Colloquium on Turbulent Reactive Flows

DURING the AIAA 22nd Aerospace Sciences Meeting in January 1984, a Colloquium was organized on the subject of Turbulent Reactive Flows. Six papers were presented by invitation, representing a cross section of the current research interests in turbulent reactive flows: diagnostics and measurement, analysis, modeling, and application. The papers dealt with the following subjects: a) Asymptotic methods for the analysis of turbulent combustion processes (F. A. Williams); b) A two-fluid approach to transport during turbulent combustion (D. B. Spalding); c) Entrainment, mixing, and unsteadiness of mixing layers (J. E. Broadwell and P. E. Dimotakis); d) Status of turbulence modeling in practical continuous combustor design (H. C. Mongia, R. S. Reynolds, and R. Srinivasan); and e) Measurements and modeling (M. C. Drake, R. W. Pitz, and M. Lapp; and S. C. Johnston, R. W. Dibble, R. W. Schefer, W. T. Ashurst, and W. Kollman). The papers, after some revision, are presented here together to provide a single entry point to some of the major directions of current research in the subject.

In every combustion device or environment, it is of interest to estimate burning velocity, stability of flame, flame size, heat release rate, rate of formation of chosen species, and lift-off, blow-off and extinction limits. Calculation of such quantities in general under turbulent conditions is obviously difficult. It is then useful to examine how those quantities are affected by flow, turbulence, and chemical reaction in well-defined regimes, both for classification of phenomenology and for obtaining solutions in limiting cases that can be utilized for clarifying and assessing complicated prediction schemes. Premixed and non-premixed combustion should be distinguished in respect of those processes, whether one is dealing with laminar or turbulent combustion. The presence of turbulence complicates the problems because of the interactive nature of a multiplicity of time and length scales of turbulence and chemistry and intensity of turbulence. On the other hand, the existence of such interactions permits the use of asymptotic methods in certain regimes. The development and application of such methods is the subject of Williams' paper. The general approach to the problem consisted of starting with the process under laminar conditions and then examining the influence of turbulence parameters in various definable regimes. In the case of non-premixed combustion, it has furthermore been possible to start with mixing of inert flows and then to add chemical reaction. Williams provides an extensive analysis for the case wherein combustion occurs in thin sheets that are wrinkled by turbulence within premixed and unmixed cases and shows in a characteristically masterly fashion both the power of the method of analysis and the striking results obtained.

The best introduction to Spalding's paper is contained in the section "The two-fluid model in perspective." It appears that the central motivation in the development of the two-fluid model of turbulence is the imperative need to account for the common observation that there appear variously recognizable pockets or islands of mixtures at any location, on a statistical basis, in turbulent mixtures of fluids; the fluids may differ in composition and thermodynamic properties, be reactive or involve phase change. Among various aspects of interaction between such pockets of mixtures, transport of material from one pocket to another is not entirely rationalized. A part of material transport must be due to differences in pressure. Spalding's concern is to show how a two-fluid model of two representative pockets of fluids can, in fact, yield significant results for pressure-gradient-driven diffusion. Now it is interesting that Spalding actually defines an interfluid mass transfer as being dependent upon the local time-average relative speed of the two representative pockets, such relative speed being due (at least in part) to the effect of any pressure gradient driving the two pockets, and a surface area. An experiment that can reasonably isolate the pressure-gradient effect on transport is valuable and being conducted. Spalding has discussed the application of the two-fluid model to combustion of premixed and unmixed reactants. Several interesting problems and approaches have been mentioned in the paper: one has to await progress over the next several years. For several years Spalding has been concerned with computational experiments utilizing a well-developed framework for calculations (such as the PHOENICS code, which has been recognized by all of its users as one of the best available tools), which permits testing new turbulence models accounting for subtle advances in physical understanding.

It is commonly agreed that turbulence is rotational and structured in various spatial scales; and turbulent transport of species, momentum, and energy is governed by length and time scales. Over nearly a century, it has been found convenient, however, to examine, a turbulent flowfield on a pointwise basis and introduce notional eddies at each point, with interactions among eddies and the prevailing strains accounted for at various levels, including spectral content. At the same time there has always been some discontent about not being able to explain turbulence processes based on the dynamics of fluid flow, i.e., the use of the fundamental building blocks of fluid flow and their interactions. In the past twenty-five years, there have been (often accidentally observed) experimental results that have clearly established a firm foundation for studying turbulence in such a traditional fluid mechanical framework. Broadwell and Dimotakis, who have participated in such a school of thinking, have devoted their paper to examining some of the turbulence processes in a mixing layer with all of the turbulent entities and their interactions treated as physically real and accountable. Their principal findings, given under "Conclusions" in the paper, should be read first to appreciate the powerfulness of the approach, based, it is noteworthy, on experimental findings.

The gas turbine design community is greatly interested in the utilization of advanced turbulence models in the design and performance estimation of gas turbine combustors. Every aerothermodynamic process in a combustor is affected in a fundamental fashion and often extensively by turbulence. The design task requires models of turbulence for various processes, models that have been shown to be well founded, that can be subjected to validation, and that can be incorporated in vast, complicated computational codes with easily identifiable and changeable features. The models must also not add too greatly to the demands on the capacity of the computers or the calculation schemes. Mongia, Reynolds, and Srinivasan (MRS) discuss in their paper the available models for turbulent reactive flows based on those considerations, and concludes that the models are effective in providing the large trends in performance due to changes in turbulence characteristics, at least in regions where generally simple flow and chemistry can be assumed. The models discussed in the MRS paper do not involve turbulence structure, either point-specified or related to finite-size vorticity-containing entities. Nevertheless, it is pointed out how greatly one is already hampered by the uncertainties in numerical accuracy of computational schemes. Another important difficulty pointed out by the MRS paper relates to the setting up of reasonably well-defined simulations of complex reactive flows.

Imaging and laser diagnostics have found great use in the study of turbulent reactive flows. Considerable developments have occurred in planar imaging techniques and data acquisition. In light scattering-based methods, those based on the use of both elastic and inelastic processes have made advances. Drake, Pitz, and Lapp (DPL) and Johnston et al. (JDSAK) describe the application of a variety of measurement and data-processing techniques. It is obviously necessary to proceed to other sources for obtaining detailed description and critique of the methods. Meanwhile, the two papers demonstrate the manner in which measurements can clarify such processes as differential diffusion, internal intermittency, internal molecular transport, finite rate reaction, breakdown of coherent structures, etc.

The MRS paper is concerned with the application of two-equation and algebraic stress models with chemical reaction accounted for by an appropriate chemical model. Kollman (in the JDSAK paper) describes two other models, one wherein second-order closure is employed and the other an approach based on the use of pdf and related closure approximations. They are both capable of considerable improvement and will eventually find application in the prediction of practical reactive flows.

The JDSAK paper also presents a discussion of Ashurst's time-dependent simulation of turbulence through the application of discrete vortex dynamics representing the initial state of flow with a group of vortices. The current investigations are restricted to two-dimensional flows. An example of inhomogeneous flow discussed in the paper is that of a mixing layer. Broadwell and Dimotakis indicate that such vortex methods may provide a means of analyzing turbulence in terms of physical structure. Ashurst provides a discussion of the application of the method to both unmixed and premixed combustion. The interest in the unmixed case is to obtain transport under turbulent conditions and in the mixed case to determine the relation of flame speed to flame structure based on vortex interaction and laminar transport, and flame velocity in the two cases.

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July 9-11	**AIAA 10th Aeroacoustics Conference** (May)	Seattle, WA	Oct. 85

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