The combustion group

The combustion group was the largest group at the 1994 Summer workshop. This reflects the importance of the area, the complexity of the physics involved, and the arriving maturity of simulation methods. Members of the group included visitors W. Ashurst, K. N. C. Bray, R. S. Cant, J. Card, J. H. Chen, F. J. Higuera, W. Kollmann, A. Liñán, S. Mahalingam, P. Orlandi, T. Poinsot, C. J. Rutland, A. Trouvé, L. Vervisch, R. Verzicco, and D. Veynante. Local hosts were K. Akselvoll, G. Bruneaux, M. Day, J. H. Ferziger, T. Mantel, R. D. Moser, and G. Ruetsch.

Simulation of turbulent combusting flows is made difficult by the thinness of most flames relative to turbulence length scales, the large number of dependent variables (some introduced by the chemistry), the fact that flame properties cannot be determined from external conditions alone, and the large number of parameters required to completely define a turbulent reacting flow. These obstacles also make experiments difficult, thus placing a premium on any contribution that simulation can make. Also, there are a number of approaches to the prediction of turbulent combustion for practical applications that need to be validated and/or improved. These include Reynolds-averaged methods, methods based on probability distribution functions (PDFs), and flamelet models.

The 1994 Summer Program had the ambition of making a contribution to each of these areas. Nine reports are included in these proceedings. The first paper concerns flames in non-turbulent flows but investigates issues that have a direct bearing on the properties of flames in turbulent flows. The next five present simulations of flames in various turbulent flows. The final three papers are primarily concerned with issues related to models for turbulent flows.

An important issue in turbulent combustion is flame stabilization. This is the process by which the flame is anchored so that it is not blown away by the flow of fresh gases. If the reactants are not premixed, the process involves diffusive mixing of reactants followed by a small premixed flame normal to the principal flow direction followed by a diffusion flame. The stability of these triple flames is investigated by Veynante *et al.* who show that there are two modes of triple flame stabilization; they also look at the interaction of these flames with a vortex.

Since complete flame chemistry models involve hundreds of reactions and dozens of species, it is important to know which effects can be treated with simpler chemistry models. Card *et al.* compare methane diffusion flames computed with one step and four step approximations to the chemistry and show that there are significant differences. A by-product of this work is a demonstration of just how difficult it is to include realistic chemistry in simulations from the numerical point of view.

Taking another tack, Ashurst *et al.* investigate the propagation of a flame whose properties do not change along the flame surface, which means that effects of the flow on flame structure are not considered. This case can be handled with a simplified model equation. They use this approach to study the geometric properties of the flame surface.

The ratio of the diffusivities for heat and chemical species (the Lewis number) has an important effect on the properties of flames. Most studies of this issue have dealt with laminar flames. The paper by Liñán *et al.* considers the effect of non-unity Lewis number on a diffusion flame in a mixing layer; the results, which show an important influence of Lewis numbers, are in general accord with laminar flame theory.

The effect of heat release, which other than the variation of transport properties with temperature is the principal effect of chemical reaction on the flow, is difficult to simulate because the incompressible equations cannot be used even though the fluid velocities are very low. Higuera and Moser consider a two-dimensional mixing layer with infinitely fast chemistry and find that, although similar phenomena are found in both the reacting and non-reacting flows, the quantitative differences are significant.

Flames may be quenched by heat transfer to solid surfaces; this phenomenon has important consequences in internal combustion engines. Bruneaux *et al* did simulations of turbulent flames in channel flow with constant temperature walls (using single step chemistry and ignoring heat release) and found significant quenching. An existing model for the quenching is inadequate, but an improved developed model fits the data very well.

Rutland and Cant investigated Reynolds averaged models for turbulent flames. In particular, the model of Bray, Moss, and Libby (BML), which obtains considerable simplification by assuming a bimodal PDF, was looked at in considerable detail and found to agree very well with simulation results for statistics up to third order. They also looked at the flux of chemical species and found it to be counter-gradient in the flame region, largely due to the effects of pressure.

Flamelet mean reaction rate models, which can be used in conjunction with Reynolds averaged flow field models, have seen increased popularity in the past few years and were looked at by Trouvé *et al.* To close the equation for flame surface density, a model is required for the turbulent flux of flame surface density. This quantity and the species flux are investigated. It is found that the species flux is co-gradient in a flow generated by the authors but counter-gradient (see preceding paragraph) in the flow of Rutland and Cant. This is believed to be a consequence of the different parameter ranges in the two flows, but further study is required.

As noted above, two principal models for turbulent flames have been of the surface density function (SDF) of PDF types. The two types of models have important advantages and disadvantages that are largely complementary. This suggests that a combination might have the best of both worlds. Vervisch *et al* made an interesting and potentially very important step towards the construction of such a model and used simulation results to test it.

As we have demonstrated, important progress in a number of directions was made at the Summer Workshop. Perhaps as importantly, the workshop has stimulated work that the participants are continuing and which should yield important results in the near future.

Joel Ferziger & Ken Bray