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The cold flow behind a backward facing step with injection of a foreign bleed gas was investigated using a simultaneous laser Doppler velocimetry - Rayleigh scattering technique. The facility simulates the flow field in the flame stabilization region in a solid fueled ramjet. Velocities and bleed gas concentrations and the resulting mixing pattern were measured. Particular attention was paid to the covariance of the velocity and bleed gas concentration which is a measure of the turbulent mass transport in the flow field. A novel reduction technique was utilized in the reported measurements.

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COMBINED LDV AND RAYLEIGH MEASUREMENTS IN A COMPLEX TURBULENT MIXING FLOW

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Abstract

The cold flow behind a backward facing step with injection of a foreign bleed gas was investigated using a simultaneous laser Doppler velocimetry - Rayleigh scattering technique. The facility simulates the flow field in the flame stabilization region in a solid fueled ramjet. Velocities and bleed gas concentrations and the resulting mixing pattern were measured. Particular attention was paid to the covariance of the velocity and bleed gas concentration which is a measure of the turbulent mass transport in the flow field. A novel reduction technique was utilized in the reported measurements. In this technique background noise due to glare, electronic noise, and scattering due to seed particles was removed from the Rayleigh scattering signal. The results obtained were in good agreement with those from an analytical model based upon a modified k-ε code. However, the model was found to somewhat underpredict the mixing downstream of reattachment and to somewhat overpredict the velocity-concentration covariance.

Introduction

Solid fueled ramjets (SFRJ), as other ramjets, require a flame anchoring region at the head of the combustion chamber. In this region the flow must be turbulent to facilitate mixing of the fuel and air and have a velocity lower than the burning speed of the mixture. Such a flow region may be generated in the recirculation zone behind a backward facing step. It is the purpose of the work in this laboratory to investigate the complex turbulent flow field which results when a fuel is injected through a porous plate (to simulate the pyrolysis of a solid fuel) into the recirculation region behind a backward facing step. The part of the study reported here deals with a cold flow simulation of this process in which the fuel was replaced by CO_2 which has a relatively large Rayleigh cross-section. Combined laser Doppler velocimetry (LDV) and molecular Rayleigh scattering were used to determine the flow velocity and bleed gas concentration distributions as well as the resulting mixing pattern. In addition, the correlation between the velocity and concentration fluctuations resulted in information about turbulent mass transport in the flow field. The results of these measurements were compared with the predicted flow field obtained using a modified k-ε model which was reported elsewhere.[1,2]

Experimental Work

The tunnel used in this investigation (Fig. 1) has previously been described in detail[1]. Briefly, air which is drawn from the laboratory passes over a backward facing step and establishes a recirculation zone. The injectant gas which simulates the pyrolysing fuel was bled into the recirculation zone through a porous floor behind the step. In the present study a CO_2-air mixture was used as the bleed gas since the Rayleigh scattering cross-section of CO_2 is 2.4 times that of air[3] and because CO_2 is relatively inexpensive. (A hydrogen-helium mixture is currently used in the same facility for combustion studies). The CO_2 was bled from a large tank which, at first, contained air at atmospheric pressure and was then filled to 100 psi using compressed CO_2 gas. The long line from the tank to the facility assured that the CO_2 entered the test section close to room temperature. In order to conserve bleed gas, injection was limited to a region between two and eight step heights behind the step. Optical access was provided through anti-reflection coated glass side windows.

Velocities and bleed gas concentrations were measured simultaneously using a combined LDV-Rayleigh scattering system. The LDV is a commercial TSI, two component system based on a 5 Watt Argon Ion laser. Two Bragg cells have been incorporated for the detection of reverse flow. The data were processed using a pair of counters and reduced in an HP-A700 computer. The Rayleigh system used the LDV laser as a light source. Scattered light was collected using an F /10 lens and focused through an interference filter onto a 500 micron diameter pin hole placed in front of a photomultiplier (HAMAMATSU R269) selected for low shot noise rather than high gain. The output from the photomultiplier was amplified and passed through an A/D converter (Preston) into the computer.

The 514.5 nm beam of the laser was used to measure the vertical velocities as well as the Rayleigh scattering since its orientation with respect to the tunnel resulted in the least background scatter entering the photomultiplier. The entire optical system was mounted on a remotely controlled actuator and inclined through a small angle to the horizontal. This allowed measurements down to .1 step heights above the floor. Closer to the porous plate, reflections from the plate interfered with the concentration measurements.

Unfortunately, the LDV and Rayleigh scattering techniques have opposing requirements. While the LDV needs seed particles in the flow for its operation, any seeding interferes with the concentration measurements. This is because the scattering cross section of the particles are many orders of magnitude larger than those of the molecules. Natural seeding in the form of dust in the laboratory air was, therefore, used in these tests. The injected flow could not be seeded since

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the particles would plug the porous plate. It will be shown that this did not cause a detectable concentration bias even close to the porous plate.

Because of the tunnel geometry and the random arrival of dust particles of a wide size distribution, the combined LDV - Rayleigh measurements reported here had to be carried out under more adverse conditions than those previously reported by other workers.[4,5] Because of the size of the tunnel the LDV measurements had to be carried out in the backscatter mode. The optical axis of the Rayleigh detection system had to be placed at an angle of 27.5 degrees to the incident beam rather than at 90 degrees which would have minimized any contribution of Mie scattering due to seed particles in the flow to the Rayleigh signal. The small ratio of step height to width of the tunnel necessary to prevent wall effects from affecting the two-dimensionality of the flow, limited the F number of the Rayleigh optics to 10. Furthermore, the scattering volume was often located in the immediate vicinity of the porous plate and surrounded by scattering surfaces causing an increase in background noise. Finally, the air drawn from the laboratory contained dust particles of various sizes which caused a widening and skewing of the concentration pdf's. The use of natural seeding also limited the data rate. This, along with the limited run time available from each tank of CO_2, resulted in a relatively small number of data points which could reasonably be acquired at any one location. This caused a certain statistical uncertainty especially for the joint measurements. All this significantly decreased the signal/noise ratio. As a result, the fluctuating scattering signals caused by the turbulent fluctuating CO_2 concentrations were seriously contaminated and needed to be corrected.

Data Analysis

In order to obtain quasi simultaneous measurements of velocity and concentration while removing the above mentioned background contributions from the molecular scattering signals, a complex data acquisition and reduction scheme was developed. For this part of the study no axial velocities were recorded. The output from the vertical component of the LDV was passed through two counters in series which were set to accept signals within a coincidence window of 10 μsec to reduce the noise in the velocity signal. Velocity signals were processed into probability density functions (pdf's) from which mean and rms velocities were calculated.

The digitized output from the Rayleigh photomultiplier was transferred to the computer's memory either as pure Rayleigh or LDV triggered Rayleigh measurements. For the pure Rayleigh measurements the photomultiplier output was transferred at a rate of 125,000 data/sec through a Preston A/D converter to the memory of the computer. Thirty two thousand Rayleigh data points were collected at each location and processed into pdf's from which mean and rms concentrations were determined. In the second technique the Rayleigh signals were measured simultaneously with those from the LDV. These signals were then stored jointly in the computer. Since the arrival time of the seed particles which gave rise to the velocity measurements was random, Rayleigh scattering data had to be acquired continuously and matched with the velocity data as they arrived from the counters. For this purpose the memory of the computer was divided into three buffers. Newly arriving Rayleigh data were stored in one 32K buffer while the velocity data were stored in a second 32K buffer until the Rayleigh buffer was filled. The LDV buffer was then searched for validated data points which were matched with the corresponding Rayleigh values. Twenty Rayleigh points at 8 μsec intervals were collected before and after each validated velocity measurement. They were averaged and stored along with their velocity values in the third memory buffer. The LDV and Rayleigh buffers were then overwritten with a new data batch. The low seed rate required for successful Rayleigh measurements resulted in a typical data rate of 10-20 data/sec. Since a full tank load of CO_2 only provided a 30 minute run time, only 1000 combined velocity-concentration data pairs were measured at each position. Rayleigh signals above a threshold voltage, selected to discard signals caused by Mie scattering from particles in the test volume while still accepting those from CO_2, were rejected.

Both continuous and LDV triggered concentration measurements were carried out at each location. In addition, pure LDV measurements were made with air as a bleed gas and with titanium dioxide particle seeding in the main flow. Because of the heavier seeding and since air rather than CO_2 was used for the bleed it was possible to obtain 10,000 velocity points per location which were compared with the results of the 1000 LDV data from the combined measurements. Furthermore, comparison of the continuous and LDV triggered concentration measurements permitted a check for possible concentration bias towards higher air concentrations when the Rayleigh signal is only accepted as a seed particle passes through the test volume. Such bias could have been possible since the bleed gas could not be seeded.

The data were reduced, at first, by assuming that the magnitude of the shot and Johnson noises associated with the photomultiplier and its circuitry, the background glare and the particle generated noise were independent of the CO_2 injection. The local CO_2 concentrations were, thus, determined at each point from the simple differences in scattering intensities between the CO_2 injection and the no injection cases. This simplified data reduction scheme resulted in CO_2 concentration profiles which were reported in a Technical Note accepted for publication in the AIAA Journal.[2]

However, a close inspection of the shape of the concentration pdf's revealed a small change in the contribution to the pdf's by dust particles depending on the local concentrations of the bleed gas. This caused minor changes in the profiles of the mean concentrations but introduced an unacceptable error in the covariances of the velocity and concentration which are far more sensitive to the quality of the data. A more sophisticated data reduction technique was, there- fore, developed. Here the dependence of the contributions of the particle noise to the measured pdf's upon the concentration of injectant gas at each point was accounted for. In addition, the actual pdf's of the electronic and particle generated noise rather than only their means were subtracted out. This paper reports the mean CO_2 concentrations obtained using the improved data reduction technique. Furthermore, the distribution of the velocity-concentration covariance in the cold flow which could not be obtained from the measurements using the simplified data reduction scheme were calculated using the velocity weighed pdf's in the new data reduction technique and are presented.

The mathematical details of this novel deconvolution technique are described in an article submitted to <u>Combustion and Flame</u>[6] and will, therefore, not be elaborated in detail here. Briefly, as shown in Fig. 2 the measured pdf's consist of a Gaussian due to electronic noise, a delta function due to glare and a contribution by the particles which was found to be double peaked. A delta function at zero intensity due to instants when no particles were in the test volume is also included. The schematic also shows delta functions due to pure air and pure CO_2 which are replaced by a single broad band pdf in the case of mixed air and CO_2. As the content of CO_2 increases, the pdf experiences a leftward shift due to a decrease in particle contamination and a rightward shift due to the measured level of CO_2. Similarly, the width of the pdf changes due to the effect of the CO_2 fluctuations and changes in the particle contributions. In order to separate these effects, an analytical method involving Fourier transforms was developed which permitted the deconvolution of the concentration pdf's as well as the joint velocity concentration pdf's.

<u>Results and Discussion</u>

Local velocity, bleed gas concentration and simultaneous velocity-concentration measurements were carried out at stations in the recirculation zone, at reattachment and downstream of reattachment. The axial inlet velocity was 70 m/sec and the bleed gas velocity was maintained at .5 m/sec. The latter corresponds to a typical gasification rate of the solid fuel in a solid fueled ramjet.

Vertical velocity profiles obtained from 10,000 data points per location using air as a bleed gas and titanium dioxide particle seeding were compared with those obtained from 1000 data points in the combined LDV-Rayleigh mode using natural seeding and CO_2 as a bleed gas. They were found to agree reasonably well. Similar agreement was obtained for the vertical turbulence intensities. This indicates that there is little loss in accuracy in the velocity measurements when using natural dust in the laboratory as seed material and restricting the number of data points to 1000.

Similar comparisons were carried out between the concentration data measured continuously using 32,000 values per station and concentrations obtained from velocity triggered measurements for which only 1000 averaged values were obtained at each location. These are shown in Fig. 3. Although there is somewhat more scattering in the concentration data obtained from the joint measurements than in those from the pure measurements, overall agreement is good. This is particularly important since it indicates that no significant concentration bias towards air was introduced by the fact that only the air and not the CO_2 could be seeded. None of the concentration pdf's were bimodel, indicating that the residence times of the bleed gases close to the porous plate zone were long enough for molecular mixing to prevent any pockets of bleed gas to be observed above .1 step heights above the bleed plate.

Fig. 3 shows representative samples of the concentration profiles at distances 5.9, 7.3 and 8.8 stepheights downstream of the step. Also shown are the profiles calculated using a modified k-ε model which has been presented elsewhere.[1] Reattachment for this flow occurs at approximately 7.3 stepheights. The measurements clearly agree well with the predicted values. The concentration gradients were generally correctly predicted in the forward parts of the recirculation zone and somewhat underpredicted past reattachment. Downstream of reattachment the main and bleed gases were, thus, slightly better mixed than predicted. Closer to the step the process was more diffusion controlled. This observation is in close agreement with the expectations from the velocity measurements.[1] Furthermore, the mean concentration data obtained using the simple data reduction technique and those presented here do not exhibit any significant differences introduced by the more sophisticated deconvolution technique.

The real power of this improved technique, however, becomes evident when calculating the velocity-concentration covariances which could not be obtained at all using the simplified data reduction scheme. Fig. 4 shows the profiles of the velocity-concentration covariances at the same locations in the test section as above. Once again the predicted values are shown as a solid line. Clearly, the agreement between the measured and calculated values of the covariance is not as good as those for the mean concentrations. This could, in part, be due to remaining uncertainties in the measured values of the covariance. However, Fig. 4b, which corresponds to the reattachment location indicates acceptable reproducibility of the data, especially considering the low signal to noise ratio of the measurements. It, therefore, appears that while the model quite accurately predicts the overall shape of the covariance profiles, it does consistently overpredict the magnitude of the covariance.

Conclusions

A novel technique for removing background noise caused by scattering from windows, walls and particles in the flow as well as shot and Johnson noise was applied to the pdf's of Rayleigh scattering signals. The resulting pdf's were used to determine the bleed gas concentration and velocity-concentration correlations in the highly turbulent flow over a backward facing step with bleeding from the wall behind the step. Molecular mixing in the recirculation was found to be excellent. Agreement between the measured bleed gas concentration profiles and those predicted using a modified k-ε model were very good, although the flow downstream of recirculation was found to be better mixed than predicted. The improved data reduction technique really showed its full potential in the extraction of the velocity-concentration covariance from the measurements which exhibited low signal to noise ratio. Despite the remaining uncertainties in the covariance it becomes clear that the k-ε model, while correctly calculating the shape of the profile, tends to overpredict the magnitude of the velocity-concentration covariance. Currently, this work is being extended by replacing the CO_2 with a hydrogen-argon mixture and running the tests under burning conditions. Velocity, concentration and temperature fields are being determined using a combined LDV-Raman technique.

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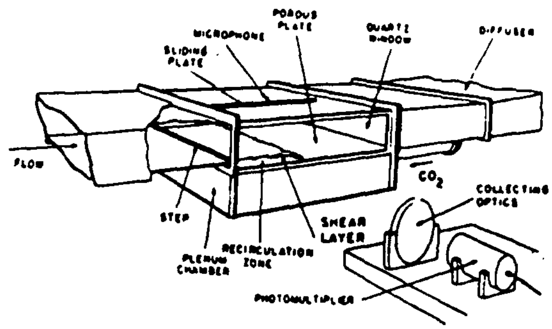

Fig. 1: Facility Schematic.

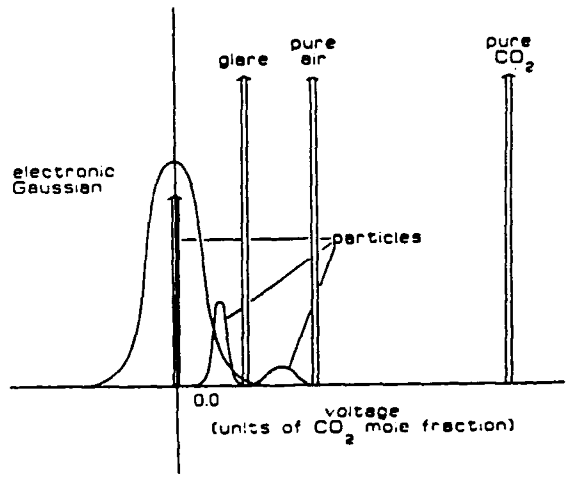

Fig. 2: Individual component pdf's of the Rayleigh molecular scattering signal. The voltage data has been converted to mole fraction units for CO_2.

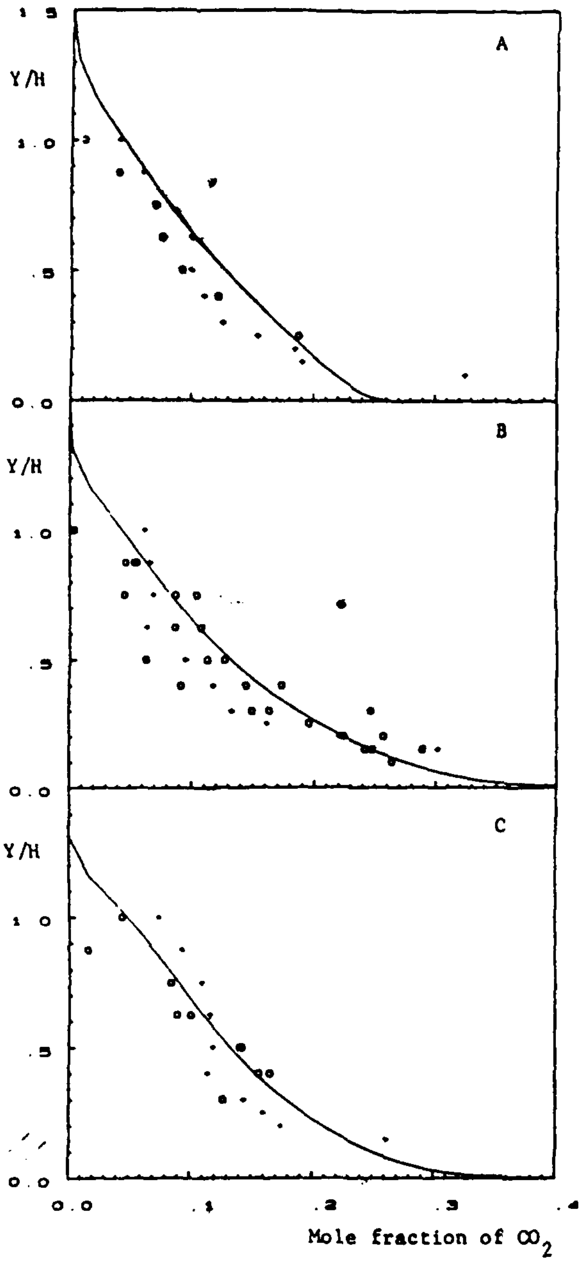

Fig. 3: Concentration of bleed gas vs. height above the tunnel floor for CO_2-air mixture as injectant gas at different axial location: A-5.9 stepheights, B-7.3 stepheights and C-8.8 stepheights. + continuous data acquisition, o seed particles triggered data acquisition, - predicted using k-ε.

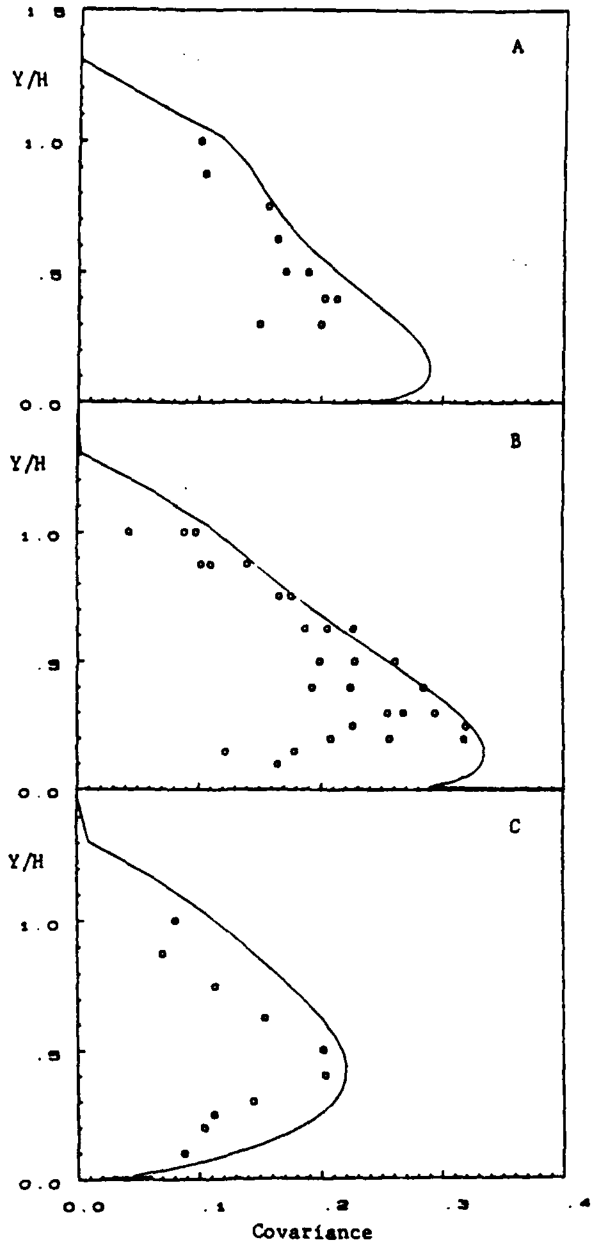

Fig. 4: Velocity-bleed gas concentration correlation vs. height above the tunnel floor for CO_2-air mixture as injectant gas at different axial locations: A- 5.9 stepheights, B-7.3 stepheights and C-8.8 stepheights. o seed particle triggered data acquisition, - predicted using k-ε.