AFOSR FINAL REPORT

HETEROGENEOUS DIFFUSION FLAME STABILIZATION

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SUMMARY

Analytical modelling and several experimental diagnostics were applied to an experimental flow in a two-dimensional subsonic windtunnel with a backward facing step and provision for injection of inerts and combustibles through the porous floor behind the step. The analytical techniques were based on a two equation model of turbulence with several variants of near wall models and numerical approaches. Conventional experimental techniques, where applicable in the cold flow, included hot film and pitot anemometry. Laser - based diagnostics in the cold and hot flows for velocity and species concentration measurements (both mean and instantaneous) included laser velocimetry in two components and Rayleigh molecular scattering.

Major findings in this complex turbulent flow with chemical reactions were a) there was general agreement between analysis and experiment in cold flow both with and without wall injection, b) this agreement occurred at the the most detailed level of turbulent shear stress and mass transport, c) in hot flow there was acceptable agreement as to the gross features of the mean flow field , but some theoretical details, such as reattachment length, went counter to experimental results. Further detailed probing of velocity, concentration and temperature along with a more sophisticated turbulence model are required for full documentation and predictability of this hot flow.

RESEARCH OBJECTIVES

The primary objective was to determine the limits of scientific understanding and predictability of a particular complex turbulent reacting flow. Secondary objectives included the development of several laser diagnostic methods operating under particularly severe conditions of signal to noise ratio and the necessary developments to modify two-equation turbulence models to treat the complex flow field studied. A tertiary objective was to provide technical information on the reattachment combustion dynamics of a flow field simulating that of a solid fueled ramjet, which was the flow field that the experimental and theoretical studies simulated.

ACCOMPLISHMENTS

Facility

The facility, which underwent continual development during the course of this program, is fully described in Ref. A, in the REFERENCES AND PUBLICATIONS section of this report. The combustion windtunnel developed was a two dimensional, backward facing step facility with provision for injection of inerts and combustibles through a porous floor behind the step. Injectants actually used were air, CO_2, CH_4 and H_2. The facility simulated the flame reattachment region of a solid-fueled ramjet. For scientific purposes, however, it was of use as a highly complex, turbulent, recirculatory reacting flow with mass addition.

Experimental Effort

As discussed above, the flame holding region of the solid fueled ramjet was simulated in this study in a facility in which air from the laboratory was drawn over a backward facing step. The evaporating solid fuel was simulated by blowing bleed gases through a porous floor behind the step. The tunnel was fitted with quartz side walls to permit access for optional diagnostics and fully instrumented with pressure and thermocouple probes. A detailed description of the facility along with its associated safety features is given in Ref. A.

The investigation of the flow in this facility was divided into three consecutive tasks: a) recirculatory flow without blowing, b) non-reacting recirculatory flow with injection of air or carbon dioxide through the porous floor, and c) reacting recirculatory flow using hydrogen or methane as fuel. The quantities measured include local velocities, turbulence intensities and shear stresses for the non-bleed flow. Mean velocities, turbulence intensities, shear stresses, bleed gas concentrations and velocity - concentration correlations were determined for the non-reacting flow with bleed. Finally, mean velocities, turbulence intensities, shear stresses, fuel concentrations and temperatures as well as the correlations of concentrations, temperatures and velocities are required for the reacting flow. All but the concentration and temperature measurements in the reacting flow have been completed.

Initially, mean velocities and turbulence intensities were measured at selected locations in the flow field without blowing using a pitot probe (mean velocities only), a hot wire and a laser Doppler velocimeter (LDV). Very good agreement between the values obtained by the three techniques were obtained. Good agreement was also observed with data reported by other workers for similar flows. These results were reported in Ref. B.

As a next step, the entire flow field without bleed was mapped out using LDV. The results obtained were in good agreement with those predicted using the modified k-ε model described in the following section. The comparisons carried out included velocity profiles at various axial locations, positions of zero axial velocities, location of the reattachment point and the axial positions of the maximum shear stresses, as reported in Refs. B and C.

The non-reacting velocity flow field with bleed was mapped for bleed flow rates corresponding to injection velocities of .5 and .25 m/s using both air and carbon dioxide as an injectant. Local bleed gas concentration distributions were determined using Rayleigh scattering for injectant velocities of .5 m/s. At selected locations the velocity and concentration measurements were carried out simultaneously in order to gain insight into the turbulent mass transport.

The results from the velocity measurements were reported in Ref. D. Blowing has very little effect upon the location of the zero axial velocity line. A shortening of the main recirculation zone at its downstream end, which had been predicted by the model, was, thus, not observed. As predicted, however, a small, secondary recirculation zone next to the step appeared upon blowing. The vertical locations of the measured maximum shear stresses at various axial locations were in good agreement with those predicted although the measured values were generally a little higher.

The local bleed gas concentrations for the cold flow were reported in Ref. E. Dust drawn with the air from the laboratory into the tunnel was used as seed particles for the LDV in the combined velocity - concentration measurements. The Mie scattering from the particles is many orders of magnitude stronger than the Rayleigh scattering from the molecules. Therefore, a data acquisition and reduction technique had to be developed which permitted the removal of the contributions by the particles and by the glare from the windows from the signal. A relatively simple data reduction scheme based upon mean noise levels was reported in Ref. E. Good agreement was obtained between the measured and calculated bleed gas concentrations except immediately behind the step where the vertical concentration gradient seemed somewhat overpredicted. Acceptable velocity concentration correlations could not, however, be obtained with the results from this simplistic data reduction technique.

A more sophisticated, Fourier transformation based date reduction technique was, therefore, developed. The details of this technique in which the actual noise pdf's generated by the particles, the glare and the electronic noise rather than only their mean contributions were removed from the signal were given in Ref. F. The results obtained with this novel reduction technique were reported in Ref. G and H. The agreement between the measured mean concentrations and those calculated using the modified k-ε model was notably improved over those reported in Ref. E. In addition, velocity - concentration data could be obtained from the improved data despite the low signal to noise ratio. It was found that the model correctly calculated the covariance profiles but tended to somewhat overpredict their magnitudes.

Reacting flow experiments were carried out using methane and hydrogen as fuels. The methane flame generally was found to be shorter and formed three axial prongs near reattachment. The hydrogen fuel resulted in a longer, smoother flame which was overall more two-dimensional in nature. Hydrogen was chosen as the fuel for all the diagnostic work not only because it resulted in a better, more stable flame but also because hydrogen flames produce a cleaner spectrum and are, therefore, more amenable to Raman measurements.

The vertical distributions of axial velocity are shown for three axial locations in Figure 1. Two of these locations are inside the recirculation zone while the third is at reattachment. These results do not agree with the model predictions, as explained below. While the model calculates a shortening of the recirculation zone for the reacting case as opposed to the cold flow, a lengthening of the recirculation zone upon heat addition is, in fact, observed. The experimental observations have, as yet, not been published, but the analysis will appear as Ref. H.

Analytical Effort

The analysis has evolved over several years roughly in accord with the experimental schedule, but the analysis has usually led the experiments in time. The analysis began through use of a numerical code generated by Imperial College, called TEACH. It is based upon a two equation (k-ε) model of turbulence for two-dimensional flows and uses what are known as law of the wall approximations to match the turbulent flow through a laminar sublayer to the wall boundary conditions. The original code and analysis was based upon incompressible flow.

The analysis and numerical code went through the following evolution process:

a) Modification of the law of the wall to incorporate wall blowing

b) Conversion of the equations to Favre averaged equations to incorporate variable density

c) Incorporation of an approximation for pressure - velocity correlations

d) Certain changes suggested in the literature to speed convergence rate

e) Change from the law of the wall model to a new type of model suggested in the literature to remove some shortcomings of the old model in combustion calculations

f) Incorporation of a calculation of transport of the variance of a conserved scalar

g) Incorporation of equilibrium combustion properties for both methane and hydrogen

h) Calculation using several assumed forms of probability density functions for the fuel element mass fraction

i) Change to finite rate chemical kinetics for hydrogen - air, as opposed to chemical equilibrium calculations

Results of calculations on item a) - c) above are contained in Refs. B - D. These calculations were made in cold flow, but incorporated wall blowing. Partial calculations in cold flow incorporating d) - f) are located in Refs. E - G. The general conclusions in cold flow, with and without blowing, are that there is quite good agreement between theory and experiment and the improvements incorporated for cold flow modelling speed both convergence rate and agreement between theory and experiment.

Results of the hot flow calculations, testing both methods of treatment of the chemistry and comparison with experiment, have been mixed in success. On the positive side, a) there is little difference in analytical results if fluctuations in species concentration are allowed or neglected (except in the region of the flow where the maximum temperature occurs) and b) the form of the assumed mixture fraction probability density function makes little analytical difference. However, in regions of the flow where the maximum temperature occurs, species fluctuation substantially depress average temperature and this turbulence effect must be included in calculation procedures. On the negative side, the calculation says that heat addition by combustion should somewhat shorten the reattachment length behind the step, whereas experimentally this length becomes somewhat larger. On the other hand, many of the gross features of the flow are preserved in a qualitative sense. It must remain as a future program to determine analytical remedies for the details of the prediction. The hot flow calculations are presented in Ref. H.

The finite rate chemistry calculations were not completed by the end of this contract and are therefore not included in this report. A future publication will contain these results and the Air Force will be properly acknowledged.

REFERENCES AND PUBLICATIONS (INCLUDING PRESENTATIONS)

A. "Combustion Test Facility and Optical Instrumentation for Complex Turbulent Reacting Flow," Walterick, R. E., De Groot, W. A., Jagoda, J. I. and Strahle, W. C., printed as AIAA Paper #88-0052, to be presented at the 26th Aerospace Sciences Meeting, Reno, Nevada, January 1988.

B. "Experiments and Analysis on Two-Dimensional Turbulent Flow over a Backward Facing Step," Walterick, R. E., Jagoda, J. I., Richardson, J. R. J., De Groot, W. A., Strahle W. C. and Hubbartt, J. E., printed as AIAA Paper #84-0013, presented at the 22nd Aerospace Science Meeting, Reno, Nevada, 1984.

C. "SFRJ Simulator Results: Experiment and Analysis in Cold Flow," Richardson, J. R. J., De Groot, W. A., Jagoda, J. I., Walterick, R. E., Hubbartt, J. E. and Strahle, W. C., printed as AIAA Paper #85-0329, presented at the 23rd Aerospace Science Meeting, Reno, Nevada, January 1985.

D. "SFRJ Simulator Results: Experiment and Analysis in Cold Flow, " Richardson, J. R. J., De Groot, W. A., Jagoda, J. I., Walterick, R. E., Hubbartt, J. E. and Strahle, W. C., Journal of Propulsion and Power, Vol. 1, Nov.-Dec. 1985, pp 488-493.

E. "Rayleigh Measurements of Species Concentration in a Complex Turbulent Flow," De Groot, W. A., Latham, R., Jagoda, J. I. and Strahle, W. C., AIAA Journal Vol. 25, No. 8, Aug. 1987, pp 1142-1144.

F. "Extraction of Useful Data from Noise-Contaminated PDFs," Strahle, W. C. and De Groot, W. A., accepted by Combustion and Flame, 1988 and

presented at the Eastern States Section of the Combustion Institute Fall Technical Meeting, San Juan, Puerto Rico, December, 1986.

G. "Combined LDV and Rayleigh Measurements in a Complex Turbulent Mixing Flow," De Groot, W. A., Walterick, R. E. and Jagoda, J. I., printed as AIAA Paper #87-1328 and presented at the 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, Hawaii, June 1987; also accepted for publication in revised form for the AIAA Journal, 1988.

H. "Flow Field behind a Backward Facing Step," Tsau, F. H. and Strahle, W. C., printed as AIAA Paper No. 88-0340 and presented at the 26th Aerospace Science Meeting, Reno, Nevada, January, 1988; submitted to AIAA Journal, 1987.

Other interactions include all AFOSR Contractors' Meetings between October, 1983 and September, 1987.

PARTICIPANTS

Co-Principal Investigators

Dr. Warren C. Strahle, Regents' Professor
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Research Engineers

Mr. Ronald E. Walterick
Dr. Wilhelmus A. de Groot

Students Graduated

Mr. F. H. Tsau, M.S., 1985
Mr. W. H. Mc Nicol, M.S., 1983
Mr. B. K. Mosoal, M.S., 1985
Dr. J. R. J. Richardson, Ph.D., 1984, dissertation entitled "Analysis of Sudden Expansion Flow in a Two-Dimensional Duct with and without

Side Wall Injection using the k-ε Turbulence Model"

Dr. W. A. de Groot, Ph.D., 1985, dissertation entitled "Laser Doppler Diagnostics of the Flow behind a Backward Facing Step"

AWARDS

Warren C. Strahle

AIAA Pendray Aerospace Literature Award, 1985
Fellow AIAA, 1987
Member of Combustion Institute International Board of Directors, 1986

Jechiel I. Jagoda

Member, AIAA Technical Committee on Propellants and Combustion, 1983-85
Sigma Xi Junior Faculty Research Award, 1985

AFOSR PROGRAM MANAGER INFORMATION

The facility developed under this program is extremely versatile and well-equipped from a diagnostic viewpoint. It should be viewed as a National facility for compilation of turbulent reacting flow data and one in which AFOSR has had a great financial stake. Consideration should be given towards using this facility for data base creation in the spirit of the Introduction and History section of "Evaluation of Data on Simple Turbulent Reacting Flows", AFOSR TR-85-0880. Sept. 1985.

Fig. 1: **HYDROGEN COMBUSTION VELOCITY PROFILES**