FLOW VISUALIZATION II

Wolfgang Merzkirch

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Preface

The methods of flow visualization are being used by engineers and scientists working in quite different fields of fluid flow research and development. Therefore, flow visualization has the character of an interdisciplinary experimental tool. The International Symposia on Flow Visualization reflect the need for an exchange of information on the development and application of these tools. The scope of this Second International Symposium was to emphasize the applicability of the methods for a great number of different problems and to point out the progress that has been made in various fields of flow research because of visualization.

The call for papers had resulted in a wide response. The Symposium was attended by 250 participants coming from 30 different countries. Because of the large number of contributed papers the authors were asked to restrict the length of their manuscripts to 5 or 6 pages. It is obvious that a paper of this length cannot provide all the information that a scientist would like to communicate of his or her work. The editor was grateful that almost all authors were kind enough to follow this suggestion for a reduction of the written text and so contributed to the possibility of producing these proceedings.

The Second International Symposium on Flow Visualization was organized by Institut für Thermo- und Fluiddynamik der Ruhr-Universität Bochum in cooperation with Verein Deutscher Ingenieure (VDI), the International Measurement Confederation (IMEKO), the American Society of Mechanical Engineers (ASME), the American Society of Civil Engineers (ASCE), and Unikontakt-University/Industry Liaison Bureau Bochum.

The organizers are grateful to Deutsche Forschungsgemeinschaft (DFG), Minister für Wissenschaft und Forschung des Landes Nordrhein, Westfalen, and Gesellschaft der Freunde, Ruhr-Universität Bochum for financial support of the symposium, and to all members of the Institut für Thermo- und Fluiddynamik who helped beyond the call of duty to make the symposium successful and informative.

W. Merzkirch

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GENERAL LECTURES

Optical Methods in Combustion Research

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The presentation is structured around applications to combustion systems rather than reviewing the methods themselves. The special constraints and opportunities which apply to flow visualisation in the vicinity of flames and in flammable mixtures are discussed. Combustion systems are then broadly classified into major categories, in terms of their structure and refractive index fields. The use of optical methods for elucidating the underlying fundamental phenomena, for the measurement of their propagation velocities and for the detailed study of their temperature and velocity fields is illustrated by drawing on an extensive range of examples.

Introduction

Professor Merzkirch, who is himself doing some interesting work in this field, requested particularly that attention should be focused on applications rather than methods. My talk * can therefore in no sense be regarded as a review of optical methods but will concentrate instead on their uses in combustion and the particular constraints and opportunities which arise in the study of flame processes. Since specific systems are mentioned only by way of illustrations, I hope I may be forgiven if I appear to lean too heavily on examples chosen from my own work.

In the present context, the term "optical methods" excludes spectroscopy and all forms of excitation. We shall be confining our attention in the main to

* Because of the necessary restrictions on length, this article is little more than an abstract of the opening address. Space does not permit any of the large number of slides shown to be reproduced here.

methods based on light from external sources interacting with phase objects - i.e. refractive index fields - and small particles. Even so, the number of optical systems, which range from the earliest applications of shadowgraphy to sophisticated laser Doppler anemometry signal processing is so large that it would be perfectly possible to take up all the available space with an incomplete list of references. A short-list of some relevant reviews and texts is appended {1 - 13}.

Constraints and Opportunities

It is of course possible to carry out certain studies relevant to combustion in cold flow models. Methods of this kind also have a venerable history {e.g. see ref.14} but will not be further discussed here because they do not differ in essence from other forms of flow visualisation.

Some constraints become immediately obvious as soon as we consider standard flow visualisation methods {15} in relation to flammable mixtures. Thus methods based on the addition of energy to premixed reactants are likely to result in premature ignition. For example the use of electric sparks for flow tracing will ignite a stoichiometric hydrocarbon air mixture as soon as the energy dissipated approaches 0.2 mJ - and less than $^{1}/10$ of that amount for more vigorous mixtures (e.g. H_2/O_2). These energy levels are sufficient to produce a continuously propagating flame ; much smaller amounts suffice to produce local perturbations. In general, flames are exceedingly sensitive to interference. Probes, for example, should not be used in the vicinity of flame reaction zones because they interact with them thermally, aerodynamically and chemically. Even smokes and fine particles are not above suspicion if they are not used with appropriate precautions. Indeed, smokes which dissociate at a particular temperature (e.g. ammonium chloride) as they approach the flame front have been used to record its instantaneous shape during turbulent fluctuations by photography of scattered light at short exposure times. Flames also interact with small particles by way of thermo-mechanical effects engendered by the steep temperature gradients encountered in combustion zones {16}. It is therefore necessary, when selecting the size of particle tracers for burning velocities within a given range, to take into account the thermo-mechanical error limit in addition to the accelerational lag limit {17}.

In general, flames are characterised by large changes in temperature, composition and velocity occurring over exceedingly small distances - fractions of millimetres in the case of laminar premixed flames (see below). Hence very small errors in the location of a point measurement can correspond to very large variations in velocity, temperature or composition. The problem is compounded by the difficulty of arranging for even a burner-stabilised flame to be absolutely stationary on that magnitude of distance scale. For example the mapping out of a velocity field, one point at a time, by laser Doppler anemometry can be made all but impossible by quite slow flame fluctuations which cause the point of measurement to move through different parts of the flame structure. This confers advantages on methods such as photographing particle tracks by temporally interrupted illumination, which yield an almost instantaneous record of velocity vectors. Freezing flame movement in such a manner does not omit any essential information as the front is merely drifting along or fluctuating slowly in a quasi steady state. In order to obviate the complementary limitations of velocimetry by laser fringe anemometry and by photographic particle tracking, a family of optical systems has recently been developed {18} which allows both types of measurement to be obtained simultaneously over extended test regions. It uses an array of cylindrical lenses and a simple beam splitter to produce a thin sheet of light from a powerful CW laser which is broken into fine interference fringes in its plane whilst being interrupted at a known frequency by a chopper.

Additional problems can arise in turbulent flames. Thus in laser Doppler anemometry the outer flame can act as a fluctuating convoluted phase object which interacts with the test beams. This has been illustrated experimentally by Hong et al. {19} who recorded an apparent velocity of a particle held stationary at the point of intersection of the two beams within a turbulent flame. There are in fact two effects responsible for such errors, one due to the changing differential phase difference between the two beams, the other due to varying deflections, both of which cause the fringe grid to move in response to the velocity of the boundary. The authors provide a theoretical analysis of these effects and suggest methods of correction, where necessary.

On the asset side, a flame can be regarded as "its own energy source for flow tracing". A few special methods are based on some particular exploitation of the high temperature - e.g. the use of sodium tracers which provide photographable yellow flashes or streaks beyond the flame front. More generally, most of our insight into the basic processes which underlie flame phenomena is due to our ability to visualise, by optical methods the otherwise, invisible changes in transparent gases which accompany the evolution of heat and combustion products. Here the extremely steep refractive index gradients become our greatest ally. Very often we do not have to use tracers because nature provides its own in the form of pockets of hot product gases or the flame front itself. Only in the related fields of plasma phenomena and shock and detonation waves do the objects of study provide their own phase boundaries. Unlike in these, however, the effects of free electrons and of pressure changes are not important parameters in the refractive index fields associated with the structure of most combustion phenomena. It may be helpful to classify flames into their major categories.

Flame Processes and their Optical Structure

The similarity in appearance of flames disguises some profound differences in mechanism. The major types are the four permutations between initially premixed and initially separate reactants with the two conditions of laminar and turbulent flow. The flames in initially separate reactants occur in the interface between fuel and oxidant. The reactants have to mix by diffusion (laminar or turbulent) before they can react. The mixing process, being much slower than the rate of reaction, therefore controls the whole phenomenon and such flames are accordingly termed "diffusion flames". The flame surface occurs close to the stoichiometric contour and the temperature there approaches the value corresponding to stoichiometric fuel/air ratio. In traversing the flame orthogonally, the refractive index profile therefore moves from its value in the cold oxidant to that in the cold fuel via a steep valley in between. Since the deflection of a light beam parallel to the flame is proportional to the refractive index gradient, there are two positions in the flame giving rise to maximum deflection. These deflections occur in opposite directions - each towards its cold reactant reservoir. Accordingly there are two "schlieren images" (unless the optical system suppresses one) and four positions of maximum marking in shadowgraphy {3}. Although temperature tends to be the dominant variable, refractive index is of course also affected by composition. In the case of diffusion flames it is generally assumed that fractional change in composition corresponds to fractional change in temperature. Such an approximation, which reduces the variation to a single parameter, cannot be absolutely correct since it presupposes a single overall reaction, constant specific heat and diffusion coefficients equal to one another and to thermal diffusivity. However it is often acceptable because of the dominance of thermal effects. In the case of heterogeneous