Introduction

The study of combustion is supported by funding agencies mainly because of public concern relating to a range of practical issues. These include measures to improve energy efficiency and reduce pollutant emissions from engines and furnaces and research aiming to reduce hazards due to fires and explosions.

In recent decades combustion science has made remarkable advances in many topics including for example the chemistry of pollutant formation in flames. However the application of such new knowledge to practical problems is still too often inhibited by our limited ability to predict the progress of turbulent combustion processes. Almost all combustion takes place in the presence of turbulent flow. Although our understanding of the interactions between combustion and turbulence is improving all the time there can be little doubt that the problem of turbulence still represents the most serious bottleneck between combustion science and its application. As noted by Williams[1] a consequence is that technology often forges ahead by trial and error or makes progress fortuitously by application of scientific misconception. To put future progress on a firmer scientific basis requires all of the wide range of disciplines and skills involved in combustion research.

As part of this process, the improved knowledge, which is being generated in all branches of combustion science, must be distilled and incorporated into theoretical models. These models in turn must form the basis of new computer codes which can then be used to improve the design of combustion equipment for optimum emissions, efficiency and safety. Such a development to meet the practical needs of society is greatly impeded by our present incomplete knowledge of turbulent reacting flows.

Turbulent flow and combustion chemistry are each characterized by a broad spectrum of length or time scales. The largest time scales in a turbulent flow are related to the physical dimensions of the apparatus and to the flow velocity while the smallest scales characterize the dissipation of turbulence energy through viscosity. The range of time scales associated with the rates of elementary combustion reactions is similarly broad and in a given problem may or may not overlap the range of turbulence time scales. A complete numerical solution of such a problem must resolve the smallest of all these scales. Because of the magnitude of this task a total Direct Numerical Simulation (DNS) in which the complete spectrum of scales characterizing say hydrocarbon combustion in a high Reynolds number turbulent flow is still not close to being possible. So-called DNS of turbulent combustion which generally assumes either a single-step global reaction rate mechanism or a reduced mechanism containing only a few steps is nevertheless limited to idealised boundary conditions and relatively low Reynolds numbers. The effects of heat loss by radiation or convection are usually neglected. These DNS are an extremely valuable research tool[2] from which much can be learned. Indeed an aim of these lectures is to illustrate the uses of such calculations. However DNS cannot and will not directly meet the pressing need for improved predictive methods to aid combustion safety studies and the design of practical high Reynolds number combustion systems for improved economy and reduced pollutant emissions.

For the foreseeable future this need must continue to be met, not by a complete solution of all the equations with all scales resolved as in DNS, but by the formulation and solution of model equations involving some form of averaging. As shown by Osborne Reynolds[3] the nonlinear equations of fluid mechanics when averaged contain additional unknown quantities, the Reynolds stresses, so the averaged equations must be supplemented by appropriate model expressions before a closed system of equations can be obtained. In these lectures we shall review various strategies for averaging and closing the equations of turbulent reactive flow. The problems posed are always similar, independently of whether averaging is carried out in time, or in an ensemble of realisations or in space as in large eddy simulation (LES).