the reflected shock technique. As a useful and essential by-product, induction time data are obtained. The strong ignition limit is, in effect, a specific measure of the capability of a given combustible gas mixture for transition to detonation and hence of the tendency to knock. This is relevant to a wide variety of combustion phenomena ranging from unconfined explosions on one hand, and reciprocating internal combustion engines on the other.

The gas-dynamic properties of exothermic processes induced behind reflected shocks have been explored in a program of studies conducted in the 1970's at the University of California, Berkeley. The structure of the flow field generated by the exothermic process associated with strong ignition was determined for hydrogen and for methane. Experimental observations were made by means of cinematographic laser schlieren and interferometric techniques. Their prominent features were confirmed by computations based on the currently available chemical kinetic data. On the basis of experience thus acquired, a simple experimental technique was developed for the determination of the strong ignition limit and the concomitant measurement of induction times. The latter involves the use of piezo-electric pressure transducers as time of arrival meters for fronts of pressure waves generated by the exothermic process.

ACCOMPLISHMENTS DURING 1977

A systematic investigation has been carried out of the strong ignition limit in a two-fuel system, methane and hydrogen. The scope of our experimental program covers a full range of compositions including two methane-oxygen mixtures, two hydrogen-oxygen mixtures, and seven different methane-hydrogen-oxygen mixtures, all diluted by 90% argon. A composition diagram for all the eleven test mixtures used is given in Fig. 1. Initial conditions behind the reflected shock

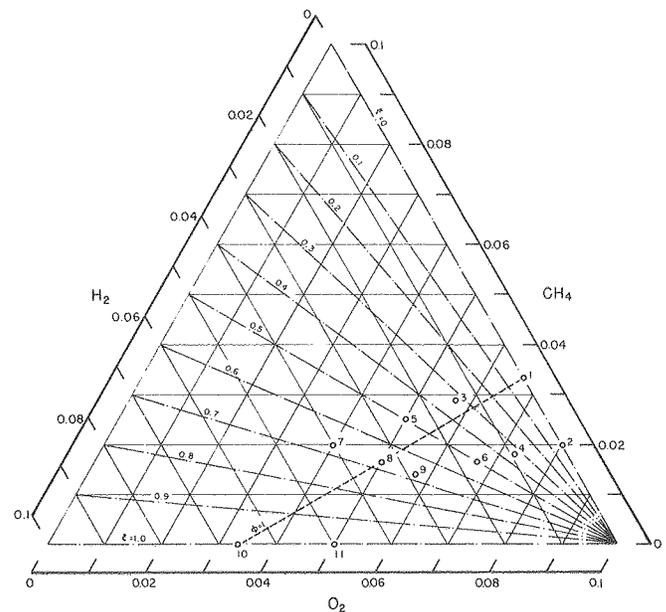


Fig. 1. Mixture compositions. (XBL 782-7388)

were in the range of 800°K to 2500°K in temperature and 1.4 atm to 3 atm in pressure. In all, some 800 viable experimental runs were performed. The gasdynamic effects of combustion were observed for a number of experimental cases by cinematographic laser schlieren and interferometric techniques, while the bulk of data was deduced from pressure transducer records.

Strong ignition limits for all the test mixtures are shown in Fig. 2. The numbers refer to compositions specified in Fig. 1. Continuous lines represent experimental data reduced by non-linear regression. The chain-broken lines are the classical "explosion" limits, the lower bounds of self-sustained exothermic reactions. The broken lines were obtained from correlation formulae.

As manifested by our results, the addition of hydrogen has a significant effect on the strong ignition limit of methane, lowering considerably the temperature level at which it occurs.

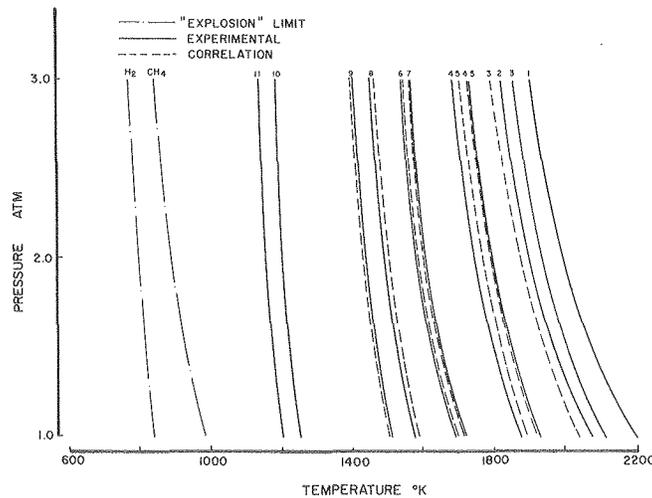


Fig. 2. Strong ignition limits. (XBL 782-7387)

LASER-INDUCED FLUORESCENCE SPECTROSCOPY APPLIED TO TURBULENT COMBUSTION FLOWS

J. W. Daily and C. Chan

One technique that shows great promise as a diagnostic tool for measuring species concentrations is that of laser-induced fluorescence spectroscopy (LIFS). The method consists of illuminating the gas with a laser source tuned to an absorption line of the species of interest. The molecules are excited, re-radiating spontaneously, and fluorescence is observed at 90° to the laser beam. The beam diameter and the collection optics define the spatial resolution which may be as fine as 0.1 to 0.5 mm.

Our work has proceeded in three areas. The first deals with the use of saturated fluorescence to measure species concentrations in flames. The second has been the study of chemical decay processes by observing fluorescence decay. The third has been the study of the collisional redistribution process and near resonant Rayleigh enhancement.

The primary difficulty with using laser induced fluorescent spectroscopy to make density measurements has been that collisional de-excitation in high pressure flames completely dominates radiative de-excitation causing fluorescence quenching. In our work we have overcome this difficulty by using a laser source of sufficient intensity to saturate the exciting transition. Preliminary work with sodium has demonstrated the feasibility of the technique, and linear curves of growth for sodium atom concentration have been obtained. The dynamic range of the measurement is approximately two orders of magnitude, limited at low number

densities by detectability limit considerations and at high number densities by radiative trapping.

Chemical reaction rates of the excited species may be examined by the fluorescent technique. If the characteristic decay time for the species of interest is of comparable length to the exciting pulse, chemical decay may be observed directly. We have observed such decay and are in the process of making measurements for a range of flame conditions.

One problem that exists for atomic fluorescence spectroscopy is that fluorescence trapping severely limits the dynamic range. One potential method for overcoming this limitation is to observe the enhanced Rayleigh scattering near resonance, rather than the fluorescence signal itself. If the laser is detuned from resonance slightly, then the spectrum of the scattered light consists of a Rayleigh scattering line at the laser frequency, a fluorescent signal which is caused by collisional redistribution of energy to the resonant state, and perhaps a three photon signal if the laser intensity is sufficiently large. We have observed the Rayleigh and the resonance peaks in sodium in flames. We have demonstrated that the Rayleigh component is not significantly trapped at number densities much higher than that for which fluorescence trapping becomes important.

We are now presently examining the use of laser induced fluorescence spectroscopy to measure radical species concentrations in flames and to study chemical reaction rates of such species.

REACTIVE AND INELASTIC SCATTERING OF H₂ + D₂

N. J. Brown and D. M. Silver*

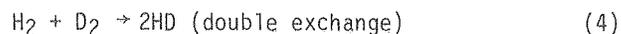
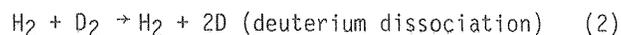
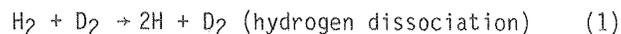
INTRODUCTION

Combustion science is concerned with chemistry and fluid mechanics and the coupling between them. A detailed knowledge of combustion chemistry remains elusive since multistep mechanisms prevail and individual reaction steps are difficult to isolate for experimental study. The application of theoretical kinetics to combustion chemistry has been rather limited relative to the experimental effort; however, some theoretical considerations are often used to eliminate potential reaction steps in a proposed chemical mechanism. One such idea is that bimolecular reactions between stable molecules generally have high reaction barriers, and thus relatively small rate coefficients. This idea has been challenged for simple exchange reactions.¹ To further investigate the feasibility of such bimolecular reactions, a theoretical study of a prototype reaction, H₂ + D₂ exchange, was undertaken.

This four part study involved the construction of four H₄ potential energy surfaces and the investigation of the inelastic and reactive scattering of H₂ + D₂ on them. The dynamics are treated quasi-classically and this formalism incorporates the following three approximations: (1) treating the dynamics with classical mechanics, (2) restricting initial molecular energies to experimentally determined eigenenergies, and (3) using Monte Carlo techniques to compute average final state properties of several collisions with identical initial energy configurations. The results of the scattering study are presented in terms of reaction probabilities, average final state properties of the molecules, and average final state energy distributions. The effects of alignment and surface properties are examined.

The initial study² of this set made use of a simple model potential energy surface of the London type which had an anomalously low reaction barrier (when compared to *ab initio* results) in the square planar saddle point configuration. This type of surface has become increasingly popular for molecular scattering calculations because of its relative ease of construction. Hence the purpose of this particular study was to provide a prototype calculation of a bimolecular reaction process occurring on a London surface. The total system energy considered in the study was less than the H₂ dissociation energy. The only reaction observed was the four center exchange reaction forming two HD molecules, and the probability of this reaction decreased with increasing initial vibrational energy since vibrational energy decreased the probability for the favored reaction geometry.

A second study employing a semi-empirical valence bond type surface was conducted at total energies of 150 kcal/mole. Four reaction paths were found.



The particular path followed by the reactants was found to be extremely sensitive to the system's initial energy configuration. In general, total reactivity was directly related to the amount of initial vibrational energy in the system, and specific reactivity along the four paths was related to the distribution of initial vibrational energy between the reactant molecules.

ACCOMPLISHMENTS DURING 1977

Three potential energy surfaces have been computed using valence bond theory to generate a simple model wave function. The surfaces are constructed using the semi-empirical treatment of the London-Eyring-Polanyi-Sato type, but modified to include all overlap and multiple exchange integrals. Different parameterizations have been used to generate the three surfaces. The surfaces are compared with *ab initio* results and, in the limit of removing one of the atoms to infinity, to H₃ results. Figure 1 shows a projection and equi-potential contour map for the London and one of the valence bond surfaces for the rectangular arrangement of four atoms. The contour intervals are one-tenth of the H₂ dissociation energy. The two surfaces are drawn to identical scale.

The results of a comparative scattering study investigating reactivity and energy transfer on the three valence bond surfaces and on a London surface have been analyzed. The calculations were performed at energies greater than the dissociation energy of molecular hydrogen. Reactivity and energy transfer characteristics have been related to surface properties. It is anticipated that two papers describing this work will be completed and submitted for publication.

FOOTNOTE AND REFERENCES

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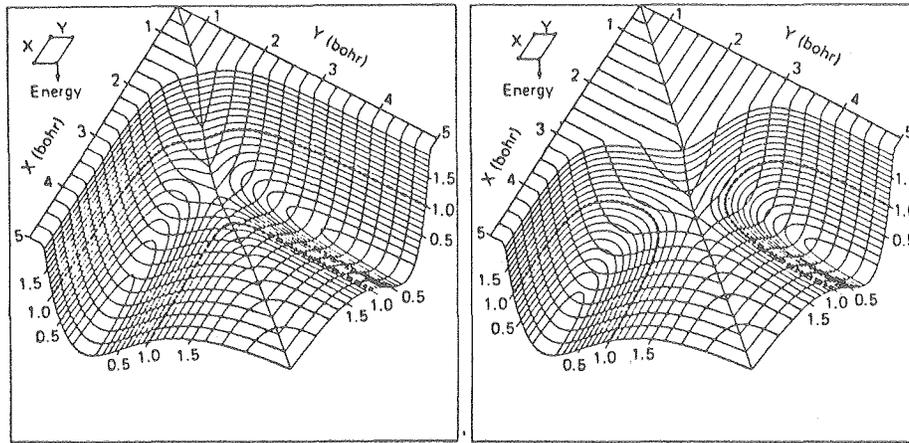


Fig. 1. Projections of Equi-potential contour maps for a London and valence bond semi-empirical H_4 potential energy surface.

JET IGNITION STUDIES

A. K. Oppenheim, F. C. Hurlbut, F. A. Robben,
K. Teichman, K. Hom, and H. E. Stewart

INTRODUCTION

Practically all combustion systems used today are, in effect, mixing controlled. In most, fuel is either introduced into the combustion chamber separately from air or it is deliberately not mixed well so that the process by which the two are brought in contact with each other is significantly slower than the chemical reaction of combustion and can serve, therefore, as means for control. Such systems have the unfortunate attribute of automatically adjusting themselves so that the production of pollutants is maximized. The flame front, where the exothermic reaction is initiated, establishes itself at the stoichiometric contour, promoting the attainment of a maximum possible temperature that enhances the generation of the largest quantity of nitric oxide. This is true, irrespective of the overall fuel-air ratio at which the system operates. Moreover, in approaching the flame in the absence of oxygen, the fuel pyrolyzes to unburned hydrocarbons and soot.

This state of affairs exists whenever there is insufficient time for fuel to vaporize and diffuse uniformly throughout the oxidant prior to the exothermic process of combustion. One could improve the situation, therefore, by the development of systems where the fuel is pre-vaporized, the reactants are premixed and preheated while combustion occurs in the presence of as much diluent, provided by excess air and exhaust gases, as is necessary in order to maintain the maximum temperature at an optimum level for efficient operation of the energy conversion system for which the combustor serves as the heat source.

Work on the development of such systems is currently in progress. The major problems

encountered are due to the progressively more difficult ignition and slower combustion process as the amount of diluent in the pre-mixed combustible medium is increased. We intend to supply the background knowledge required to solve these problems.

In spark ignition engines using near stoichiometric mixtures, combustion is initiated at a point by a relatively weak spark forming a single laminar flame kernel. With the use of significantly leaner mixtures, weak spark discharge is insufficient for ignition and, as a consequence of a lower temperature level due to dilution, the laminar flame, even if successfully initiated, would be too slow for satisfactory operation. One has to resort to other means that provide zonal or multi-point ignition sources so that, by creating a multitude of flames, sufficiently high overall rate of combustion can be achieved in spite of the relatively low individual flame speed. In principle this can be accomplished by the use of jets of active radicals that offer the prospect of sufficiently good penetration and distribution of ignition sources for such purpose.

The fact that jets of active radicals offer attractive means for ignition of lean mixtures has been known for quite some time and the technical literature is full of publications bearing evidence of this fact. Most of these publications are primarily concerned with the operation of some particular device; relatively few of them report studies on fundamental properties of such ignitions systems. Jet ignition can be considered as an advanced version of the stratified charge concept. The main difference is that, instead of a flame torch--a typical feature of conventional stratified charge systems--jet ignition is based on the use of distributed active radicals. There are two ways by which the

radicals can be generated: by combustion or by electrical discharge.

Combustion generated radical jet ignition has been developed at the Institute of Chemical Physics in Moscow on the basis of theoretical studies by Semenov¹ and the experimental research program conducted by Gussak.^{2,3} Semenov presents his theory in three parts. First he sets out the fundamental concepts by which he demonstrates that chain kinetic processes, in their simplest cases, constitute autocatalysis by ultimate products. Secondly he considers the limitations imposed by the interaction between active particles, and thirdly he analyses wall effects. The work of Gussak and his associates at the Institute led to the establishment of the concept of Avalanche Activated Combustion (or LAG, its acronym in Russian), and to the development of a variety of practical devices for its technological realization. As its name implies, the LAG process is based on the exploitation of active radicals to provide an abundance of chain carriers, especially hydrogen atoms, that significantly enhance the chain-branching steps and, hence, the rate of the reaction at relatively low temperatures corresponding to combustion of mixtures whose composition is far from stoichiometric proportions. In order to generate the radicals, the process is based on the use of an extra-rich mixture (equivalence ratio of an order of 2) in a pre-combustion chamber, while the charge in the main chamber can be ultra-lean (equivalence ratio of 0.5, or less at part loads). An investigation to test the viability of the LAG process in an internal combustion engine, conducted at General Motors, demonstrated its positive effect on the reduction of emissions of carbon monoxide and oxides of nitrogen, but was otherwise inconclusive.

A considerable amount of work has been done on the development of plasma jet ignition systems for automotive applications. A fundamental program of studies of plasma jets has been carried out by Weinberg and his associates at the Imperial College, University of London. After laying the groundwork in a book on electrical aspects of combustion,⁴ Weinberg conducted a study of the effectiveness of different plasmas for enhancing combustion rates in a steady flow system. Under investigation at the same time was the effect of mixing, achieved by the use of a magnetic field, both to sustain combustion under stirred flow conditions and to enhance ignition. Nitrogen was found to be most effective for flame stabilization under steady flow conditions. Its plasma was subsequently demonstrated to provide practical means for the removal of soot and the reduction of NO concentration in exhaust products. In a parallel study to that reported here, in which Weinberg collaborated with us, distinct effects of various chemical species used for the plasma jet on the ignition of an ultra-lean methane-air mixture were observed, with methane showing clear superiority in this respect over hydrogen and nitrogen.

ACCOMPLISHMENTS DURING 1977

Preliminary experiments were carried out using a cylindrical, stainless steel vessel, fitted with optical glass windows 9 cm in diameter at a distance of 9 cm between their inner faces. Figure 1 is a photograph of the vessel showing at the right the instrument plug, fitted with inlet tubing for the test gas, and the plasma plug on top.

The combustion radical jet generator is shown in Fig. 2. Its body is made out of hexagonal steel stock, and the combustion chamber it provides is in the form of a cylinder 45 mm long and 3.6 mm in diameter; the effective volume of the gas used for the generation of the jet is thus 460 mm³. For a stoichiometric methane-oxygen mixture we used, at a pressure of 1 atm and a temperature of 20°C, this corresponds to 5J of energy expended for the projection of the jet.

The plasma radical jet generator is shown in Fig. 3. The unit consists of the electrode and porcelain insulator of a Champion J-61Y spark plug which is fitted into a teflon insert, forming the side-walls of the discharge chamber; the main body and the bushing holder on top were made out of brass. The discharge chamber is cylindrical in shape, 6.1 mm long and 2.4 mm in diameter, providing a volume of 28 mm³ for the gas used in the production of the production of the plasma jet. At the exit, the plasma generator is furnished with an orifice plate which is attached to the body by three small screws. For the current study we employed primarily an orifice 1.2 mm in diameter, while an alternative one 2 mm in diameter was used only to investigate the influence of its size on the properties of the jet.

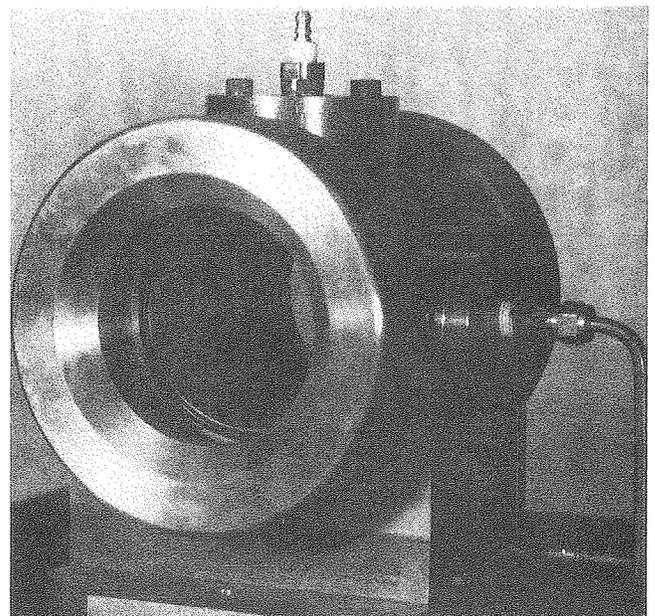


Fig. 1. Explosion vessel.

(XBB 782-3371)

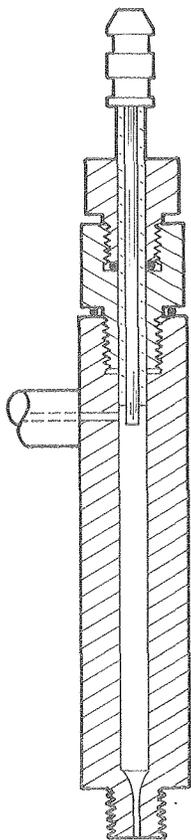


Fig. 2. Combustion jet generator. (XBL 782-7381)

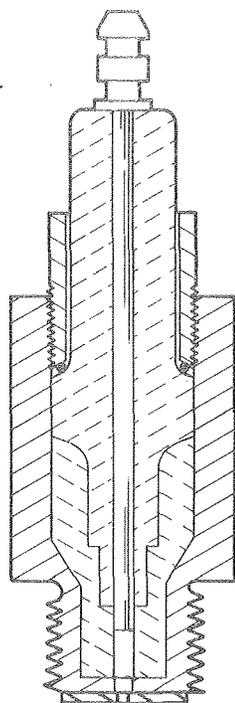


Fig. 3. Plasma jet generator. (XBL 7711-11333)

Major results of the preliminary studies are in the form of schlieren flash photographs obtained with an open shutter camera using a sub-microsecond spark discharge in air as a point light source. An example of such records is shown in Fig. 4. The figure consists of a set of four photographs depicting a sequence of events taking place under the same operating conditions. Each of them was taken from a different experiment, and the sequence obtained by shifting the time delay used for triggering the light source, while the vessel was filled initially with a methane-air mixture at atmospheric pressure and room temperature. The equivalence ratio of the mixture was 0.5, corresponding to 5% volumetric fraction of methane. Under such conditions this was below the normal flammability limit which, according to data of the U. S. Bureau of Mines, is at 5.3%. The orifice diameter was 2.4 mm while the energy discharged in the plasma generator was 2.5 J. The first photograph was taken 1 msec after the discharge was initiated. Here one observes the turbulent plume propagating towards the center of the enclosure. Superimposed on it is the direct image of the light emitted by the jet due to the illumination of the plasma. In the next photograph taken at 10 msec, the combustion has started, appearing in the form of a turbulent flame kernel. In the next frame, at 50 msec, the combustion front acquired a laminar flame structure, and, in the last frame at 100 msec, it reached the walls of the vessel.

Our preliminary studies of jet ignition have led to the following conclusions:

(1) If the initial velocity of the jet is sufficiently high, its gasdynamic properties are, in general, the same, irrespective of whether it has been formed by combustion or by electric discharge.

(2) The jets enter the combustion chamber in the form of turbulent plumes which are embedded in blast waves headed by hemispherical shock fronts.

(3) The blast wave effects are dissipated by the time combustion starts. The latter always occurs in the turbulent zone of the plume.

(4) Combustion is initiated as a set of turbulent flames which later tend to acquire a more laminar structure. This is in direct contrast to the sequence of events associated with spark ignition.

(5) The depth of penetration of the jet depends on its initial velocity, which can be controlled by the specific energy used for its production as well as by the size of the orifice through which it is injected.

To sum up, insofar as its fluid mechanic properties are concerned, jet ignition offers the following advantages:

(a) A controllable depth of penetration, providing the capability for starting the combustion process at any desired location within the charge

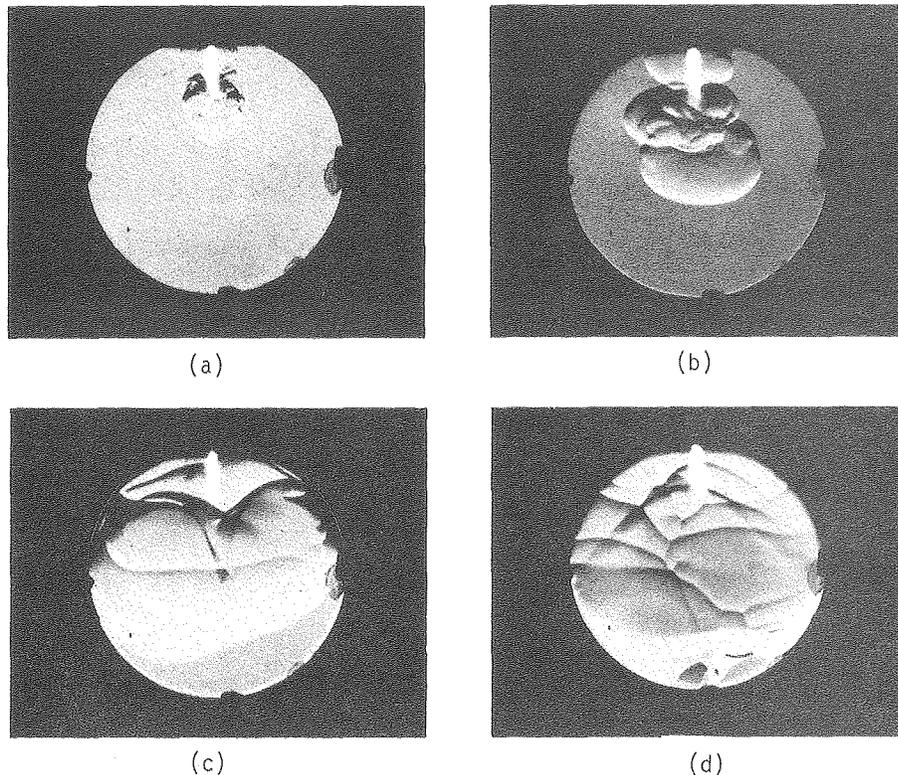


Fig. 4. Schlieren flash photographs of events associated with ignition produced by plasma jet. Discharge energy: 2.5J, Orifice diameter: 2.4 mm. (a) 1 msec, (b) 10 msec, (c) 50 msec, (d) 100 msec.
(XBB 782-2372)

and, in particular, protecting the process from the destructive effects of walls.

(b) Zonal pre-turbulization, furnishing optimum conditions for ignition and thus enhancing the combustion of lean mixtures.

(c) Wide dispersion of ignition sources, yielding multi-point initiation of combustion--a feature of particular importance to lead mixtures for it yields high overall rates in spite of relatively low individual flame speeds.

PLANNED ACTIVITIES FOR 1978

The major effort in the next phase of this research program is to be spent on a systematic study of the fluid mechanic properties of the jets and their effectiveness as ignitors.

The combustion generator investigation will include the following effects:

- (1) chemical composition of fuel,
- (2) chemical composition of oxidizer--ranging from pure oxygen to air--and its relative amount, the equivalence ratio,
- (3) method of ignition--single or multi-source,
- (4) pressure and temperature of combustion products ahead of the ejection nozzle,

- (5) shape and size of the ejection nozzle and its orientation at the exit, as it governs the formation of the shear layer--the actual source of turbulence.

The plasma generator investigation will focus on the following features:

- (1) size and shape of the discharge cavity,
- (2) size of orifice controlling the momentum of the jet
- (3) net amount of electrical energy expended in the discharge,
- (4) shape of the discharge power pulse and its duration,
- (5) electro-magnetic stirring or expulsion
- (6) chemical composition of medium used for the production of plasma.

The most important properties of the process of jet ignition are chemical in nature. These will be studied by two associated programs of research. One will concentrate on optical measurements using conventional spectroscopy at first and later, as they become available, laser-based fluorescence and scattering techniques. The other will be concerned with the measurement of time-resolved local concentrations using a molecular beam sampling technique associated with a quadrupole mass spectrometer. This strategy is based upon the premise that non-interactive laser-based instruments are not

yet developed to a point where they can be relied upon for a program of studies involving the acquisition of knowledge about a novel process, such as ours. Hopefully, they may become available in time for our experiments to serve as a convenient proving ground for testing their performance.

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ENGINE COMBUSTION WITH EXCESS AIR

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INTRODUCTION

A square piston, single-pulse, compression-expansion machine has been employed to study reciprocating engine combustion under well controlled laboratory conditions simulating the operation of a spark ignition engine. The single-pulse machine, built by researchers in the Department of Mechanical Engineering, has the unique feature of providing optical access to the entire combustion process. This work was originally sponsored by the National Science Foundation/Research Applied to National Needs but during 1977 came under Department of Energy support. Current studies are on the combustion of lean mixtures because of the advantages such mixtures offer in terms of increased fuel economy and reduced pollutant emissions in comparison with conventional engine combustion which occurs at mixture ratios near to the stoichiometric amount.

The research is being conducted under four major tasks: (1) ignition process, directed by Professor A. K. Oppenheim, (2) flame propagation phenomena, directed by Professor R. F. Sawyer (who also serves as principal investigator for the project), (3) wall quenching processes, directed by Professor John W. Daily, and (4) heat transfer phenomena, directed by Professor R. Greif. In all cases the recording of the combustion events through high speed schlieren cinematography provides detailed information on the complex engine combustion processes. In all cases methane has been used as a model hydrocarbon fuel because of the information available on its oxidation kinetics.

ACCOMPLISHMENTS DURING 1977

Studies of ignition processes have demonstrated the ability to ignite mixtures beyond their ordinary lean flammability limits through use of both chemical and plasma torch igniters. Detailed information on jet ignition is presented in the preceding article.

A postulated process of "bulk quenching," which is brought about during the piston expansion period in the combustion of mixtures near the lean flammability limit, has been observed and measured. Such processes, which prevent the completion of combustion and result in reduced efficiency and increased hydrocarbon emissions, present a constraint upon the operation of "lean burn" engines. This work has included a cooperative effort with the Lawrence Livermore Laboratory which has provided a computer based model of the quench model.

A second and generally dominant mechanism controlling the emission of hydrocarbons from engines is the quenching of combustion in a thermal boundary layer which is a necessary consequence of cold combustion chamber walls. This boundary layer is scraped off the wall into a vortex through the motion of the piston. The nature of this "roll-up" vortex has been observed to be strongly influenced by the piston and cylinder head geometry.

Unsteady, time-resolved heat transfer to the end wall of the combustion chamber has been measured using a thin-film platinum resistance thermometer during the combustion stroke without combustion. A theoretical laminar boundary layer model is in good agreement with the experimental observations. Time varying heat transfer coefficients are extracted from the heat flux data and show a non-monotonic variation.

PLANNED ACTIVITIES FOR 1978

Ignition studies are focused on gaining an understanding of the importance of radical species produced in the plasma to the initiation of the combustion processes. Flame propagation studies are to be extended to a range of hydrocarbon fuels with the objective of providing energy release rate data of use to combustion chamber design. Wall quenching studies will focus upon the fate of the roll-up vortex produced during the exhaust stroke. Heat transfer measurements are being extended to cases with combustion.

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