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THE SEVENTEENTH (INTERNATIONAL) SYMPOSIUM
ON COMBUSTION

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29 December 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Seventeenth International Symposium on Combustion convened 20-25 August 1978 at the University of Leeds, UK. Sponsored by the Combustion Institute, the Symposium contained three colloquia on coal combustion, turbulent-combustion interaction, and fire and explosion. Papers discussed in this report are in the areas in which advances appear to be stimulating and technologically useful, such as soot, turbulent-combustion interactions, fire and explosion, coal combustion, propellants and explosives, deflagration to

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detonation transition, kinetics, and new measurement techniques.

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THE SEVENTEENTH (INTERNATIONAL) SYMPOSIUM ON COMBUSTION

The Seventeenth (International) Symposium on Combustion convened
at the University of Leeds in England during 20-25 August 1978, with
the participation of over 1000 scientists and engineers from all over
the world. The Combustion Institute has become a truly international
organization devoted to the science and technology of combustion. The
Combustion Institute and the Organizing Committee of the Seventeenth
Symposium are to be congratulated for bringing together, as in past Sym-
posia, the combustion community in large numbers and from various spe-
cial disciplines in a single meeting. The large attendance at these Sym-
posia in recent years, of course, also reflects the enormous concern all
over the world on combustion technology. Furthermore, there is also
the growing impact of advanced measurement techniques and computational
methods on combustion science and technology, which has brought much en-
thusiasm in this field. The Symposium was conducted through three simul-
taneous sessions, all of which were attended to capacity. Such partici-
pation in the technical meetings, not to mention the stimulating and ex-
tensive discussions in the hallways and during breaks and social events,
is further testimony to the vigorous pursuit of this technology and sci-
ence by so large a body of combustion scientists and technologists.

It has been the practice in these Symposia to begin the proceedings
with a plenary lecture. During the Seventeenth Symposium, the plenary
lecture was delivered by Heinz G. Wagner on the subject of "Soot Forma-
tion in Combustion." The Symposium organized three colloquia on coal
combustion, turbulent-combustion interaction, and fire and explosion.
In the area of what may be described as combustion science, there were
sessions on kinetics, flame structure and chemistry, combustion studies,
droplets, combustion oscillations, and soot. Two sessions were held on
problems related to propellants and explosives, one of those devoted to
deflagration-to-detonation transition. The development of measurement
techniques is advancing rapidly, and a session was devoted to that sub-
ject exclusively, while many papers in other sessions also included dis-
cussions on measurements. In the area of practical combustion devices,
two sessions were devoted to furnace combustion and engine combustion.
The foregoing subject areas are, generally speaking, the principal areas
in which significant developments are currently being attempted. It is
useful in this connection to review the published proceedings of past
symposia, which contain the more important papers presented then, and
which can throw some light on the historical development of some subject
areas in this broad field. The Seventeenth Symposium may not have in-
cluded any remarkable outstanding contributions, but one could observe
steady and stimulating developments in a number of areas, most notably
in measurements.

In a review of this Symposium, it is obviously impossible to refer
to each of the 148 papers presented. An attempt will be made here to
refer to some of the principal directions in which advances appear to
be stimulating and technologically useful.

First, the subject of _soot_: Wagner's plenary lecture provided an excellent review on the subject. The amount of soot formed during combustion may be described as the result of a sequence of steps: the pyrolysis of the fuel, the formation of gas-phase, large precursor molecules, nucleation, particle growth, agglomeration and coagulation, and partial oxidation of the particulates. In such a description, several questions arise regarding differences between (a) aliphatic and aromatic hydrocarbons, (b) premixed and diffusion flames, and (c) laminar and turbulent flames. These questions hold the key to various proposed methods for soot reduction. The formation of soot, its growth, and its eventual structure and size depend upon various characteristic times and scales which in turn depend upon the local (environmental) conditions. For instance, the paper by B.S. Haynes, H. Jander and Wagner on the subject of "Metal Additives on the Formation of Soot in Pre-mixed Flames," showed that the addition of metals (alkali and alkali-earth metals) does not reduce the amount of soot but changes the size distribution. Smaller particles increase in numbers compared to larger particles, an effect directly relatable to the ionization potential of the metallic component and the resulting repulsion between soot particles. Thus, if one is interested in soot reduction, there should be a thorough understanding of the fuel pyrolysis and soot burn-up processes. An attempt was made by B.F. Magnussen et al. in the paper entitled "Effects of Turbulent Structure and Local Concentrations on Soot Formation and Combustion in C_2H_2 Diffusion Flames," to relate the fuel pyrolysis and soot burn-up processes through the influence of the fine structure of turbulence. Generally a decrease in Reynolds number increases soot formation, but that effect may be due to reduction in soot burn-up when oxygen concentration is reduced around the soot particle. Further research is required before the precise influence of turbulence on soot formation and build-up is established. Incidentally, the foregoing paper also refers to the dramatic reduction in soot formation with the addition of water (and also N_2) to the fuel in a diffusion flame, although it is not yet clear if water plays a chemical or thermal role during fuel pyrolysis.

Next, the Colloquium on Turbulent-Combustion Interactions. One of the most important aspects of combustion modeling is the interaction between turbulence and combustion, which is indisputably a two-way process. K.N.C. Bray discussed the implications of this interaction in his invited paper on "The Interaction between Turbulence and Combustion." In a practical sense such interaction influences turbulent flame speed, minimum ignition energy, flame stabilization boundaries, and pollutant formation. In general, there is greater understanding of the influence of turbulence on combustion (reference may be made to the ONR SQUID Workshop on Turbulent Mixing in Non-Reactive and Reactive Flows, Proceedings published by Plenum Press, New York, 1976) than of combustion on turbulence. The latter has an important influence on turbulent transport flux and dissipation rate that in turn depend upon turbulence kinetic energy and length scales. In setting up equations governing turbulent combustion phenomena, it has now become common practice to employ Favre-averaged (density-weighted averages) quantities, although no definitive experiment has yet been performed to establish the precise differences in turbulent transport based on Favre-averages without and with combustion. In this connection,

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the paper by I.M. Kennedy and J.H. Kent on measurements of the behavior
of scalar quantities in turbulent flows was valuable. They addressed
the question of whether Favre quantities in variable density flows be-
have as conventional quantities in isothermal flows and showed, by
measurements, that Favre probability density function (PDF) may be simi-
lar to conventional, isothermal PDF, but Favre means are lower than sam-
pled conventional means. However, these deductions were based on several
assumptions (both in experiment and in interpretation of data) that need
further examination.

It should be noted that combustion and enthalpy-release are finite
rate processes (except in carefully selected examples of infinitely slow
or infinitely fast reactions, the latter, for example, occurring in nitric
oxide formation from atmospheric nitrogen) and, furthermore, create density
fluctuations and dilation. It has also now become common practice in
modeling turbulent combustion to take fluctuations into account at the
PDF level. Several questions then arise: Where can one specify *a priori*
an expression for the PDF?; Is there a sufficiently detailed connection
between the existence of coherent structures and the postulated PDF?;
What part of the PDF expression is most sensitive in different situations?;
Among various attempts at modeling turbulent combustion, what quantity,
in fact, should be represented at the PDF level?; and, Is there need for
setting up a transport equation for PDFs? The last has become a central
issue in modeling. Generally, there is a lack of data on scalar mixing
functions in mixing-limited combustion situations. The need for such
experimental data was brought out in a clear manner by the continuous
progress in the powerful analysis on the modeling of spectral scales of
the fluctuations of velocity and species by interrelating them, reported
on by R. Borghi and D. Dutoya. Meanwhile, even that analysis is suspect
in some respects, although it is capable of systematic improvement.

The general progress in turbulent flame modeling can be seen in the
papers by D. Brian Spalding, J.A. Mobsby, D.E. Fussey, and P. Botros and
T.A. Brzustowski. These were in the nature of progress reports.

The problem of practical combustors becomes further complicated by
the presence of fuel droplets as was pointed out by A.M. Mellor in his
paper entitled "Turbulence-Combustion Interaction Models for Practical
High Intensity Combustors." It is clear that there is no progress in
evolving a quantitative model for such practical situations, although
qualitative, interpretative synthesis of the influence of combustor geom-
etry, inlet conditions, and fuel and injector properties on emissions,
heat transfer, lean blowout limit, pattern factor, ignition, and relight
are being attempted continuously. In this connection, the research com-
bustor studies reported by W.P. Jones and C.H. Priddin and the spray e
evaporation studies reported by F. Boyson and J. Swithenbank were note-
worthy. In the latter, dealing with recirculating flows, the gaseous
flow field and the liquid-spray flow field (with spray size changes) are
still essentially uncoupled. The paper of M.M.M. Abou Ellail and E.E.
Khalil was also interesting in regard to the calculation of gas-spray
coupled flow field. Somewhat more definitive experiments on diffusion-

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controlled gaseous fuel combustors were described by J.A. Senecal and
C.W. Shipman and M.J. Oven, F.C. Gouldin, and S.W. McLean, the latter
in a swirl-stabilized combustor. These experiments should be examined
in relation to other definitive experiments being carried out at the
Wright-Patterson Air Force Aero-Propulsion Laboratory, OH, and the Sandia
Laboratories at Livermore, CA.

Another example of some progress in a problem related to practical
combustors was provided in the paper by J. Chomiak wherein an experimental
and analytical study was described on the subject of flame development
from an ignition kernel. In turbulent flows, it was concluded that the
local turbulent energy dissipation rate may determine the turbulence mixing
intensity and that in turn may determine flame development time. It
is, of course, too early to develop a theory, based on this reasoning,
that stochastic energy feed rate and heat loss govern flame development.

The colloquium seemed to indicate that there was further progress
in understanding the detailed structure of premixed flames. The mixing
and combustion processes associated with different eddy sizes need further
clarification in regard to the influence of turbulence scale and also
of boundary conditions. The basic experimental configurations discussed
by R.G. Abdel-Gayed et al., K.J. Lewis, and J.B. Moses, T. Suzuki, T.
Hirano and H. Tsuji need further examination.

The Colloquium also included a group of papers on combustion noise.
Generally the ideas of Warren C. Strahle seem to find favor with inves-
tigators on the relation between turbulence intensity and combustion
noise.

The Colloquium on Fire and Explosion began with an invited paper
by J. de Ris which dealt with pool fires. A review was also presented
by Howard W. Emmons on the prediction of building fires, wherein one has
to take into account pyrolysis, flames, plumes, hot layers, radiative
and conductive heat transfer, and a variety of flows. Such a task may
only be undertaken on the basis of a modular approach. Emmons also dis-
cussed the basic philosophy behind setting up predictive schemes, namely
obtaining the right balance between the physics of various identified
processes and internal consistency in modeling such processes.

Broadly, three problems repeatedly referenced pertained to lack of
adequate theories and experimental data on (a) nonhomogeneous radiation,
(b) soot formation, (c) effects of vitiation and (d) ignition character-
istics.

A third review-type lecture presented during the Colloquium was on
a physical description of coal mine explosions by J.K. Richmond, et al.
A central difficulty in modeling coal explosions relates to the funda-
mental difficulty of describing coal dust motion (light, inertia free
particles?) behind shockwaves. In general the papers presented on ex-
plosions were rather qualitative in content.

Coal combustion was the subject of the third Colloquium in this Symposium. Two invited review papers were presented, one on coal combustion in boilers (pulverized coal and coal/oil/water mixture combustion and cyclone burners) by A. Macek and the other on the modeling of fluidized bed combustors (larger size particles than pulverized coal, with lower combustion temperatures) by A.F. Sarofim and J.M. Beer.

Regarding coal combustion in boilers, two unknowns are (1) existence of even local equilibrium and (2) aerodynamics of the flow field. The first of these is important from the point of view of NO_x formation starting with the release of fuel-bound N_2. The two together have a profound influence on ash production and hence on the total particulate mass (1-5 %) leaving the combustor. Careful experimentation is required in this area before modeling of the type suggested by R.C. Flagan can be more than a parametric study. Similar considerations apply to fly-ash radiation that is known to be a major part of furnace heat transfer. The gas and particle phase radiation can be separated only when further data become available on particle optical properties, although there is now improved confidence in predicting particle size distribution (generally bimodal with a secondary peak at a particle diameter of a few microns). A basic model for radiative flux (anisotropic and multiple-scattering) can be set up as illustrated by S.A. Varma and D.T. Pratt, but the physical information needed in such a model is still lacking. The structure of pulverized coal flames can be understood at a fundamental level only when there are further advances in the areas of coal volatilization and gas-phase radiation.

There was not much discussion on the subject of combustion of coal/oil/water mixtures. Macek, as stated earlier, drew attention to several outstanding problems in this connection. An important aspect of slurried oil combustion, when mixed with water, is the stability of the flame. Considerable attention is being paid to this subject in the broad area of emulsified fuels.

In addition to the three Colloquia, there were, as stated earlier, several sessions devoted to various broad subject areas. The study of soot was one for which Wagner's plenary lecture set the tone.

Two sessions were devoted to the subjects of propellants and explosives, and deflagration to detonation transition. The discussion on propellants, per se, was related to combustion mechanism of double-base propellants with and without additives such as aluminum or lead and copper salts. It has been known for sometime that little is known about gases resulting from the condensed phase degradation and the influence of high pressure where primary and secondary flames are merged. The principal non-US contribution here came from Guy Lengelle et al. (

Concerning the shock sensitivity of liquid propellants, the two papers by P. Beeley, P. Gray (chairman of the Leeds Subcommittee which, as host, was in charge of local arrangements), and J.F. Griffiths, and A.P. Glaskova were both significant. The latter described further experiments in his laboratory on the effect of catalysis over a wide range of pressures (up

to 1000 atm) in the deflagration of nitro and nitroso compounds. However, the effect of catalysts has to be understood in relation to the chemical kinetic processes occurring during various stages of reaction. The time-scale for chemical reaction, in the range of 1-50 ms, determines the type of experiments that are needed in this subject.

The subject of deflagration to detonation transition (DDT) has become extremely important in connection with transport, storage, and handling of large quantities of flammables and propellants. It is clear that DDR possibly cannot occur in the absence of some confinement or obstruction, although in unconfined conditions one can obtain fairly strong shockwaves caused by pockets of gases enclosed in "folded" turbulent sheets, exploding under essentially constant volume conditions. The paper by R. Knystautas et al. and Wagner described an experiment using a hot turbulent gas jet to establish the mechanism of detonation initiation, but the experiment seemed to take no account of turbulent scales involved.

Meanwhile, there are a number of attempts at modeling dynamic behavior in granular propellants taking into account the presence of multiple phases.

In the subject of <u>kinetics</u>, the papers in the two sessions could be broadly divided into those dealing with rate constant measurements and others dealing with mechanistic studies. Advances in the accurate determination of rate constants are of fundamental importance in the total field of combustion. The shock-tube studies on formaldehyde pyrolysis, described by A.M. Deat et al., and the fast flow reactor studies described by C. Vinckier and W. Debruyn were excellent examples of both the stimulating character and the eventual practical impact of such investigations. Errors in rate constants are proverbial and carefully obtained experimental data are needed urgently. Meanwhile, such data can also lead to understanding the reaction mechanism, e.g., should the data of Dean et al. have been interpreted on molecular rather than chain mechanism?

Generally, the mechanistic studies reported during the session were more impressive. The Göttingen group from the Institut für Physikalische Chemie is very active in this area.

The discussion of NO_x, SO_x, was not entirely confined to the one session dealing specifically with that subject.

NO_x is thought to be of primary concern because of its formation in gas turbine engines and environmental restrictions placed on manufacturing and naval installations testing such engines. Elements related to NO_x are related to material presented in the sessions on Turbulent Combustion, Kinetics, and Droplets as well as the NO_x - SO_x session. Further, one of the longer term concerns of the military must be the ability to burn fuels which are "heavy" and highly aromatic. Such fuels produce large amounts of soot that can be disastrous to the lifetime of

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the combustor can in an aircraft gas turbine and that can make testing difficult and expensive due to environmental restrictions. Also, the soot problem is of primary interest in the general operation of any diesel prime mover, another power plant of general concern to the Navy. Many believe that the understanding of soot formation and destruction processes will be the primary problem of combustion scientists in the next decade. The experimental measurement of NO_x from practical combustors has been studied for many years. However, there are still some important unsolved problems, and presentations made at the Symposium showed that progress is being made. A question that has remained unanswered is whether the NO_2 concentration measured in many combustion experiments was that that actually exists in the flow field or whether it was the NO_2 formed in the sampling probe. The paper by G.M. Johnson et al., on "The Presence of NO_2 in Premixed Flames," gives further evidence that the NO_2/NO ratios determined by probe techniques are principally the consequence of reactions that produce NO_2 in the probes. Some results by M.J. Oven et al., "Temperature and Species Concentration Measurements in a Swirl-Stabilized Combustion," seem to dispute this conclusion, however.

C.P. Fenimore in his paper "Studies of Fuel Nitrogen Species in Rich Flame Gases" continues to contribute further to the understanding of the NO formation problem from fuel bound nitrogen species by reporting that the oxidation of HCN formed in combustion processes is destroyed mostly by hydroxyl radical and that the biomolecular rate is of the order of 10^{12}. He reported further that the biomolecular rate for reaction of NH_2 radicals with NO is 5 ($\pm 30\%$) $\times 10^{12}$.

Using precise shock tube techniques, J.P. Monat et al., in a paper entitled "Shock Tube Determination of the Rate Coefficient for the Reaction $N_2 + 0 \rightarrow NO + N$," showed that they have reduced the uncertainty of this rate coefficient. For the temperature range 2384-3850 K they report a pre-exponential factor of $1.84.10^{14}$ and an activation energy of 78,250 cal/mole.

In the previously mentioned paper by M.J. Oven, et al., it was reported that large amounts of NO_2 were present in a swirl burner that consisted of a premixed fuel-air mixture concentric with an outer air stream. Both streams had an imposed swirl. They also found a systematic variation of the NO_2/NO ratio at many locations in their burner. The large amounts of NO_2 were observed in the cooler regions of the flow outside and downstream of the recirculation zone. These results would be consistent with the belief that NO_2 reduction reactions are quenched.

A.A. Nizami and N.P. Cernansky in their paper on "NO_x Formation in Monodisperse Fuel Spray Combustion" reported experimental results indicating that the NO_x formation in the spray of isopropyl alcohol is affected by droplet diameter, equivalence ratio, fuel feed rate, and the distribution of dispersion and dilution air. The most significant effect is the decrease of NO_x with droplet diameter, which reaches a minimum around 50 μm and then increases. They attribute this minimum to transition from a diffusion flame to premixed burning.

One of the most notable advances in recent years has been in the area of measurement techniques, in particular the development of nonintrusive techniques for the study of the combustion process. The most important measurements pertain to temperature, specie concentration, droplet size and velocity, and dynamics of other particulates. These are required because most practical combustion processes are turbulent in nature and invariably the flames have some soot in them. Measurements of concentration and temperature are, of course, urgently needed in the modeling of reactive turbulent flow fields. Similarly, droplet dynamics constitute an important aspect of modeling any liquid fuel combustion system.

During the past few years there have been steady improvements in the application of Raman scattering (spontaneous as well as coherent anti-Stokes) and fluorescence techniques to the study of concentration and temperature fields. Several papers dealt with advances in these techniques. A.C. Eckbreth's paper on CARS was in particular noteworthy for progress in measurements of temperature and concentration in sooty, laminar flames. In addition, there have also been attempts at using Rayleigh scattering with a chopped beam. While there has generally been some concern about background noise in applying Rayleigh scattering, K. Muller-Dethlefs and F.J. Weinburg showed results of considerable promise.

Another technique that seemed promising was the so-called quantitative schlieren method to obtain information on the convection velocity and scale of well-defined and ordered structures within turbulent flames. This technique, developed at the Univ. of Southampton, was described by K.J. Lewis and J.B. Moses.

In regard to measurements in fuel sprays, the high-speed photographic technique, developed at the United Technologies Research Center and described by J.J. Sangiovanni and L.G. Dodge, was noteworthy. It was shown that flame characteristics such as shape, location, and temperature profiles can indeed be established for the combustion of single and parallel mono-dispersed droplet streams. The technique developed provides an ability to observe visually spacing of droplets whose flame structures interact when droplets are close enough so that in a flow system one droplet is in the wake of another. The wake becomes a fuel rich zone, not enclosed by an oxidizer field, and is more prone to soot formation.

The Symposia of the Combustion Institute have grown in both participation and the variety of subjects discussed. The Program Committee obviously had a difficult time in obtaining a balanced subject and nation participation. Nevertheless, this Symposium provided a unique forum for the combustion community to get together under a single organization.

The next (Eighteenth) Sympsoium is expected to be held in 1980 at the Univ. of Waterloo, Canada.

APPENDIX 1

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