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# FLOW PROCESS IN COMBUSTORS

FINAL TECHNICAL REPORT ON GRANT NSG-3019

NASA Lewis Research Center

C. J. Marek, Technical Monitor



Prepared by F. C. Gouldin

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## INTRODUCTION

Research on this grant consisted primarily of studies of fluid mechanical effects on combustion processes in steady flow combustors, especially gas turbine combustors. Flow features of most interest were vorticity, especially swirl, and turbulence. The research included theoretical analyses, numerical calculations and experiment. The theoretical and numerical work focused on noncombusting flows, while the experimental work, which formed the bulk of the research program during the later years of the grant, consisted of both reacting and non-reacting flow studies. Our objective in this research was to form a better understanding of the influence of vorticity (swirl) and turbulence on fluid dynamics and combustion dynamics occurring in combustors of interest to Lewis and to develop an experimental data set, e.g. velocity, temperature and composition, for a swirl flow combustor which could be used by combustion modelers for development and validation work. We believe we have been quite successful in achieving these specific research goals. In addition, our NASA grant has helped support and train a large number of graduate students both for the M.S. and the Ph.D. degrees, see Appendix I.

The scope of our research is clearly indicated in the list of papers and publications resulting in whole or in part from grant research, Appendix III, and by the list of theses related to the Grant, Appendix II. Work on the grant and results are fully reported in these theses, reports and publications (copies of the most recent ones are attached). Therefore, details of the work and results will not be presented here. Instead, a brief summary of our findings and their implications for research, development and design is presented.

## RESEARCH SUMMARY

### Swirl Flows

Studies of swirling recirculating flow* formed a major component of Grant research efforts. Professor Leibovich led a series of studies on vortex breakdown in high Reynolds number flow which built on previous work wherein ideas by Benjamin [1] had been exploited and a trapped wave model for the axisymmetric form of vortex breakdown was developed [2,3]. Faler [4] made careful observations of vortex breakdown forms for different flow conditions and measured the velocity field of an axisymmetric vortex breakdown. Complicated, unsteady nonaxisymmetric flow features were observed by Faler in the central recirculation zone and are attributed to flow instabilities. Further observations of these flow patterns at higher Reynolds numbers were made by Garg [5], while a complementary theoretical study of these instabilities was made by Huang [6]. Coherent flow patterns are frequently observed in turbulent, as well as laminar, swirling flows, and many important questions concerning them, including their connection to instability phenomena, remain to be answered. Professor Leibovich continues work on instability problems with other sponsorship.

A series of numerical calculations were carried out with grant support building on work for laminar swirling flows by Torrance and Kopecky [7]. Under Professor Gouldin's guidance several turbulent flows were studied using a k-$\epsilon$ turbulence model. Kubo [8] used a stream function-vorticity, finite difference code to evaluate the effect of various flow parameters on the

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* Lin and Moore [25] on a previous NASA Grant (NGL-33-010-042) studied flow recirculation induced by azimuthal vorticity (smoke rings) rather than swirl.

recirculation zone formed in a confined concentric swirling jet flow composed of a circular jet surrounded by a second annular jet. Coudeyras [9] modified Kubo's code to study flow behind a single NASA swirl-can module, while Leu [10] investigated the same code to assess the solution sensitivity to changes of inlet conditions and the rate of convergence. Multiple recirculation zones were found by Coudeyras for the swirl-module, and Haines [11] attempted to verify this observation by studying an actual swirl module in a water flow facility. He found that the flow was highly unsteady with discrete low frequency oscillations and that the inlet flow (to the test section) from the module in the mean was not axisymmetric as assumed in the calculations. Leu found very slow convergence for the calculations in the vortex core region.

Based on the work described so far a number of conclusions were reached. The generation of flow reversal in the swirling flows which we have studied is an inertia dominated process (viscous forces and Reynolds stresses may be neglected). A proper prediction of these flows requires accurate specification of the inlet and boundary conditions. An accurate turbulence model is of secondary importance to the prediction of recirculation but is required to predict flow in the recirculation zone and for predicting species and energy transport in combusting flows. The instabilities observed in laminar flow must be modeled if these flows are to be fully understood and discrete frequency oscillations related to these instabilities may be important in turbulent flow as well.

Vu and Gouldin [12], using pressure probes and hot-wire anemometers, conducted velocity measurements in an experimental flow tunnel with a concentric jet configuration similar to that studied numerically by Kubo [8]. A five-hole pressure probe operated in the null mode was used to find mean flow speed and direction, while a single element hot-wire sensor was used to measure velocity fluctuation characteristics such as the turbulence intensity and the Reynolds stresses. The influence of swirl level on the recirculation zone was studied and extensive measurements of mean flow and turblence quantities for two flow conditions were made to provide data for numerical model development and validation. These data have been supplied to a number of investigators including researchers at Garrett, General Electric, United Technologies and Brigham Young University. These measurements are considered quite successful. (Results of recent laser doppler velocimetry (LDV) measurements at Carnegie-Mellon University [13] on an almost identical flow apparatus have confirmed the results.) Additional velocity measurements with LDV in this flow configuration have been made at Cornell in combusting and noncombusting flows with emphasis on mean velocity and rms velocity fluctuations [14,15].

## Combustion Studies

Experimental investigations of the combustion characteristics of a premixed gaseous-fueled swirl combustor with a concentric jet configuration similar to the one described above formed a second major component of our grant research. The combustor was fired on methane and propane and was operated at atmospheric pressure without preheating. Construction and early testing of the combustor including the determination of blow-out limits for methane firing were carried out under SNF funding [16]. With NASA support exhaust emissions and combustion efficiency were measured as a function of flow conditions [20,21] for methane and propane firing. For two specific flow conditons sampling and thermocouple probes were used to measure mean temperature and gas composition distributions in the combustor [17], while

Beyler and Gouldin [18] measurement chemi-luminsecent emissions from the combustor to determine the time-mean location of the reaction zone for the same two conditions.

From these measurements and velocity measurements [14,15] the following picture of the combustion process emerges:

1. Combustion occurs in a relatively thin (few mm) turbulent reaction zone with characteristics very similar to a premixed turbulent flame.
2. Reaction begins on the combustor centerline upstream of the recirculation zone where the local effective turbulent flame speed equals the local mean axial velocity.
3. The reaction zone propagates radially as it is carried downstream.
4. The reaction zone lies in the boundary layer flow around the recirculation zone.
5. The primary role of the recirculation zone in flame stabilization is to provide a low mean velocity region upstream of its front stagnation point.
6. Temperatures are high in the recirculation zone and therefore $NO_x$ formation rates and concentrations are high. The contirbution of this region to exhaust $NO_x$ is not known since the flux of $NO_x$ out of the recirculation zone by turbulence has not been established.
7. Significant amounts of $NO_2$ are observed in the exhaust flow and the $NO_2/NO_x$ fraction is larger for conditions which promote mixing of the two jet streams - inner premixed fuel/air and outer air. Reasonable chemical kinetic mechanisms for the conversion of NO to $NO_2$ have been proposed by Chen [19].
8. Combustion eficiency is low in this configuration in part becasue of the absence of high pressure and preheat. Efficiency is determined by the

ability of the flame to propagate radially across flow streamlines. In turn, this ability is determined by the turbulence levels which influence flame speed, by the mean velocity patterns and by the mixng between the two jets. These different factors interact in a complex way. Small, apparently minor changes in flow conditions result in significant changes in efficiency [21]. Similar results are obtrained for methane and propane firing implying that chemical kinetics play a secondary role in determining the flame speed and hence combustion efficiency.

9. Swirl induces significant radial pressure gradients which affect turbulence levels in cold flow and to a much larger extent in hot flow where density fluctuations introduce new terms into the turbulence equations. This interaction explains the dramatic change in flame appearance which we observe when swirl levels are changed.

Two important final observations can be made regarding the implications of our findings on swirling flow combustion with premixed reactants. The formation of a recirculation zone is dominated by inertial effects - viscous and turbulent stress terms may be neglected in the mean flow equations - and wave motions may be important to the process. On the other hand combustion processes which are influenced by heat and mass transfer are greatly influenced by turbulent transport, and therefore good turbulence models are required to model combusting flows. Research on flow field prediction has tended to emphasize turbulence model development. In part this concern is misguided and diverts attention from the important questions of proper inlet and wall boundary layer specification, of numerical convergence and numerical error and of the roles of flow asymmetry and instability. In view of what we now know concerning swirling flow proceses one is forced to conclude that no numerical code is satisfactory for flow prediction when a central recirculation zone is present and that agreement obtained so far is fortuitious.

In diffusion controlled combustors with liquid fuel sprayed into the recirculation zone, reaction occurs for the most part in the mixing region between the recirculation zone and the surrounding flow. This is not the case for a premixed combustor where fuel is injected upstream of the recirculation zone and then flows around the recirculation zone. In premixed flows, high combustion efficiency depends on the ability of reaction to penetrate this surrounding flow, for a flame to propagate away from the recirculation zone. For such combustors turbulent flame dynamics are of paramount importance, while the recirculation zone plays a secondary role. This important distinction between premixed, prevaporized combustors and liquid fueled, diffusion controlled combustors is not fully appreciated.

Turbulent Flame Studies

A third major componet of our NASA funded research was a study of premixed turbulent flames. The motivation for this work is two fold - to study the influence of turbulence on combustion in an uncomplicated flow field and to improve our understanding of turbulent flame processes which are important in premixed, prevaporized combustors. This work began with modeling efforts by Gouldin [22] who proposed a flame speed correlation and concluded with a series of experiments on a laboratory burner. These experiments composed the major portion of our research on turbulent flames and were the work of two successful Ph.D. candidates - K. O. Smith and K. V. Dandekar.

Smith [23] developed a burner for studying combustion in a well defined turbulent flow-grid turbulence-and he developed and refined a novel technique for measuring the turbulent flame speed as a function of position in the flow. Preliminary laser velocimetry measurements and temperature measurements were performed by Smith as well. A large amount of data of good precision were obtained by Smith for a range of flow conditions in methane-air flames.

The flame speed measurement technique was further refined by Dandekar [24] who measured flame speed for propane-air, ethylene-air and methane-air mixtures. Dandekar used laser velocimetry and Rayleigh scattering to make extensive measurements of velocity and molecular number density (the reciprocal of temperature) in methane-air flames. Velocity measurements revealed considerable streamline curvature across the reaction zone which is dependent on the mixture strength and flame angle with respect to the reactant flow. Large changes in velocity fluctuation levels in the reaction zone were also observed indicating a coupling between combustion dynamics and turbulence dynamics. The density measurements implied a wrinkled-laminar-flame structure for the turbulent flame which is consistant with other findings. The laminar flame thickness was found to be the same order as the turbulent flame thickness, a common situation for flames in low turbulent Reynolds number flows.Frequency spectral analyses of the density data indicated that the wrinkling of the laminar flamelets or flame sheets is not determined solely by the turbulence dynamics but that instabilities of the flamelets may be triggered by the turbulence. These expeiments clearly show that the combustion affects turbulence fluctuations and that there is a strong coupling between chemical dynamics and heat release and turbulence dynamics. Further studies of these dynamics are of great importance to the understanding of premixed turbulent flames and we plan to continue our research in this area.

## CLOSURE

Over a seven year period we have received support from by NASA Lewis. With this continued support we have been able to attack and solve a variety of flow and combustion problems. The constancy of this support has allowed us to attack large and complex problems from more than one prospective, while regular review of our work has helped to maintain our focus on NASA problems. This support also has helped train a number of graduate students who are now either still in school or are active in industry and teaching and thus a benefit to the nation. This NASA support is greatly appreciated and gratefully acknowledged.

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## APPENDIX I - STUDENTS AND STAFF SUPPORTED BY GRANT NSG-3019

| NAME | CURRENT EMPLOYMENT |
| --- | --- |
| M. S. Anand | Cornell University, Ph.D. candidate |
| C. L. Beyler | Harvard University, Ph.D. candidate |
| J-Y. Chen | Cornell Univeristy, Ph.D. candidate |
| C. J. Coudeyras | Unknown |
| K. V. Dandekar | Assistant Professor<br>University of Illinois, Chicago Circle |
| J. H. Faler | Corning Glass Works<br>Wilmington, NC |
| A. K. Garg | Cornell University, Ph.D. candidate |
| J. R. Haines | McDonald-Douglas Corporation<br>Oak Ridge, TN |
| D. Hatziavramidis | Shell Research and Development<br>Houston, Texas |
| L-J. Leu | Associated Technologies Incorporated<br>Clifton, NJ |
| M.J. Oven | Foster-Miller Assoc. Inc.<br>Waltham, Mass |
| K. O. Smith | Solar<br>San Diego, CA |
| B. T. Vu | Avco Everett<br>Cambridge, Mass |
| R. A. Yetter | Princeton University, Ph.D. candidate |

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