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(NASA-CR-162284) AIR POLLUTION FROM  
AIRCRAFT Final Report, Feb. 1969 - Oct.  
1978 (Massachusetts Inst. of Tech.) 43 p  
HC A03/MF A01 CSCL 13B

N79-31840

G3/45 Unclas  
35761

# AIR POLLUTION FROM AIRCRAFT

Final Technical Report on  
NASA GRANT NGR 22-009-378\*

February 1969 - October 1978

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June 26, 1979



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## 1. BACKGROUND

This report summarizes technical aspects of work conducted on NASA Grant NGR 22-009-378. The grant was initiated at MIT in 1969 to study the production and dispersion of pollutants from aircraft jet engines. In the course of the grant, a series of basic problems have been examined. Work completed at MIT includes an analysis of the soot formation and oxidation rates in gas turbine combustors, modelling the nitric oxide formation process in gas turbine combustors, a study of the mechanisms causing high carbon monoxide emissions from gas turbines at low power, an analysis of the dispersion of pollutants from aircraft both around large airports and from the wakes of subsonic and supersonic aircraft, a study of the combustion and flow characteristics of the NASA swirl can modular combustor and the development and verification of  $\text{NO}_x$  and CO emissions models, an analysis of the influence of fuel atomizer characteristics on the fuel-air mixing process in liquid fuel spray flames, and the development of models which predict the stability limits of fully and partially premixed fuel-air mixtures:

In addition to this work at MIT, an extension to the program in July 1973 was approved by NASA to support more detailed experimental studies of the swirl can module wake region in the Fuel Technology Laboratory at the University of Sheffield. This program complemented and extended the MIT program, by providing substantial new information

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In addition to this work at MIT, an extension to the program in July 1973 was approved by NASA to support more detailed experimental studies of the swirl can module wake region in the Fuel Technology Laboratory at the University of Sheffield. This program complemented and extended the MIT program, by providing substantial new information

on the atomization and fuel distribution characteristics of the swirler assembly, on the detailed flow pattern in the module wake, and on the species concentration distributions and the extent of spatial fuel-air ratio non-uniformities in the region where most of the  $\text{NO}_x$  emissions are formed. Included in this activity were the development of several new diagnostic techniques.

## 2. TECHNICAL SUMMARY OF WORK AT MIT

### 2.1 Pollutant Formation Mechanisms in Gas Turbine Combustors

A major part of the research supported by this grant was devoted to developing models of the mechanisms by which soot, nitric oxide (NO) and carbon monoxide (CO) form inside a gas turbine combustor.

The formation and oxidation of soot under conditions typical of jet engine combustors was examined at an overall and then fundamental level. A review of conditions--local fuel-air equivalence ratio, pressure and temperature--inside a typical combustor relative to factors known to be important for soot formation in simple laboratory flames confirmed which zones within the combustor were critical in the soot formation process. A fundamental study of soot formation in shock heated premixed fuel-air-diluent mixtures in a shock tube for selected gaseous hydrocarbon fuels showed that the critical carbon:oxygen molar ratio above which soot formation occurred increased with increasing temp-

erature. Thus data obtained in laboratory flame studies with ambient temperature air should be extrapolated to gas turbine combustor conditions with considerable caution.

In a series of studies of the soot oxidation process, several proposed kinetic models of soot oxidation were applied to gas turbine combustor conditions. A model developed for pyrographite oxidation where the oxidation rate depends on the partial pressure of  $O_2$  and the temperature, was shown to fit the more limited flame-based soot oxidation models. It predicted that within a gas turbine combustor, maximum burn-up rates occurred for the fuel-air equivalence ratio between 0.7 and 0.8.

Extensive work was done on the mechanism of nitric oxide (NO) formation. A kinetic model for the formation process with an appropriate set of assumptions for the high pressure, high temperature gas turbine context was developed. Using simple reactor flow models for the major regions of a combustor, the effects of compressor exit air temperature and pressure, fuel-air equivalence ratio, residence time and nonuniformities in fuel distribution were examined. The effect of nonuniformities in equivalence ratio in the burned gases was shown to be an especially important factor in determining the variation in  $NO_x$  emissions with overall fuel:air ratio. A stochastic mixing model which permits these nonuniformities to be incorporated into the reactor flow models, and simulates the coupled turbulent mixing and chemical reaction processes, was developed and successfully applied to the  $NO_x$  formation problem.

A study to determine the origin of CO emissions at light load from a gas turbine was carried out. A kinetic mechanism for the CO oxidation process following partial oxidation of a hydrocarbon fuel-air mixture was developed. It was based on the partial equilibrium approach to reacting gas mixtures and the important kinetic constraints were found to be (1) the rate of change in the number of molecules per unit mass of gas due to recombination, and (2) the CO oxidation step by OH. The validity of the model was checked in a burner experiment where combustion gases were quenched in a heat exchanger.

This kinetic model was then used with simple flow models of the primary and secondary zones of a gas turbine combustor to determine the regions in the flow where the CO emissions originate, and to explore the effect of engine operating conditions. Nonuniformities in fuel distribution in the primary zone, and the equivalence ratio and temperature distribution created as dilution air jets mix with the bulk flow were taken into account. It was shown that rapid quenching of the CO oxidation process by the mixing of combustion gases with the dilution air jets was the primary factor in determining CO emissions. The model was able to predict adequately the variation in CO emissions with engine load in an industrial gas turbine engine.

## 2.2 Dispersion of Pollutants from Aircraft

A part of the research effort was devoted to the problem of the dilution and dispersion of aircraft engine exhaust trails. A simple model for the growth and motion of an aircraft's exhaust stream, when jet momentum and then buoyancy dominate over the effects of atmospheric turbulence, was developed. The model was used to predict the growth of the trail and the corresponding dilution of the exhaust products from an individual aircraft. A simple model for the cumulative deposition of exhaust products from aircraft landing and leaving an airport at regular intervals was also developed to show how pollutants are likely to be concentrated in a narrow corridor extending downwind from the airport.

A more detailed model which describes the early time history of the wake of an aircraft was developed. This theory shows that far downstream of the aircraft, buoyancy dominates the wake growth. For a supersonic transport flying in the stratosphere, the stable stratification of the stratosphere will limit the growth of the wake. Also, it was shown that the exhaust gases in the stratosphere can sink due to differential radiative cooling caused by the high concentration of water vapor and lower concentration of ozone in the wake.



### 2.3 Research on the Swirl Can Combustor

A study was made of NO and CO formation in the NASA swirl can combustor concept. Models which predict the emission of these pollutants as a function of combustor design and operating variables were developed and compared with the available NASA emissions data.

The model for predicting NO emissions incorporated a stirred reactor primary combustion zone and one or more plug flow dilution zones. Statistical means for accounting for fuel-air ratio nonuniformities and turbulent mixing during dilution were developed, and coupled with the extended Zeldovich kinetic scheme for NO formation. Predictions of NO emissions were compared with experimental data over a wide range of fuel-air ratios, air temperatures and pressures and good agreement was obtained.

Experimental work was carried out on a single swirl can module to verify various assumptions and parameter values used in the NO model as applied to the swirl can combustor. The experimental techniques used included stroboscopic, time-exposure and high speed motion pictures, and smoke, water and helium-filled soap bubble flow-tracing techniques to define the liquid fuel droplet breakup process and turbulent recirculating flow pattern. A nonburning tracer experiment was used to define the dilution rate of flow through the center of the can, in cold flow. A burning experiment was used to map the fuel-air equivalence ratio distribution, and determine the composition and degree of unmixedness in the primary recirculation zone downstream of the swirl

can module.

A more detailed model of the primary combustion region was investigated in an attempt to predict swirl can combustor CO emissions. A stochastically mixed partially stirred reactor technique was developed to follow the turbulent fuel-air mixing process and couple with the CO chemistry. This chemistry was modelled with the constrained partial-equilibrium technique developed previously, where the relevant constraints are on the number of moles per unit mass through the three body recombination processes, and on the oxidation of CO by OH radicals. Model predictions showed reasonable agreement with available experimental data.

#### 2.4 Research on Fuel-Air Mixing Processes

Studies were carried out to determine the relationship between fuel injector design and operating characteristics and the fuel-air mixing rate in the primary combustion region of a burner. The fuel-air ratio nonuniformities that result from the detailed processes of fuel atomization, fuel droplet trajectories, fuel droplet vaporization, and fuel-air vapor mixing are known to affect the combustor operating characteristics, stability and emissions.

Experiments with gaseous fuel in three geometrically similar simple tubular burners were used to provide data on fuel-air mixing rates as a function of fuel jet kinetic energy, swirl and characteristic dimensions. A scaling law for the average turbulent mixing intensity in the primary combustion region derived from turbulence theory was shown to correlate the data over a wide range of operating

conditions, and thus provide a predictive capability.

Experiments with liquid fuels with various designs of pressure and air-assist atomizers and with various fuels were carried out to determine the influence of the fuel evaporation process on the fuel-air mixing rate. It was shown that with air-assist atomizers the jet mixing process is rate controlling, and the fuel evaporation process is not significant. With pressure atomizers, characteristic droplet evaporation and mixing times are comparable and the evaporating drops in the liquid fuel spray are an important mechanism in distributing fuel through the primary combustion region.

A technique was developed for estimating the unmixedness in a turbulent burned gas flow from time-average measurements of species concentrations. It was shown that under normal burner operating conditions the standard deviation of the fuel-air equivalence ratio distribution, due to turbulent composition fluctuations, was of the order of half the local mean value in the primary combustion region. Nonuniformities decayed as the flow moved downstream.

## 2.5 Lean Ignition and Blowout Studies

Because in premixed prevaporized combustor concepts, flame stability limits are an important practical constraint, a substantial research activity on ignition and blowout was initiated and completed. Models for predicting ignition and blowout in lean mixtures as a function of mixture temperature, pressure,

fuel-air ratio uniformity and velocity have been developed and verified.

A correlation for blowoff velocity based on the basic quantities of turbulent flow and the laminar flame speed of the fuel-air mixture was developed. It showed good agreement with the experimentally observed trends for variations in equivalence ratio, flameholder characteristic size, free stream temperature and pressure, and turbulent Reynold's number.

A statistical model based on a Monte Carlo calculation procedure was developed to follow the combustion chemistry through the mixing processes that occur in the flame stabilizing zone in a burner. An overall kinetic rate equation for methane was used to describe the fuel oxidation process. The model was used to predict the lean ignition and blowout limits of premixed turbulent flames and of flames where the mixture fuel-air ratio nonuniformity, modelled by a gaussian distribution, was increased.

The trends in model predictions were verified by experimental work on an atmospheric pressure constant cross-sectional area tubular combustor. Lean ignition and blowout data as a function of air temperature, air velocity and mixture nonuniformity were obtained. An important new result was the demonstration that nonuniformities in fuel-air ratio in the inlet stream to a combustor improve the lean ignition and blowout limits by up to a factor of two.

### 3. TECHNICAL SUMMARY OF WORK AT SHEFFIELD

#### 3.1 Flame Characteristics of a NASA Contra Swirl Module

A study was made of unconfined flames stabilized on a NASA contra-swirl module. A wide range of flames was stabilized. The flame structure was found to depend upon the reference velocity and fuel-air ratio. Highly compact flames were obtained over a narrow band of fuel-air ratios at a reference velocity of 28 m/s.

Studies were made of the effect of change in preheat temperature on temperature and species concentration distributions in propane flames. When the inlet air temperature  $T_0$  was varied from 300 to 673 K, the maximum temperature in the flame was found to increase by approximately 50 K per 100 K increase in  $T_0$ . The point of maximum temperature on the centerline moved downstream as  $T_0$  was increased.  $O_2$ , CO,  $H_2$  and  $CH_4$  were found together in gas samples taken from the flame, including regions of high temperature. This showed a high degree of unmixedness in parts of the flame.

#### 3.2 Particle Size and Velocity Measurement by Laser Anemometry

A Laser Anemometer was specially developed for the simultaneous measurement of size and velocity of droplets in liquid spray flames. Rapid measurements were made in spray flames of particles with diameters larger than the fringe spacing--up to 300  $\mu m$ . Time dependent variations in local spray structure were measured at particle counting rate of 2 kHz with spray densities of  $10^{10}$  particles/ $m^3$ . Particle sizes are derived from pulse height analysis of mean LDA signals.

Measurements show that droplet velocity is a function of droplet diameter for both burning and non-burning conditions. Temporally averaged local size distributions were measured directly and spatially averaged size distributions were derived from the simultaneously acquired velocity data. Significant differences were found between spatially and temporally averaged size distributions. Comparison of results obtained under burning and non-burning conditions showed changes in size distribution due to preferential vaporization of small droplets, acceleration due to thermal expansion of gases and corresponding changes in droplet momentum.

APPENDIX I

REPORTS, PUBLICATIONS

AND THESES AT MIT

COMPLETED ON NASA GRANT NGR 22-009-378

APPENDIX I: REPORTS AND PUBLICATIONS COMPLETED ON NASA GRANT NGR 22-009-378

Fay, J. A., "Air Pollution from Future Giant Jetports," Fluid Mech. Lab.

Publ. No. 70-6, M.I.T. (1970).

ABSTRACT: The planned expansion of major airports could lead to a new type of air pollution problem. These giant jetports will be capable of handling annually a hundred million passengers and more than a million aircraft operations. The pollutants emitted by aircraft during landing, taxing, and take-off will cause higher ambient levels than is now encountered at existing airports. Because aircraft arrive and depart in a generally upwind direction, the pollutants are deposited in a narrow corridor extending downwind of the airport. Vertical mixing in the turbulent atmosphere will not dilute such a trail, since the pollutants are distributed vertically during the landing and take-off operations. As a consequence, airport pollution may persist twenty to forty miles downwind without much attenuation. Based on this simple meteorological model, calculations of the ambient levels of nitric oxide and particulates to be expected downwind of a giant jetport show them to be about equal to those in present urban environments. These calculations are based on measured emission rates from jet engines and estimates of aircraft and traffic for future jetports.

Linden, L. H. and Heywood, J. B., "Smoke Emission from Jet Engines,"

Combustion Science and Technology, Vol. 2, pp. 401-411, 1971.

ABSTRACT: The fundamental processes determining the amount of smoke in the exhaust of a gas turbine engine are examined. First, the configuration of modern combustors and the state of knowledge of the processes occurring within the combustor are reviewed. Data from laboratory flame studies of carbon formation are then discussed and correlated with engine and combustor exhaust studies. It is seen that solid carbon is the nonequilibrium product of fuel vapor - air combustion in locally fuel rich zones. Calculation of carbon oxidation rates are then used to show that significant fractions of the carbon formed in the rich regions of the primary zone may be consumed in the leaner regions of the primary zone and in the secondary zone. Finally, combustor design features desirable for minimal exhaust smoke are summarized, and areas where further research would be most beneficial are identified.



Heywood, J. B., Fay, J. A., and Linden, L. H., "Jet Aircraft Air Pollutant Production and Dispersion," AIAA paper 70-115, presented at 8th Aerospace Sciences Meeting, New York, Jan. 1970; AIAA Journal, May 1971, pp. 841-850.

**ABSTRACT:** In this paper two aspects of pollution from jet engines are considered in detail. Firstly, it is shown that at or near full load, the most important air pollutants are nitric oxide and soot, and the production processes of these two pollutants are then discussed. A kinetic analysis shows that nitric oxide is formed mainly in the combustor primary zone, in regions of the flow where the equivalence ratio is greater than about 0.8, and that freezing occurs as the gas is diluted and cooled in the secondary zone. Calculated results for nitric oxide concentrations in the combustion products are presented and compared with existing experimental data. The mechanisms important in the formation of carbon in the fuel-rich regions of the primary zone are reviewed. The oxidation of this carbon in the remainder of the combustor is then considered, and the oxidation rates attainable within the combustor are computed from existing rate data. Secondly, the dispersion of the exhaust plume in the atmosphere is analyzed, the two effects considered being the entrainment of surrounding air due to turbulent motion of the jet and the motion induced by the buoyancy of the trail. For short times, mixing proceeds as in ordinary wakes; for longer times, mixing is dominated by motion induced by buoyancy.

Fay, J. A., and Heywood, J. B., "The Dispersion of Pollutants from Aircraft," SAE paper 710322, presented at Conference on Aircraft and the Environment, Washington, D.C., Feb. 1971.

**ABSTRACT:** Two aspects of the dispersion of pollutants from aircraft are reviewed. The first is the dispersal of aircraft exhaust emissions in the vicinity of airports; the second is the dispersal of exhaust trails in the upper atmosphere.

Techniques available for modeling this dispersal and how they might be applied to the airport problem are discussed. Field studies of airport pollution are then reviewed to assess current pollutant levels around airports and the aircraft's contribution to those levels. The possibility of contrail formation from jet emissions at high altitude is then considered and the effect of uncertainties in the trail mixing processes evaluated.

Radcliffe, Samuel W. and Appleton, John P., "Shock-Tube Measurements of Carbon to Oxygen Atom Ratios for Incipient Soot Formation with  $C_2H_2$ ,  $C_2H_4$ , and  $C_2F_6$  Fuels," Fluid Mech. Lab. Publ. No. 71-3, M.I.T., April 1971, Combustion Sc. & Tech., Vol. 3, pp. 255-263, 1971.

**ABSTRACT:** The critical atomic carbon to oxygen ratios,  $o_c$ , for incipient soot formation in shock-heated acetylene, ethylene, ethane/oxygen/argon mixtures has been measured over the temperature range 2000°K to 2500°K for reactant partial pressures between 0.1 and 0.4 atmos. Absorption of light from a He-Ne laser at 6328°A was used to detect soot. It was observed that the values of  $o_c$  for all three fuels increased uniformly with temperature such that at the highest temperatures  $o_c$  was considerably greater than unity, i.e. greater than the value of about unity at which solid carbon should have been precipitated on a thermochemical equilibrium basis. Observations were made over periods extending up to about one millisecond, which was well in excess of the time required for the major heat release of the combustion reactions. The relevance of these experimental findings to the problem of soot formation in gas turbine combustion chambers is discussed.

Radcliffe, Samuel W. and Appleton, John P., "Soot Oxidation Rates in Gas Turbine Engines," Fluid Mech. Lab. Publ. No. 71-12, Combustion Sc. & Tech., Vol. 4, pp. 171-175, 1971.

**ABSTRACT:** A basis for extrapolating soot oxidation rate measurements obtained in laboratory flames to the more extreme operating conditions of gas turbine combustion chambers is proposed. The proposal is based on the observation that, within probable experimental uncertainty, the limited soot oxidation measurements correlate with the more extensive measurements of the surface oxidation rates of macroscopic sized samples of pyrographite. The soot oxidation rates thus determined for the conditions of a typical gas turbine combustion chamber are considerably lower than previous estimates which were based on simple extrapolations of the flame data.

Heywood, John B., "Gas Turbine Combustor Modeling for Calculating Nitric Oxide Emissions," AIAA Paper No. 71-172, presented at AIAA/SAE 7th Propulsion Joint Specialist Conference, Salt Lake City, Utah, June 14-18, 1971.

**ABSTRACT:** Two aspects of models used to predict nitric oxide formation in gas turbine combustors are examined. At typical combustor primary zone conditions, the validity of assuming O, OH, H, and O<sub>2</sub> in equilibrium in the burnt gas where most of the NO is formed in steady state, or in equilibrium, and the effect of additional reactions in the NO kinetic scheme are evaluated. The techniques which have been used to model the flow are summarized, and the importance of including nonuniformities in gas temperature and composition and a distribution of residence times are reviewed. It is shown that nonuniformities in the flow must be included before satisfactory agreement with exhaust measurements over a wide range of engine loads can be obtained. The effects of variations in mean primary zone equivalence ratio, engine compressor pressure ratio, and mean residence time are discussed.

Overcamp, T. J. and Fay, J.A., "Dispersion and Subsidence of the Exhaust of a Supersonic Transport in the Stratosphere," AIAA Paper 72-650, presented at the 5th Fluid and Plasma Dynamics Conference, Boston, Mass., June 26-28, 1973, Journal of Aircraft, Vol. 10, No. 12, December 1973, pp. 720-728.

**ABSTRACT:** A theoretical model is presented that describes the early time history of the wake of an aircraft. This theory shows that far downstream of the aircraft, buoyancy dominates the growth of the wake. For a supersonic transport flying in the stratosphere, the stable stratification will limit the growth of the wake. Data of the visible width of the wake from laboratory experiments in a towing tank and from studies on the growth of contrails from subsonic aircraft verify the model for a neutral atmosphere. A model is developed to show that the exhaust gases of a supersonic transport can sink due to differential radiative cooling caused by the high concentration of water vapor and the lower concentration of ozone in the wake. Estimates of the rate of subsidence are given for aircraft flying between 16 and 27 km.

Heywood, John B., and Mikus, "Parameters Controlling Nitric Oxide Emissions from Gas Turbine Combustors," presented at the AGARD Propulsion and Energetics Panel 41st Meeting, London, England, April 9-13, 1973.

**ABSTRACT:** Nitric oxide forms in the primary zone of gas turbine combustors where the burnt gas composition is close to stoichiometric and gas temperatures are highest. It has been found that combustor air inlet conditions, mean primary zone fuel-air ratio, residence time, and the uniformity of the primary zone are the most important variables affecting nitric oxide emissions. Relatively simple models of the flow in a gas turbine combustor, coupled with a rate equation for nitric oxide formation via the Zeldovich mechanism are shown to correlate the variation in measured  $\text{NO}_x$  emissions. Data from a number of different combustor concepts are analyzed and shown to be in reasonable agreement with predictions. The  $\text{NO}_x$  formation model is used to assess the extent to which an advanced combustor concept, the NASA swirl can, has produced a lean well-mixed primary zone generally believed to be the best low  $\text{NO}_x$  emissions burner type.

Flagan, R. C., and Appleton, J. P., "A Stochastic Model of Turbulent Mixing with Chemical Reaction: Nitric Oxide Formation in a Plug-Flow Burner," M.I.T. Fluid Mech. Lab. Publ. 73-10 (1973), Combustion and Flame 23, 249-267 (1974).

**ABSTRACT:** A stochastic model of turbulent mixing has been developed for a reactor in which mixing is represented by n-body fluid particle interactions ( $n = 2, 3, \dots, 6$ ). The model has been used to justify the assumption (made in previous investigations of the role of turbulent mixing on burner generated thermal nitric oxide and carbon monoxide emissions) that for a simple plug flow reactor, composition nonuniformities can be described by a Gaussian distribution function in the local fuel:air equivalence ratio. Recent extensions of this stochastic model to include the combined effects of turbulent mixing and secondary air entrainment on thermal generation of nitric oxide in gas turbine combustors are discussed. Finally, rate limited upper and lower bounds of the nitric oxide produced by thermal fixation of molecular nitrogen and oxidation of organically bound fuel nitrogen are estimated on the basis of the stochastic model for a plug flow burner; these are compared with experimental measurements obtained using a laboratory burner operated over a wide range of test conditions; good agreement is obtained.

Morr, A. R., and Heywood, J. B., "A Partial Equilibrium Model for Predicting Carbon Monoxide Concentrations in Steady Flow Combustion Systems," M.I.T. Fluid Mech. Lab. Publ. No. 73-11 (1973), Acta Astronautica, Vol. 1, pp. 949-166 (1974).

**ABSTRACT:** A simple kinetic model, based upon the concept of partial equilibrium, is developed for predicting carbon monoxide concentrations in such steady flow hydrocarbon-air combustion systems as gas turbine combustors. The only two kinetic constraints used in the model are (i) on the rate of change of the total number of gaseous particles in the system, and (ii) on the rate of change of the CO concentration. The accuracy of the model is verified by comparison with experimental results obtained by burning kerosene with air in a 130,000 Btu/hr atmospheric pressure steady flow burner. Burnt gas cooling rates of  $10^6$  K/sec, about the magnitude encountered in the dilution zone of gas turbine combustors, were obtained with a compact water-cooled heat exchanger. Good agreement between measured CO concentrations and the values predicted by the partial equilibrium model was obtained.

Morr, A. R., Heywood, J. B. and Fitch, A. H., "Measurements and Predictions of Carbon Monoxide Emissions from an Industrial Gas Turbine," Combustion, Science and Technology, Vol. 11, pp. 97-109, 1975.

**ABSTRACT:** The gaseous emissions of carbon monoxide, nitric oxide and unburned hydrocarbons have been measured in the exhaust of a small industrial gas turbine engine. Using a rate limited partial equilibrium approach, the mechanisms are studied for the entire turbine power range. A simple model is formulated from these mechanisms which yields reasonable agreement with measured values and predicts the CO emissions variation with load. It is shown that excessive CO emissions are caused by the rapid quenching of primary zone combustion gas by the dilution air jets. At the jet interfaces, a fraction of the gas contains CO concentrations far above equilibrium. A contributing factor to excessive CO emissions is the poor fuel distribution in the primary zone. Where fuel burns with air at an equivalence ratio less than 0.6, some of the CO formed by rapid partial oxidation of the fuel remains throughout the engine. Minimum CO emission rates from the industrial gas turbine engine studied would be obtained by burning a uniform mixture of fuel and air in the primary zone at an equivalence ratio of 0.7.

Appleton, John P., "Soot Oxidation Kinetics at Combustion Temperatures," presented at the AGARD Propulsion and Energetics Panel 41st Meeting, London, England, April 9-13, 1973.

**ABSTRACT:** Comparisons between soot oxidation rate measurements obtained in laboratory flames and in a recent shock-tube investigation are made with previously reported measurements of the surface oxidation rate of bulk samples of pyrolytic graphite. On the basis of these comparisons it is concluded that the surface oxidation rate mechanisms for soot and pyrolytic graphite are the same and that the rates are predicted by a semi-empirical expression, originally proposed by Nagle and Strickland-Constable for graphite oxidation, which expresses the specific surface oxidation rate in terms of the surface temperature and the gas-phase partial pressure of oxygen. This expression provides a method of estimating soot oxidation rates which is suitable for use in engineering design and performance studies of most practical combustion systems, such as gas-turbine combustors.

Komiyama, K., Flagan, R.C. and Heywood, J.B., "The Influence of Droplet Evaporation on Fuel-Air Mixing Rate in a Burner," Sixteenth Symposium (International) on Combustion, pp. 549-560, August 16-20, 1976.

**ABSTRACT:** The importance of droplet evaporation in the overall fuel-air mixing process in liquid fuel spray flames is examined with a series of experiments in a simple atmospheric pressure burner burning a range of hydrocarbon fuels. Two types of fuel atomizers were studied--air-assist and pressure jet--which have substantially different operating characteristics. Fuel-air mixing rates were determined from time-averaged oxygen concentrations. measured with overall burner operation stoichiometric. It is shown that with air-assist atomizers, the kinetic energy of the atomizer jet determines the mixing rate intensity for both liquid and gaseous fuels. Since the droplet evaporation time is much less than the mixing time, the details of the evaporation process are not important and the jet length scale and kinetic energy govern the mixing process. With pressure jet atomizers, the characteristic evaporation and mixing times are comparable. The evaporating fuel drops create fuel vapor concentration nonuniformities on a scale much smaller than the fuel jet scale. Mixing rate intensities comparable to those obtained with air-assist atomizers can, therefore, be achieved with much lower turbulent kinetic energy dissipation rates. With pressure jet atomizers, both the kinetic energy of the fuel jet and the evaporation characteristics of the fuel droplets control the initial fuel-air mixing rate.

Mikus, T., Heywood, J.B. and Hicks, R.E., "Nitric Oxide Formation in Gas Turbine Engines: A Theoretical and Experimental Study," NASA Contractor Report 2977, April 1978.

**ABSTRACT:** The scope of this report is to develop a calculational model for the formation of  $\text{NO}_x$  in gas turbine engines. This model is general in nature and should be applicable to a range of combustor concepts and combustor geometries; however, the examples and discussions are generally directed toward aircraft applications. Emphasis is placed on the application of this model to the NASA swirl-can modular combustor, and comparisons of modeling prediction with experimental  $\text{NO}_x$  data are now available. The report also makes immediate use of predictions generated by this  $\text{NO}_x$  model. Experimental data are obtained to support assumptions and parameter values used in the model, so that the modeling predictions may be used with some confidence.

Radhakrishnan, K., Heywood, J.B. and Tabaczynski, R.J., "Premixing Quality and Flame Stability: A Theoretical and Experimental Study," Contractor Report NGR 22-009-378, NASA, 1979.

**ABSTRACT:** Models for predicting flame ignition and blowout in a combustor primary zone are presented. A correlation for the blowoff velocity of premixed turbulent flames is developed using the basic quantities of turbulent flow, and the laminar flame speed. The correlation for blowoff velocity shows the correct trends for variations in equivalence ratio, flameholder characteristic size, free stream temperature and pressure, and turbulent Reynolds number. A statistical model employing a Monte Carlo calculation procedure to follow a chemical reaction through the course of a mixing process is developed to account for nonuniformities in a combustor primary zone. An overall kinetic rate equation is used to describe the fuel oxidation process. The model is used to predict the lean ignition and blow-out limits of premixed turbulent flames; the effects of mixture nonuniformity on the lean ignition limit are explored using an assumed distribution of fuel-air ratios. The model predictions of the flammability limits show the correct trends for variations in mixture temperature, pressure and velocity. With increased mixture nonuniformity, the model predicts a substantial reduction in the lean ignition limit. The trends in the model predictions are verified by experimental work on an atmospheric pressure-constant cross-sectional area tubular combustor. Data on the effects of variations in inlet temperature, reference velocity and mixture uniformity on the lean ignition and blowout limits of gaseous propane-air flames are presented. The experimental work demonstrates that nonuniformities significantly reduce the lean ignition and blowout limits; however, nonuniformities substantially increase the emission levels of nitrogen oxides for lean mixtures.



Radhakrishnan, Krishnan; Heywood, John B. and Tabaczynski, Rodney J.,  
"Blowoff Velocity and Turbulent Flame Speed Correlations Based on  
Coherent Structures in Turbulent Flows," to be submitted to  
Combustion and Flame, July 1979.

ABSTRACT: Correlations for the blowoff velocity of premixed  
turbulent flames stabilized by bluff bodies and  
for the turbulent flame speed of premixed flames are  
developed using a model for coherent structures in  
turbulent flows. The correlation for the blowoff  
velocity shows the correct trends for variations in  
equivalence ratio, free stream pressure and tempera-  
ture, flameholder characteristic size, and turbulent  
Reynolds number. Good agreement with published  
experimental data is obtained for both blowoff  
velocity and turbulent flamespeed correlations.

Radhakrishnan, Krishnan and Heywood, John B., "Effects of Combustor  
Inlet Conditions on Flame Stability," to be submitted to Combustion  
Science and Technology, July 1979.

ABSTRACT: A model for predicting flame ignition and blowout in a  
combustor primary zone is presented. The model employs  
a Monte Carlo calculation procedure to follow a chemical  
reaction through a mixing process to account for composi-  
tion nonuniformities in a combustor primary zone. The  
fuel oxidation process is described by an overall kinetic  
rate equation. The model is used to predict the lean  
ignition and blowout limits of premixed turbulent  
flames; the effect of composition nonuniformity on the  
lean ignition limit is explored using an assumed distribu-  
tion of fuel fractions. The variations of the predicted lean  
limits with mixture temperature, pressure and velocity  
compare favorably with experimental magnitudes and trends.  
With increased mixture nonuniformity, the model predicts  
a substantial reduction in the lean ignition limit.

The predicted trends are verified by experimental work  
on atmospheric pressure, constant cross-sectional area  
tubular combustor. Data on the effects of variations in

inlet temperature, reference velocity and mixture uniformity on the lean ignition and blowout limits of gaseous propane-air flames are presented. The experimental work demonstrates that nonuniformities significantly reduce the lean ignition and blowout limits; however, nonuniformities substantially increase the emission levels of nitrogen oxides for lean mixtures.

Flagan, R.D. and O'Leary, J.A., "Application of a Stochastic Model to Prediction of Carbon Monoxide and Nitric Oxide Emissions from a Gas Turbine Combustor," NASA Contractors Report, 1979.

**ABSTRACT:** A Monte Carlo Method is developed to model NO and CO emissions from gas turbines. The combustor is modelled as a combination of a partially stirred tank reactor, representing the recirculation zone, and an imperfectly mixed plug-flow reactor with mass addition, representing the downstream dilution zone. This model is applied to the NASA swirl can combustor using four empirically determined parameters. Nitric oxide emissions, calculated using the extended Zeldovich mechanism and equilibrium for the H-C-O reactions, are in good agreement with data for two different inlet air temperatures. Carbon monoxide emissions are calculated using a partial equilibrium model for CO oxidation. These are also in good agreement with experimental data. The computed NO emissions decrease substantially when the partial equilibrium model is used. Further development is required before the model is suitable for the calculation of simultaneous exothermic and endothermic reactions.

## MIT GRADUATE THESES

### Masters Theses

Linden, Lawrence H., "The Production of Solid Carbon in Gas Turbine Combustors," MIT, May 1970.

**ABSTRACT:** In this thesis the fundamental processes determining the amount of smoke in the exhaust of a gas turbine engine are examined. First, the importance of the problem is discussed; it is seen that the problem is primarily an aesthetic one. It is then shown that no droplet combustion of the classical (spherical flame) type can take place. This follows from a consideration of the characteristic times of the deceleration and the evaporation processes; the existence of regions of fuel-rich combustion in the primary zone is a consequence. A one-dimensional model for the secondary zone is then discussed.

From consideration of the data on the smoke output of laboratory flames, it is seen that the most important variables affecting combustor smoke emission level should be pressure, primary zone equivalence ratio, and the details of how the air is channeled into the combustor. This is confirmed in a review of combustor and engine tests, and the "fixes" used by engine manufacturers to eliminate exhaust smoke.

It is then shown that the data available on carbon oxidation rates does not lie in the region of interest for gas turbine combustors. Calculations based on extrapolations of this data, however, are seen to imply that soot particle oxidation may play an important role in determining smoke exhaust level. It is also shown that particle coagulation may be important in the secondary zone.

Bainbridge, G.D., "Model Experiments of Jet Aircraft Exhaust Plumes,"

MIT, May 1971.

**ABSTRACT:** A model of the growth and rise of a jet aircraft exhaust plume is presented and comparisons to an axisymmetric wake and a buoyant smokestack plume are made. A dimensional analysis of the governing equations is made and the appropriate scaling lengths presented. Experiments based on this model were conducted with heated air plumes in a low speed wind tunnel. The experimental measurements of the plume growth and rise were compared with the growth and rise of a model smokestack plume and the growth of an axisymmetric wake. The experiments demonstrated the validity of the theoretical model.

O'Leary, J. A., "Model for Predicting Nitric Oxide and Carbon Monoxide

Emissions from Gas Turbine Combustors," M.I.T. S.M. Thesis, January 1975.

**ABSTRACT:** Composition non-uniformities and mixing play an important role in determining the emissions of carbon monoxide and nitric oxide from gas turbine combustors. A model is developed to predict these emissions which uses a stochastic mixing model to simulate the turbulent mixing process. Calculations are performed for the NASA swirl can combustor, modelling the recirculation zone as a stochastically mixed, partially stirred reactor. The secondary zone of the combustor is modelled as a stochastically mixed plug flow combustor with air entrainment. The finite rate chemistry is modelled using the rate-constrained, partial equilibrium method with constraints on the carbon dioxide and nitric oxide concentrations and on the number of moles per unit mass in the system. Model predictions are compared with experimentally determined emission levels of CO and NO.

PhD Theses

Overcamp, Thomas J., "Dispersion of the Exhaust of a Supersonic Transport,"

MIT, September 1972.

**ABSTRACT:** A theoretical model is presented that describes the early time history of the wake of an aircraft. This theory shows that far downstream of the aircraft, buoyancy dominates the growth of the wake. For a supersonic transport flying in the stratosphere, the stable stratification will limit the growth of the wake. Data of the visible width of the wake from laboratory experiments in a towing tank and from studies on the growth of contrails from subsonic aircraft verify the model for a neutral atmosphere. The model is developed to show that the exhaust gases of a supersonic transport can sink due to differential radiative cooling caused by the high concentration of water vapor and the lower concentration of ozone in the wake. Estimates of the rate of subsidence are given for aircraft flying between 16 and 27 km.

Flagan, Richard C., "The Formation of Nitric Oxide from Organic

Nitrogen Contained in Fossil Fuels," MIT, May 1973.

**ABSTRACT:** Experiments, carried out in an atmospheric pressure oil-fired burner, which were designed to investigate the formation of nitric oxide from organic nitrogen contained in fossil fuels show that turbulent mixing significantly affects the NO emissions. In combustion characterized by poor initial fuel:air mixing, the exhaust NO concentration is much less than that observed in a flow of more uniform composition. A kinetic model for the conversion process is deduced from the results of premixed flame experiments. The interaction of chemical kinetics and turbulent mixing is explored, and a statistical collision model for the interaction is developed. The kinetic model is incorporated into a simple model describing the flow nonuniformities in the burner and is shown to predict the observed NO emissions.

Morr, Alan Ray, "A Model for Carbon Monoxide Emissions from an Industrial Gas Turbine Engine," MIT, March 1973.

**ABSTRACT:** A kinetic model is developed for predicting carbon monoxide concentrations in steady flow hydrocarbon-air combustion systems. The accuracy of this model, which is based upon the concept of partial equilibrium, is verified by experimental results obtained by burning kerosene with air in an atmospheric pressure steady flow burner. The burnt gas cooling rate achieved in the burner by means of a water cooled heat exchanger is  $10^6$ ° Kelvin/second, about the same as encountered in gas turbine combustors. Agreement between theory and experiment is good.

In order to provide a framework for analytical modelling, experimental measurements were taken from an industrial gas turbine engine. A complete exhaust gas analysis was performed while the engine was operated at controlled power levels. The gaseous emissions of carbon monoxide, unburned hydrocarbons, nitric oxide and oxygen were measured, as were several engine operating variables.

The mechanisms responsible for undesirably high carbon monoxide emissions are identified and given a quantitative description. These mechanisms are formulated into a model for predicting carbon monoxide emissions from gas turbine engines giving reasonable agreement with experimental results. The trend toward higher CO emissions at lower power levels is successfully predicted.

Excessive carbon monoxide emissions are in part caused by rapid quenching of the primary zone combustion gas by the dilution air jets. These jets freeze a fraction of the gas at CO concentrations far above equilibrium values. Excessive emissions are also caused by poor fuel distribution in the primary zone. In eddies which burn fuel lean, (equivalence ratio less than 0.6), the carbon monoxide oxidation kinetics are sufficiently slow that most of the carbon monoxide formed by the rapid partial oxidation of the fuel remains in that form throughout the engine. Based upon these findings, the optimum operating condition for minimizing CO emissions from the industrial gas turbine engine studied is a uniform mixture of fuel and air in the primary zone at an equivalence ratio of 0.7. This condition should be maintained constant for all turbine power levels in order to achieve minimum carbon monoxide emissions.

Mikus, Thomas, "Nitric Oxide Formation in Gas Turbine Engines: A Theoretical and Experimental Study," MIT, November 1975.

**ABSTRACT:** A model for predicting  $\text{NO}_x$  emissions from gas turbine combustors is presented. A modified Zeldovich kinetic scheme is described for the prediction of nitric oxide formation in the burned gases. Statistical means of accounting for nonuniformities in fuel-air ratio are set forth. A primary zone treatment based upon an assumed distribution of fuel-air ratios is used. This is followed by one or more dilution zones in which a Monte Carlo calculation is employed to follow the mixing and dilution processes.

Predictions of  $\text{NO}_x$  emissions are compared with various available experimental data, and quite satisfactory agreement is achieved. In particular, the model is applied to the NASA swirl-can modular combustor. The operating characteristics of this combustor which can be inferred from the modeling predictions are described. Parametric studies are presented which examine the influence of the modeling parameters on the  $\text{NO}_x$  emission level as well as its pressure dependency.

Calculations which support various assumptions and parameter values used in the  $\text{NO}_x$  model as applied to the NASA combustor are described. Streamline calculations adapted from an existing computer program show a recirculation zone 1.8 module diameters long. Fuel droplet formation and evaporation calculations indicate an evaporation distance shorter than 0.1 module diameter.

Experimental work is reported further verifying this modeling application. A series of flow visualization experiments including stroboscopic, time-exposure, high-speed motion picture, forward-scatter lighting, shadowgraph, smoke, water, and helium-filled soap bubble techniques, demonstrates the fuel droplet breakup and turbulent recirculation processes. A nonburning tracer experiment quantitatively follows the jets from the swirler as they move downstream and entrain surrounding gases. Techniques are developed for calculating both fuel-air ratio and degree of nonuniformity from imperfect measurements of  $\text{CO}_2$ , CO,  $\text{O}_2$ , and hydrocarbons. A burning experiment makes use of these techniques to map out the flow field in terms of local equivalence ratio and mixture nonuniformity.

Komiyama, Kunihiro, "The Effects of Fuel Injector Characteristics on Fuel-Air Mixing in a Burner," MIT, January 1975.

**ABSTRACT:** The fuel injected in the combustor does not completely mix with the air to form unburnt or burnt gases of uniform composition or temperature. These nonuniformities, which result from the detailed process of fuel atomization, fuel droplet trajectories, fuel droplet vaporization, fuel-air mixing, recirculation, have important effects on combustor characteristics such as emissions of pollutants, combustion efficiency, flame stability, heat transfer from the combustion zone. In the present research, the fuel-air mixing and combustion in a simple cylindrical combustor with air-assist atomizers and pressure jet atomizers, which can be approximated as a plug flow combustor, was studied.

With an air-assist atomizer, the atomizer jet kinetic energy is the primary source for the turbulent kinetic energy which is dissipated in the turbulent fuel-air mixing process. The primary air swirl provides for more efficient kinetic energy transfer from the mean to the turbulent flow; thus a higher turbulence kinetic energy dissipation rate results with higher swirl for the same input jet kinetic energy.

In the turbulent mixing of gaseous fuel jet with air, the length scale which determines the time scale of mixing is an integral scale (i.e. combustor diameter); hence the mixing intensity is determined by the energy dissipation rate and the integral scale. All these results can be correlated with the relationship:

$$\beta / (P_j / MD^2)^{1/3} = C_E$$

developed from the turbulence theory, where  $\beta$  is the turbulent mixing intensity,  $P_j$  the atomizer jet kinetic energy,  $M$  the total mass for the mixing,  $D$  the combustor diameter, and  $C_E$  is a constant of order 1 representing the efficiency of transfer of kinetic energy to turbulent flow which varies with primary air swirl.

In the combustion of a liquid fuel, the length scale which determines the mixing rate intensity depends on the relationship of the characteristic evaporation time and the mixing time, and the relative velocity of the drop compared with the critical velocity above which a droplet envelope flame is unstable. Two situations were analyzed.



(a) For the air-assist atomizers, the evaporation time was less than the mixing time, and the relative velocity greater than the critical velocity. Thus the length scale which determines the mixing rate intensity is again the integral scale and the results are similar to the gaseous fuel situations.

(b) For the pressure jet atomizers, the evaporation time was comparable to the mixing time, and the relative velocity lower than the critical velocity. Thus the length scale which determines the mixing rate intensity is the droplet length scale and

$$\beta \approx (P_j / M \ell_d^2)^{1/3}$$

where  $\ell_d$  is the droplet length scale.

Radhakrishnan, Krishnan, "Premixing Quality and Flame Stability: A Theoretical and Experimental Study," MIT, October 1978.

**ABSTRACT:** Models for predicting flame ignition and blowout in a combustor recirculation zone are presented. A correlation for the blowoff velocity of premixed turbulent flames is developed using the basic quantities of turbulent flow, and the laminar flame speed. The correlation for blowoff velocity shows the correct trends for variations in equivalence ratio, flameholder characteristic size, free stream temperature and pressure, and turbulent Reynolds number.

A statistical model employing a Monte Carlo calculation to follow the mixing process is developed to account for nonuniformities in a combustor primary zone. An overall kinetic rate equation is used to describe the fuel oxidation process. The model is used to predict the lean ignition and blowout limits of premixed turbulent flames; the effects of mixture nonuniformity on the lean ignition limit are explored using an assumed distribution of fuel-air ratios. The model predictions of the flammability limits show the correct trends for variations in mixture temperature, pressure and velocity. With increased mixture nonuniformity, the model predicts a substantial reduction in the lean ignition limit.

The trends in the model predictions are verified by experimental work on a constant cross-sectional area tubular combustor. Effects of inlet temperature, reference velocity and mixture uniformity on the lean ignition and blowout limits of gaseous propane-air mixtures are presented. The experimental work demonstrates that nonuniformities significantly reduce the lean ignition and blowout limits; however, nonuniformities substantially increase the emission levels of nitrogen oxides for lean mixtures.

Mechanical Engineer Thesis

Bigio, David I., "Fuel/Air Mixing Characteristics of Commerical Fuel Atomizers in a Combustor," MIT, September 1978.

**ABSTRACT:** We have tested different commercially-available fuel atomizers in a swirl can combustor and have generated a data base of combustion products and prevalent parameters. The purpose is to give a detailed mapping of the nature of the combustion field for each atomizer and to compare the role the atomizers have on the initial fuel/air mixing process.

We have identified spatial equivalence ratio non-uniformities which persisted far downstream in the combustor. We believe that the hardware upstream of the swirler causes aerodynamic wakes or disturbances which are transmitted through the swirlers. The combustion process magnifies these disturbances, due to the swirling flow. The upstream configuration was redesigned and, in our subsequent tests, we found that the nonuniformities in equivalence ratios were eliminated. However, in areas where the equivalence ratio is uniform, contours of the combustion products (e.g. carbon monoxide, unburned hydrocarbons) may not be uniform.

Four commercially-available atomizers were tested in a combustor: Delevan 30609-11 air-assist atomizer, Delevan GPH-70°A hollow cone pressure injector, Delevan GPH-70°B solid cone pressure injector, and Sonicore 0-2H. Samples of the combustion products were taken using a water-cooled probe. These samples were taken at three axial locations,  $Z/D = 1.0, 2.0, \text{ and } 4.0$  in a detailed grid so as to be able to describe the nature of the field at each cross-section. Profiles were drawn of the combustion products, equivalence ratio, combustion efficiency, and a turbulence "mixing" parameter. Magnitudes of the fuel flow rate, primary air flow rate, and injector air flow rate, where applicable, were used to calculate the Reynolds number, swirl number, and jet momenta within the flow so as to characterize the fluid dynamics of the jet/environment relationship. The turbulent mixing parameter  $s$  is a powerful tool in characterizing the performance of a combustion system and is a most sensitive measure to the nature of the mixing of the flow.

APPENDIX II

REPORTS AND PUBLICATIONS

FROM UNIVERSITY OF SHEFFIELD

COMPLETED ON NASA GRANT NGR 22-009-378

Chigier, N.A., A. Ungut and S. Atakan, "Particle Size Measurement by Laser Anemometry," Internal Report, Department of Fuel Technology and Chemical Engineering, University of Sheffield, November 1975.

**ABSTRACT:** A laser anemometer system has been used in order to examine the possibility of measuring particle size. The amplitude of scattered light has been measured as a function of particle diameter. The beam intersection angle and scattering angles have been varied as well as the traverse position through the control volume. Glass fibres were attached to a rotating disc so that cylinders of glass were traversed at known velocity and cylinder diameter through well defined positions in the control volume. The concept of visibility was found to be unacceptable since for the size range investigated there was no significant d.c. voltage. For certain fixed values of beam intersection angle,  $\theta = 5.532^\circ$ , and scattering angle  $\phi = 0.152^\circ$ , an almost linear relationship was found between signal amplitude and particle diameter in the range 80 - 500  $\mu\text{m}$ . The traverse position of the particle through the control volume was found to be a significant parameter with maximum amplitude measured when the particle traversed through the centre of the control volume. Signal amplitude can be used as a measure of particle size provided that a separate indication can be given of the location of the traverse position through the control volume. The number of fringes crossed or number of Doppler cycles could be used as an indication of the traverse position.

Chigier, N.A., "Laser Velocimetry for Combustion Measurements in Jet Propulsion Systems," Project Squid Workshop Proceedings, Purdue University, pp. 64-84, 1976.

**ABSTRACT:** Laser Velocimetry is examined as a means of making velocity measurements in gas turbine combustion chambers. Problems associated with making measurements in a high temperature radiating environment, laden with solid and liquid particles, is discussed; also, the special problems associated with optically clear viewing windows in high temperature and high pressure combustors. Experiments at the University of Sheffield are described.

Thompson, D., N.A. Chigier and I. Vince, "The Effect of Temperature Fluctuations on Nitric Oxide Formation," 2nd European Symposium on Combustion, Orleans, France, 303-308, September 1975.

**ABSTRACT:** Spatial inhomogeneity in flames and post flame gases, which is regularly observed as local temperature fluctuations is discussed in the light of recent developments in the description of fluid mixing. A description of the flame itself is developed, and combined with the known characteristics of nitric oxide formation, to obtain a model of nitric oxide formation in the flame-region. It is concluded that prompt NO formation is dominant, and the formation rate in the flame is not significantly affected by temperature fluctuations. In the post flame region, the Zeldovich mechanism is dominant, and the formation of nitric oxide is significantly affected by temperature fluctuations. The rate may be greater than that predicted under the assumption that O and O<sub>2</sub> are equilibrated, due to diffusional transfer of H<sub>2</sub> between high and low temperature regions, and consequent changes in radical concentrations.

Nitric oxide concentrations distributions observed in three experimental combustors are compared with those predicted from the model derived, and found to be in general agreement.

Chigier, N.A., "Combustion Diagnostics by Laser Velocimetry," AIAA 14th Aerospace Sciences Meeting, Washington, D.C., January 1976.

**ABSTRACT:** This paper examines the present state-of-the-art of laser velocimetry and summarizes the principal conclusions that have been obtained in experimental studies using laser velocimetry in combustion systems. A critical examination is made of the various possible alternative systems, together with an examination of current problems and the attempts being made to solve them. Recommendations are made as to the most suitable system to be used at present for gas turbine and jet propulsion studies and indication is given of possible future developments.

Thompson, D., N.A. Chigier, A. Ungut and C. Pomfret, "Flame Characteristics for Single Swirler Module from NASA Gas Turbine Combustor," Report to NASA-Lewis Research Center, Department of Chemical Engineering and Fuel Technology, University of Sheffield, December 1976. Presented at the Central States Section Meeting, The Combustion Institute, NASA-Lewis Research Center, Cleveland, Ohio, March 28-30, 1977.

**ABSTRACT:** The approach to data analysis in this report reflects two recent major advances in the description of phenomena which arise in turbulent combustion. These phenomena are observed in two forms; the aerodynamics of both hot and cold flow systems have been shown to be ill-described by the classical model of turbulence; data on the chemical composition of combustion products is inconsistent with small-scale mixing processes. The fundamental change in the description of mixing processes implied is the same in each case - large-scale turbulent mixing is much more prevalent than hitherto supposed.

The aerodynamic aspect involves the recognition that transient large-scale flow-direction changes occur regularly. Evidence for the regular occurrence of such changes has been obtained in its most elegant form during studies of non-reacting flows, and the large-scale mixing phenomenon attains its most ordered form in the development of so-called coherent structures in the transition region of non-reacting jets. It is inherently probable that this type of phenomenon also occurs in at least some combustion systems, and this has been unequivocally shown to be true for methane jet flames and shown to be highly likely to occur in other flames. A more directly applicable aspect of the same type of large-scale process is the established tendency of recirculation zones to exhibit much larger variations in form, due to changes in direction of flow over larger volumes by comparison with the total volume of the recirculation core than hitherto expected. The consequence for the present investigation is the need for use of the most advanced laser Doppler anemometry data analysis techniques, in order to derive directional intermittency values for the recirculation core of the flame under investigation.

The chemical aspect involves the apparent co-existence of carbon monoxide and hydrogen, and oxygen which results from the necessarily very poor time resolution of chemical sampling by probe. Hitherto there appears to have been a tendency to attribute the apparent co-existence of these species to the complexity of combustion processes, perhaps by considering that radical persistence in the post flame gases of premixed flames can be expected to be paralleled by an even more complex phenomenon of the same type in turbulent diffusion flame gases. There is now much evidence that this is not the case: the rate of carbon monoxide burnout is well established and there is no direct evidence that radical concentration overshoot occurs and persists at a very high level in turbulent diffusion flames (with much kinetic evidence to the contrary). The rate of CO burnout is too fast to support CO, H<sub>2</sub> and O<sub>2</sub> co-existence in a near-homogeneous concentration field, other than in the presence of high radical concentrations; addition of diffusion rate data applied to typical simple geometries precludes the co-existence of small-scale elements of such species as near-neighbours. We are, therefore, led to the conclusion that their apparent co-existence reflects the presence of large-scale chemical inhomogeneity, which arises because much of the mixing which occurs is 'rapid' when we consider such phenomena as transient combustor liner overheat, where thermal lag is high, but 'slow' when we consider molecular collision processes necessary for chemical conversion to occur - the mixed elements can be transferred significant distances before interdiffusion destroys their chemical identity.



Chigier, N.A., "Instrumentation Technique for Studying Heterogeneous Combustion," invited review paper presented at Central States Section Meeting, The Combustion Institute, NASA-Lewis Research Center, Cleveland, Ohio, March 28-30, 1977.

**ABSTRACT:** Diagnosis of heterogeneous combustion systems requires the measurement of physical and chemical properties in flames laden with liquid and solid particles. For liquid-fueled combustors, the characteristics of the spray require to be determined, including the trajectories of individual droplets and their interaction with gas streams. Vaporization rates can be determined from measurement of the rate of change of diameter of individual droplets. Particulate matter emitted from combustion chambers is mainly in the solid phase and consists of both unburned fuel and nonburnable material. With heavy fuel oils, particles of the order of 100  $\mu\text{m}$  can be emitted while, for the lighter fuels, particulate emissions are mainly in the sub-micron size region. The laser anemometer can be used for simultaneous measurement of velocity and particle size of individual droplets and particles in spray flames. Laser diffraction techniques can be used for measurement of overall size distributions. Laser Raman spectroscopy offers the possibility of simultaneous measurement of temperature and species concentration in flames. Presence of particles results in laser irradiated particulate heating and incandescence, which can lead to the swamping of signals. The use of coherent anti-Stokes Raman and near-resonant Raman offers possibilities for making laser Raman measurements in particle laden flames.

Solid probes for measuring temperature and species concentration require special adaptation when used in particle laden flows. Particles may damage probes by direct impingement and cause blockage of orifices. Thermocouples can be used in sprays but the effects of direct droplet impingement must be considered. Diagnostic techniques have been developed in which thermocouple signals are digitized and recorded on a computer. This system permits the rapid measurement of time constants and, subsequently, digital frequency compensation of temperature time histories, providing a frequency response of the order of 1 kHz. Information on spray boundaries is provided by both laser anemometer and thermocouple measurements. Gas sampling probes, specially designed to separate liquid and solid particles from the gas, are used for removal of samples from within

the flame. Size analysis of particles is made by micro-photography and computer image analyser. Species concentration in the gas is measured by gas phase chromatography, flame ionization detectors, non-dispersive infra-red and ultra-violet detectors and chemiluminescent analysers.

All measurement diagnostic techniques are affected by the presence of large-scale coherent eddy structures in the turbulent flow systems. The need for increasing frequency response, recording and analysis of variations with time and the use of conditional sampling in intermittent flows is emphasized. The coupling of high-speed movies with laser optical probes to give simultaneous recording of visual and signal events is recommended.

Yule, A.J., N.A. Chigier and D. Thompson, "Coherent Structures in Combustion," Symposium on Turbulent Shear Flows, Pennsylvania State University, April 1977.

**ABSTRACT:** It is proposed, on the basis of experimental evidence, that many combustion flows contain coherent burning structures, or 'flamelets,' which interact as they are convected downstream. Photographic evidence for gas diffusion and liquid spray flames indicates that these flamelets are associated with coherent large eddies in these flows. The coherent structures are particularly evident for a gas diffusion flame impinging on a flat plate which contains three-dimensional flamelets. These flamelets have a wide range of sizes and trajectories at a fixed point which results in a typical intermittent, turbulent form for temperature fluctuations. Models are proposed for eddies/flamelets in transitional and turbulent regimes of various flows. It is described how coherent large eddies can result in reduced efficiency of combustion and high levels of emission of pollutants. Recognition of their existence provides an opportunity for more accurate modeling of combustion flows.

Yule, A.J., N.A. Chigier, S. Atakan and A. Ungut, "Particle Size and Velocity Measurement by Laser Anemometry," Journal of Energy 1, 4, 220-228, 1977.

**ABSTRACT:** The size and velocity of droplets are measured simultaneously by particle counting Laser Doppler Anemometer (LDA) in kerosene fuel sprays under both burning and non-burning conditions. This measurement technique enables rapid measurement of size and velocity of particles in spray flames for particle diameters larger than the fringe spacing up to, at least, 300  $\mu\text{m}$ . The time dependent variations in local spray structure can be measured at particle counting rates of 2 kHz with spray densities of, at least,  $10^{10}$  particles/ $\text{m}^3$ . Particle sizes are derived from pulse height analysis of the mean LDA signals and velocities are determined simultaneously, by measuring Doppler shift frequencies. The performance and accuracy of the system is determined by analysis, using geometrical optics theory, coupled with calibrations using a monosized particle generator. The measurements demonstrate that droplet velocity is a function of droplet diameter for both burning and non-burning conditions. The technique enables temporally averaged local size distributions to be measured. Spatially averaged size distributions are derived from the simultaneously acquired velocity data. Significant differences are found between spatially and temporally averaged size distributions. Comparison of results obtained under burning and non-burning conditions show changes in size distribution due to preferential vaporization of small droplets, acceleration due to thermal expansion of gases and corresponding changes in droplet momentum.

Thompson, D., N.A. Chigier and A. Ungut, "Flame Characteristics of a NASA Contra Swirler Module," ASME, 78-GT-163, 1978.

**ABSTRACT:** The structure of unconfined flames stabilized on a NASA contra-swirl can has been examined. A wide range of flame types may be stabilized. The structure depends on reference velocity and fuel-air ratio, and photographic illustrations of representative examples of each flame type are shown. A highly compact flame is obtained over a narrow band of fuel-air ratios, within the total range over which flames may be stabilized, at high reference velocity (27.8 m/s). The compact structure can only be obtained with careful fuel nozzle location.

Yule, A.J., D.S. Taylor and N.A. Chigier, "On-Line Digital Compensation and Processing of Thermocouple Signals for Temperature Measurement in Turbulent Flames," AIAA Sixteenth Aerospace Sciences Meeting, Huntsville, Alabama, Paper No. 78-30, 1978.

**ABSTRACT:** An investigation has been made of means for the improvement of high frequency temperature measurement in turbulent combustion by using the fine wire thermocouple. In particular, when the thermocouple is suitably interfaced with a microcomputer, it is demonstrated that a range of new possibilities arise for investigating and increasing the measurement accuracy of the thermocouple. Results of the investigation show that, in general it is necessary to account for the thermocouple geometry in more detail than has been usual in the past in order that the heat transfer characteristics of the thermocouple can be accurately determined for a wide frequency range. In addition, time dependency of the heat transfer characteristics of the thermocouple is significant in highly turbulent flows. Measures of geometrical and time dependency effects are obtained, and included in the subsequent digital compensation of the thermocouple signal, by suitable design of probe, interface and software. Compared with purely analogue techniques the digital techniques introduce the possibility of increased accuracy and flexibility in fluctuating temperature measurement. Measurements are less sensitive to signal/noise ratio problems and the technique is suited to high resolution point measurements, such as those involving thermocouple-laser anemometer cross-correlations, which are required to increase fundamental understanding of turbulent combustion.

Thompson, D. and N.A. Chigier, "The Effect of Preheat on the Structure of a Swirl Stabilized Flame," AIAA Sixteenth Aerospace Sciences Meeting, Huntsville, Alabama, Paper No. 78-28, 1978.

**ABSTRACT:** The effect of preheat on the temperature and species distributions in propane flames stabilised on a NASA contra swirl can has been examined. Flames with compact, stable structure, with inner swirler airflow  $9.1 \times 10^{-3} \text{ kg s}^{-1}$  outer swirler plus bypass airflow  $20.3 \times 10^{-3} \text{ kg s}^{-1}$  and propane injected 1 mm upstream of the inner swirler hub has been selected for detailed study. Over the inlet air temperature ( $T_0$ ) range 300 - 673K the maximum temperature in the flame increased by 40 to 60K per 100K increase in  $T_0$ . The point of maximum temperature on the centreline

approached the exit plane as  $T_0$  was increased. Oxygen,  $CO_2$ , and methane were found together in gas samples taken from the flame, including the regions of maximum temperature.

Ungut, A., A.J. Yule, D.S. Taylor and N.A. Chigier, "Simultaneous Velocity and Particle Size Measurements in Two Phase Flows by Laser Anemometry," AIAA Sixteenth Aerospace Sciences Meeting, Huntsville, Alabama, Paper No. 78-74, 1978.

**ABSTRACT:** At the 15th Aerospace Sciences Meeting the authors described a technique for particle size measurement by using Laser Doppler Anemometry. The present paper reports on developments which have taken place since that time. An additional gate photomultiplier has been introduced at right angles to the optical axis in order to select only those particles passing through the central region of the measurement control volume. This development eliminates the dependence of the measurements on position of the particle along the length of the measurement volume and thus simplifies the analytical method of correcting data for the effect of particles being equally likely to pass through any position in the measurement volume. Particle sizing measurements have been made in sprays of glass particles using the modified Laser Anemometry system. Measurements in fuel sprays are also reported and compared with the results obtained by a photographic technique. The application of the particle sizing technique to opaque particles is investigated and suitable optical arrangements are suggested. Light scattering characteristics of Laser Anemometry systems for different optical geometries are calculated to select the optimum optical arrangement for the particle sizing measurements.