Chemically Reacting Turbulent Shear Layers with Significant Heat Release

A.K. WALLACE

Research Fellow, Department of Mechanical Engineering, The University of Adelaide

1   INTRODUCTION

The effects of heat release on the turbulent mixing processes are virtually unknown, yet fundamental to our understanding and prediction of countless combustion situations in engineering.   Research has concentrated on the case where molecular scale chemical kinetics are arbitrarily fast compared with the rate of mixing, so that the overall reaction rate approaches the so-called diffusion limited asymptote. Toor (1962) pioneered the prediction of diffusion limited reaction rates in mixing fluids, by showing that, with a few restrictions, the scalar species in reacting flows would behave analogously to those in non-reacting flows.   The main restriction is that there is negligible heat release in order to avoid the complication of non-uniform density and diffusinities.   Insight into the structure of turbulent shear flows (e.g. Roshko, 1976) has prompted many questions about the role of rapid, large density changes during the mixing process.

We have undertaken to answer these questions by an experimental study of a simple plane shear layer, reacting ozone and nitric oxide of concentrations high enough to cause temperature rises of several hundred degrees centigrade.

The reaction

$$O_3 + NO \rightarrow NO_2 + O_2$$
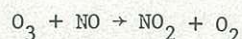
was chosen because it is very fast, spontaneous, uni-directional and highly exothermic.   Its speed enables the flow used to practically achieve the diffusion limited asymptote.   Another feature is the separability of the optical absorption spectrum of ozone and nitrogen dioxide, enabling their independent detection with UV and blue light respectively.   This property was exploited to take simultaneous pictures of ozone and nitrogen dioxide.

2   EXPERIMENTAL CONSIDERATIONS

A short running time dual blow-down facility was used.   The gas charge for each of the two streams - one containing ozone and the other containing nitric oxide - was mixed and stored in an FEP Teflon bag inside a 174 litre steel pressure vessel. These two pressure vessels were maintained at constant pressure by a very large reservoir of compressed air.   A fast operating ball valve on each cylinder started and stopped the flow, which passed through variable area choked metering valves and flow straightening screens into two essentially parallel ducts 100 mm wide separated by a finely tapering splitter plate.   After the contraction, at the end of the splitter plate, the nozzles were 100 x 50 and 100 x 25 mm for the low and high speed streams respectively.   At this point turbulence levels were less than 0.5% and the boundary layer

Re (based on Thwaite's method) of order 100 for the results presented here.   The pressure gradient could be adjusted or minimised by moveable side walls and the whole test section was enclosed by perspex side plates with UV quality silica glass windows adjacent to the shear layer.   A third FEP Teflon bag collected all the exhaust gas at atmospheric pressure for temporary storage while scrubbing.

Nitrogen and nitric oxide were obtained from a bottled supply, but ozone was generated and concentrated on site.   An electric discharge ozonator produced 1 to 2% ozone in oxygen, which was passed through a bed of very cold (-120 to -150°C) silica gel until the desired quantity of ozone had been adsorbed.   As the silica gel was slowly warmed, the ozone was given off into a stream of nitrogen and carried into one of the storage vessels.   The whole system was carefully designed to contain any explosion caused by the spontaneous breakdown of concentrated ozone.

Flow velocity was measured by a pitot tube and high speed electronic manometer, the local density being obtained from the local mean temperature as measured by a small thermocouple.   The thermocouple used was 0.002" diameter Chromel-Alumel and was sufficiently fast to realise the mean temperature profile when traversed across the layer in approximately 1 second. A UV absorption device measured the free stream ozone concentration during the run.   Such a detector was not necessary for nitric oxide since it could be accurately set using partial pressures.   Photographing both ozone and nitrogen dioxide simultaneously required pulsed light source with a wide bandwidth, 250-100 mm.   This was achieved with a high energy air-arc and combined with suitable band-pass filters.

3   FLOW PICTURES

Flow visualisation of reacting shear layers shows only apparently superficial changes in the overall flow characteristics from non-reacting layers, as shown in figure 1.   These shadowgraphs were taken with blue light to show the nitrogen dioxide formation.   The velocity ratio was 1:5, the maximum Reynolds number based on layer thickness of order 5000, and the carrier gas was nitrogen in both streams.   The minimum mean temperature rises are 10 and 160°C respectively, and despite the volume expansion of 1.5, the visual growth rate is almost unchanged.   Figures 2 and 3 are of non-reacting and reacting shear layers between helium and nitrogen and 25 and 5 m/s^{-1}.   The maximum mean temperature rise in the reacting case is 120°C, and the non-uniform refractive index signature is strong enough to show a substantial suppression of the finer turbulent scales in the flow, also slightly
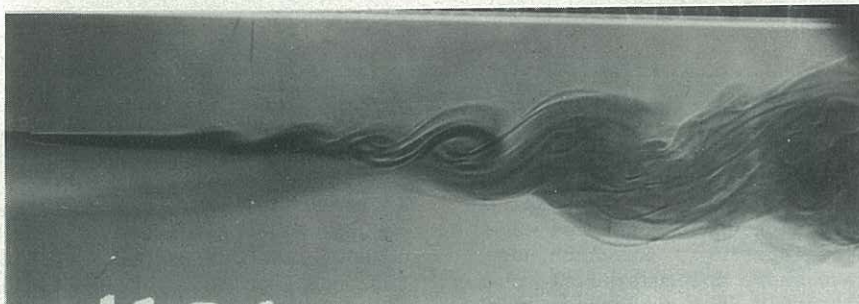
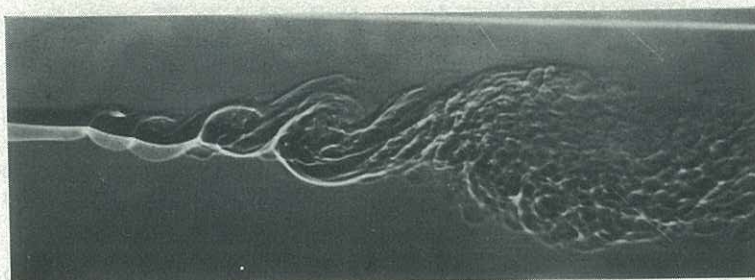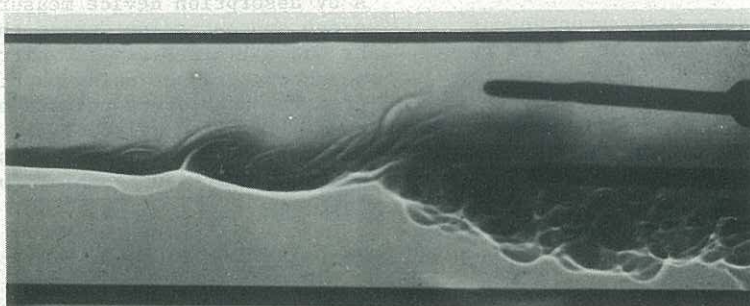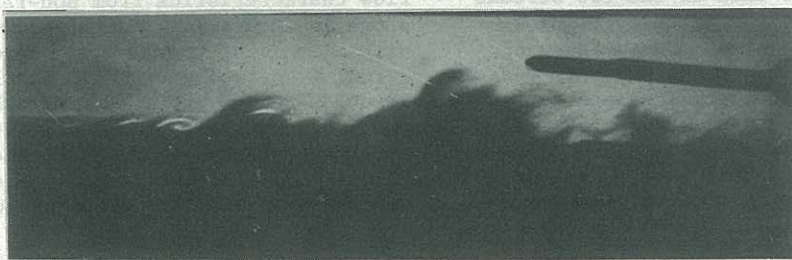FIG.1   Low speed reacting shear layers in nitrogen.   Maximum mean temperature rises (a) 10°K, (b) 160°K.

FIG. 2   Non-reacting shear layer.   Upper stream He, lower stream N_2.

FIG. 3   Simultaneous shadowgraphs of (a) nitrogen dioxide and (b) ozone in reacting shear layer.
Free stream as for Fig. 2.