AD-A280 446

[REPORT DOCUMENTA]TION PAGE

Form Approved
OMB No. 0704-0188

Pu[blic reporting burden for this collection of information is estimated to ave]rage 1 hour per response, including the time for reviewing instructions, searching existing data sources, ga[thering and maintaining the data needed, and completing and reviewing] the collection of information. Send comments regarding this burden estimate or any other aspect of this coll[ection of information, including suggestions for reducing this burden, to] Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Dav[is Highway, ... and to the Office of M]anagement and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 92/4/1	3. REPORT TYPE AND DATES COVERED annual 92/2 to 93/2

4. TITLE AND SUBTITLE
Fundamentals of Acoustic Instabilities in Liquid-Propellant Rockets

5. FUNDING NUMBERS
G - 91-0130

6. AUTHOR(S)
F. A. Williams

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California San Diego
9500 Gilman Drive
La Jolla, CA 92093-0310

DTIC ELECTE JUN 21 1994 S G D

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 94 0367

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

68 94-18980

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In this program, equations were written describing combustion instability in liquid-propellant rocket motors. The nonhomogeneous nature of the acoustic medium was taken into account, with the possibility of both subcritical and supercritical bifurcations occurring in the liquid-gas system. Attention was focused on characteristic times of the various flow, mixing and combustion processes as they arise in the newer engines of interest to the Air Force, in an effort to identify important physical phenomena in the instability and to achieve tractable descriptions of the instability processes. Theory was compared with available experimental observations in an effort to evaluate current theoretical capabilities.

14. SUBJECT TERMS
Combustion Instability, Liquid-Propellant Rocket[s]

15. NUMBER OF PAGES 6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

94 6 20 047

91-0130

AFOSR-TR- 94 0367

Fundamentals of Acoustic Instabilities in Liquid Propellant Rockets
AFOSR G - 91-0130

INTRODUCTION

This research addressed problems of combustion instability in liquid-propellant rocket motors, with attention given to both hydrogen-oxygen systems and storables. The studies were theoretical and involved both asymptotic and statistical methods of applied mathematics. The aim was to improve understanding of the phenomena of combustion instability and to indicate potentially useful approaches to instability analyses.

OBJECTIVES

The overall objective of this research was to improve understanding of the mechanisms by which flow, mixing and combustion process are coupled to acoustic fields in liquid-propellant rocket motors. Particular attention was focused on effects of spatial and temporal inhomogeneities of the acoustic media which are associated with turbulence and with two-phase flow. Appropriate statistical approaches were provided for different types of inhomogeneities. In addition, amplification mechanisms coupled with finite-rate chemical reactions were analyzed by use of activation-energy asymptotics and other asymptotic methods.

ACCOMPLISHMENTS

Rotational Inviscid Flow Effects in Laterally Burning Motors

As a first step towards investigating instabilities, steady-state flow fields in rocket motors were addressed. A theoretical analysis to determine the effects of mass addition on the inviscid but rotational and compressible flowfield in a porous duct with the injection rate dependent of the local pressure was performed for large ratios of length to duct diameter. The problem of describing the flow was reduced to the solution of a single integral equation. The ratio of specific heats, γ, and a constant pressure exponent, n, measuring the dependence of the rate of mass injection on the local pressure, are the parameters of the solutions. The integral equation was solved numerically, and parametric results were obtained for γ varying from 1 to $\frac{5}{3}$ and for n varying from 0 to 1. A choking phenomenon is exhibited at a critical length of the duct in the vicinity of which the Mach number approaches unity. The choking condition, which is relevant to the operation of nozzleless solid-propellant rocket motors, was obtained parametrically in the present study and compared with corresponding results for irrotational, quasi-one-dimensional flow. The rotationality reduces the choking pressure.

Effects of Spatial and Temporal Inhomogeneities Produced by Turbulence and by Two-Phase Flow

Two distinct approaches to the theory of stochastic effects in the combustion instability of liquid-propellant rockets were developed. In one approach, dealing with effects of spatial inhomogeneities in the acoustic medium associated with two-phase flow and with turbulence, attention is restricted to the particular class of interactions in which the characteristic time scale of turbulence is asymptotically large compared with that of acoustic waves, so that the acoustic medium is considered to be a quasistationary random medium. In addition, it is assumed that the acoustic wavelength is long compared with any scale of inhomogeneity within the chamber, motivating a homogenized description, in which averages of state variable becomes appropriate. On the basis of these assumptions, the Navier-Stokes equations for two-phase flows were reduced to a nonhomogeneous stochastic Helmholtz equation. Source terms of the equation were identified as arising mainly from phase change, from homogeneous chemical reaction, and from spatial variations of wave properties such as sound speed.

To handle the stochastic wave equation, the method of smooth perturbation was used and resulted in a Helmholtz equation for an equivalent deterministic acoustic medium. With use made of Green's integral theorem, the dispersion relation for transverse acoustic modes in cylindrical chambers was obtained in the form $k^2 = k_0^2 + ik_0^2 a + k_0 \mathbf{b} \cdot \mathbf{k} + k_0^4 c$, where $a, \mathbf{b}$ and c are calculated from appropriate averages of source terms. In particular, the $k_0^4 c$ term corresponds to the stochastic contributions arising mainly from the spatial correlations of the sound speed with the pressure response function, and of the local Mach number with the velocity response function. Compared with the deterministic contributions to the linear growth (or damping) rate, the stochastic contributions are found to be of the order of $(\ell_t/R)^{3/2}$ where ℓ_t is the characteristic length scale for turbulence and R is the chamber diameter, thus implying that most of the stochastic contributions comes from the larger turbulent eddies. The stochastic effects are expected to be significant in the transition regime in which the deterministic growth rate is close enough to zero for transition between stable and unstable domains to occur reasonably frequently by stochastic variations of the growth rate.

In another approach, emphasizing influences of turbulent-induced noise, the behavior of high-frequency combustion instabilities influenced by random temporal variation of the linear growth rate in this same transition regime are addressed. The Rayleigh criterion was generalized to account for turbulence-related spatial variations of the combustion response. Special attention was given to the distinguished limit in which the acoustic oscillations are rapid compared with the turbulent fluctuations, which in turn are rapid compared with the linear growth rate of the instability. It was shown that nonlinear acoustics of the instabilities need to be considered to describe the influences of turbulence. When this nonlinearity involves supercritical bifurcation, the turbulence tends to decrease the most probable intensity of the instability. When it involves subcritical bifurcation, the turbulence can produce a bimodal probability density function for the intensity of the instability, with appreciable probabilities of high-amplitude and low-amplitude acoustic oscillations but small probabilities of oscillations of intermediate amplitudes. These phenomena can have a bearing on erratic pressure-amplitude bursts sometimes observed in liquid-propellant engines.

A key observation of this last study is that the turbulence influences on the acoustics appear as multiplicative rather than additive noise. Comparison of the turbulence coherence time with the characteristic time of the combustion instabilities identifies two distinct interaction classes, depending on whether the coherence time is or is not much smaller than the characteristic instability growth time. Larger instabilities are associated with the second of these classes while the transition behavior in the first class involves random walks of the stochastic linear growth rate, requiring a statistical description. In a white-noise approximation, the Stratonovich rather Ito interpretation of the stochastic integral must be employed, and the Markov property of the white-noise process then enables the evolution of the probability density of the pressure amplitude to be described by a Fokker-Planck equation, whose stationary solutions lead to transition behavior that depends on the character of the bifurcation. There is a bimodal behavior for subcritical bifurcation in the hysteresis region. The size of the bimodal transition region is proportional to the time integral of the autocorrelation function of the turbulence-induced fluctuations of the linear growth rate. This result provides a possible mechanism for resurging patterns of the pressure amplitude.

Amplification Mechanisms Coupled with Finite-Rate Chemistry

Many different processes can contribute to linear amplification of acoustic oscillations in liquid-propellant rockets, and asymptotic analyses of these processes can help in assessing combustion instabilities. It is the intent of the present investigation to analyze a number of these processes. One such process is the strained planar diffusion flame considered here. Previous studies of diffusion-flame response postulated infinite chemical reaction rates (the Burke-Schumann approximation), while the present work is taking into account the influences of finite-rate chemistry, which can become important in environments having high turbulence intensities. The results demonstrate that the high sensitivity of the chemical reaction rates to temperature fluctuations can underlie important amplification mechanisms. As an initial simplification, a one-step, irreversible Arrhenius-type chemical reaction rate is employed, and a gaseous counterflow diffusion flame is adopted to represent flamelets subjected to nonuniform flow fields caused by turbulent fluctuations. It is intended later to introduce rate-ratio asymptotics for hydrogen-oxygen systems.

The analysis was performed by activation-energy asymptotics. The resulting flame structure for a given value of the reaction-sheet location is described by two sets of equations, one for the transport of momentum, thermal energy and reactant, and the other for the corresponding overall reaction rate of the flame. The acoustic response of the flame, obtained from the linear analysis, is found to be determined by two mechanisms, namely, oscillations of the reaction sheet induced by acoustic-produced fluctuations of the reaction rate, and oscillations of the field variables produced by the transport-zone response. The results show that analyses for the acoustic response of flames that do not consider finite reaction rates could significantly underestimate the amplification rate. Future works will apply similar methods to different types of flamelets which may be more realistic for rocket-engine combustion, such as single-droplet combustion, with and without forced convection and supercriticality.

CONCLUSION

This research has contributed to our understanding of ways to describe combustion instabilities in liquid-propellant rocket motors.

PUBLICATIONS

1. G. Balakrishnan, A. Liñán and F. A. Williams, Rotational Inviscid Flow in Laterally Burning Solid-Propellant Rocket Motors, *Journal of Propulsion and Power*, 8, pp. 1167-1176 (1992).

2. J. S. Kim, A Formulation for Transverse Acoustic Instability in Liquid-Propellant Rocket Motors, CECR Report No. 92-01, University of California at San Diego, La Jolla, CA, 1992, also to appear in *Proceedings of the First International Symposium on Liquid Rocket Engine Combustion Instability.*

3. P. Clavin, J. S. Kim and F. A. Williams, Turbulence-Induced Noise Effects on High-Frequency Combustion Instabilities, CECR Report No. 93-01, University of California at San Diego, La Jolla, CA, 1993, also to appear in *Combustion Science and Technology.*

4. J. S. Kim and F. A. Williams, Contribution of Strained Diffusion Flames to Acoustic Pressure Response, CECR Report No. 93-02, University of California at San Diego, La Jolla, CA, 1993, also to appear in *Combustion and Flame.*