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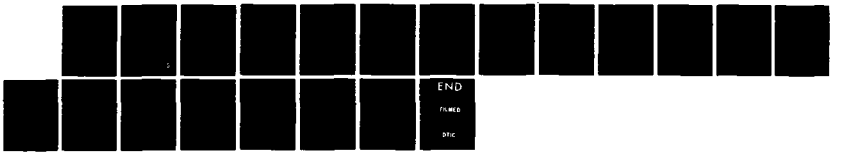

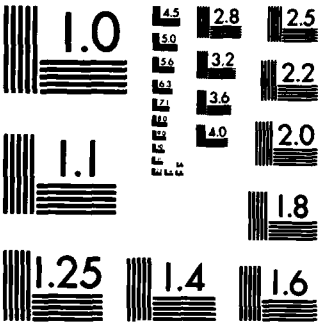

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AFOSR INTERIM SCIENTIFIC REPORT

on

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

Prepared for

Air Force Office of Scientific Research
Aerospace Sciences Directorate
Bolling Air Force Base

Co-Principal Investigators

Ben T. Zinn
Brady R. Daniel

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

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20. Abstract (cont'd)

increases as the thickness of the acoustic boundary layer increases. Experimental facilities for studying oscillating duct flows in the presence and absence of flames were developed. The cold flow studies verified the presence of an excess velocity region within the acoustic boundary layer (i.e., the Richardson Effect) and the dependence of the boundary layer thickness upon the frequency and wall injection velocity. The reactive flow studies showed that the behavior of the flame depends upon its location relative to the standing acoustic wave. When the flame was positioned next to a velocity antinode, unexpected instabilities appeared on its surface eventually resulting in severe flame distortion. Also, the measured C-C and C-H radiation signals were periodic and they oscillated with the same frequency as the acoustic wave.

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ABSTRACT

The primary objective of this study is the determination of the fundamental mechanisms responsible for the driving of axial instabilities by solid propellant flames. During the reporting period, the behavior of a premixed flame stabilized on the side wall of a duct in the presence of an axial acoustic field has been investigated both theoretically and experimentally. The developed model solutions show that driving occurs due to the combustion process heat addition while outside the reaction zone the waves are damped by viscous processes. This damping increases as the thickness of the acoustic boundary layer increases. Experimental facilities for studying oscillating duct flows in the presence and absence of flames were developed. The cold flow studies verified the presence of an excess velocity region within the acoustic boundary layer (i.e., the Richardson Effect) and the dependence of the boundary layer thickness upon the frequency and wall injection velocity. The reactive flow studies showed that the behavior of the flame depends upon its location relative to the standing acoustic wave. When the flame was positioned next to a velocity antinode, unexpected instabilities appeared on its surface eventually resulting in severe flame distortion. Also, the measured C-C and C-H radiation signals were periodic and they oscillated with the same frequency as the acoustic wave.

INTRODUCTION

At present the mechanisms which control the burn rates of solid propellants in unstable rocket motors are not clearly understood. These mechanisms involve solid and gas phase chemical reactions and heat, momentum and mass transfer and they generally occur within extremely thin regions (i.e., of the order tens of microns). Consequently, practically no experimental studies of these combustion processes have been undertaken to date, and all efforts in this area were confined to the development of theoretical models whose validity is open to question.

The objectives of this research program are:

(1) The determination of the characteristics of solid propellant gas flames in unstable solid propellant rocket motors; and

(2) The determination of the validity of state of the art solid propellant combustion response models.

The above are problems of much practical interest because it is well known that the interaction of the solid propellant flames with the flow oscillations is responsible for the driving of instabilities in rocket motors. Consequently, developing an understanding of the fundamental processes which control this interaction may lead to the development of practical solutions for reducing the driving provided by solid propellant flames. Furthermore, it is believed that the development of a fundamental understanding of oscillatory flames will also improve existing capabilities to

deal with other oscillatory flame phenomena, such as those encountered in unstable ramjets, pulsejets, and pulsating combustors.

To gain an understanding of oscillatory flames and their interaction with acoustic fields, the behavior of a premixed flame attached to the side wall of a duct with an axial acoustic oscillation (see Fig. 1) has been investigated during the reporting period. This flame was chosen for this study because it eliminated difficulties associated with diffusion processes while providing the investigator with a flame which possesses many of the features of actual propellant flames. Furthermore, such flames are amenable to experimental probing and they can be modelled using approaches similar to those utilized in solid propellant studies. By comparing the experimental and theoretical results this program will attempt to answer the following questions:

1. What features of the flame (e.g., maximum flame temperature, heat transfer to the propellant surface, rate and spatial distribution of the heat release, possible presence of oscillating vortices and so on) contributes the most to flame driving/damping of core flow acoustic oscillations, and

2. Are state of the art models of unsteady solid propellant flames capable of predicting the characteristics of such or similar flames under conditions simulating those encountered in unstable solid propellant rocket motors.

RESEARCH ACCOMPLISHMENTS

Efforts during the reporting period consisted of experimental and theoretical investigations of the interaction between the core flow oscillations and the flame shown in Fig. 1. The theoretical study solved the acoustic boundary layer equations in the presence and absence of chemical reactions. The solutions were required to satisfy an acoustic admittance boundary condition at the porous duct wall and boundary conditions imposed by the core flow acoustic oscillations at the boundary layer edge. The developed model differed from previous investigations of this problem (e.g., see Ref. 1) by the retention of all terms proportional to $\partial \bar{u}/\partial x$ in the conservation equations as it was felt that the velocity shear is not negligible within the boundary layer region. Comparisons between the predictions of the reactive and nonreactive models and the predictions of previous studies are expected to provide information about the effects of the mean flow shear and the chemical reactions upon the investigated phenomenon.

The following were predicted by the nonreactive model:

1. The damping provided by the wall region is proportional to the acoustic boundary layer thickness. The latter increases with increasing injection velocity at the porous wall and decreasing frequency.

2. A region of excess velocity, where the magnitude of axial acoustic velocity is larger than the corresponding velocity outside the acoustic boundary layer, exists within the acoustic boundary layer in

the presence and absence of flow injection through the porous wall. This corresponds to the well known Richardson Effect which had been discovered earlier (2) for oscillatory flows next to solid walls.

3. The developed cold flow model was used to predict the experimental trends observed in the studies of Hersh and Walker (3) investigated flow turning losses under AFRPL support. The model predictions were in agreement with the data measured in experiments conducted under conditions consistent with the model assumptions. This agreement strongly suggests that the so-called flow turning losses are due to viscous losses in the acoustic boundary layer.

Subsequent investigations with the reactive acoustic boundary model provided the following predictions:

1. The effect of mean flow shear is important near the acoustic velocity antinode where the magnitude of $\partial p'/\partial x$ is significant. Comparisons of the predictions of the present model with those of Ref.1 revealed that the two deviate considerably as the velocity antinode region is approached.

2. The model predicted the behavior of the dependent variables across the acoustic boundary layer under different operating conditions (e. g., see Fig. 2); predictions which will be checked in experimental phase of this program. Figure 2 describes the characteristics of both the steady flame and the acoustic boundary

layer. Significantly, v_r' which is a measure of the acoustic boundary layer driving increases in magnitude in the region where the reaction rate $\bar{w}q$ is nonzero and both quantities have their maxima at the same position. This result clearly shows that the driving is caused by the heat addition due to the combustion process. The observed decrease in v_r' beyond the maximum point is due to viscous effects, indicating that in this region viscous effects dominate the driving by the combustion process.

3. The model also predicted the presence of periodic vortex sheets within the flame region. This result is not surprising if one considers the vorticity equation

$$\frac{d\vec{\xi}}{dt} + \vec{\xi}(\vec{\nabla}\cdot\vec{v}) = \vec{\xi}\cdot\vec{\nabla}\vec{v} + (\vec{\nabla}\rho \times \vec{\nabla}p)/\rho^2 \qquad (1)$$

which shows that nonparallel pressure and density gradients (i.e., when $\vec{\nabla}\rho \times \vec{\nabla}p/\rho^2 \neq 0$) will produce vorticity. This term is indeed nonzero inside the investigated flame region as the presence of the flame creates a density gradient in the y direction and the imposed core flow acoustic pressure oscillation establisheds a nonzero, time dependent pressure gradient in the axial direction. These vortex sheets merit further study as depending upon the magnitude of their velocity jump they may experience Kelvin-Helmholtz type instabilities which may drastically change the character of the flow in the flame region.

The experimental phase of this program consisted of both cold and hot flow studies. The cold flow studies were conducted in a round porous tube closed at one end and connected through a valve to a vacuum chamber at the other end. A standing acoustic wave of desired frequency and amplitude was established in the tube by means of an acoustic driver and the velocity field in the vicinity of the wall was measured with a hot wire. The measured data was in good agreement with the predictions of the developed model. Specifically, both showed the existence of a Richardson layer with the velocity peaks occurring in nearly the same location and both showed that the thickness of the acoustic boundary layer increases as the magnitude of the injection velocity at the wall increases.

The experimental reactive flow studies included the development of a flat flame burner which was utilized to optimize the fuel/air mixing processes used in the preparation of a homogeneous combustible mixture; to investigate the stabilization of the flat flame on top of a porous ceramic plate; to investigate the seeding of the flame through the porous burner face which will be required in future flame LDV studies; and to investigate the potential use of the inclined slit technique in the determination of the steady temperature distribution in a direction normal to the flat flame surface. All of the developed solutions have been and/or will be utilized in the proposed experimental studies.

A schematic of the developed experimental setup is shown in Fig. 3. The acoustic drivers can be used to excite a standing acoustic wave of desired properties in the tube and capabilities exist for positioning the flat flame on any desired location on the standing acoustic wave. Experiments

can be conducted in the presence or absence of a hot mean flow. Capabilities have also been developed for shadowgraphy/Schlieren high speed cine visualization of the flow, flame radiation measurements and acoustic pressure and steady flame temperature measurements.

High speed cine flame visualizations at various locations on the standing acoustic wave revealed the following:

1. In regions away from a velocity antinode, the flame remains essentially flat and it is displaced up and down relative to the wall. The time dependence of the flame position oscillations were measured and correlated with the corresponding pressure oscillations. The results will be compared with the model predictions.

2. When the flame is positioned near a velocity antinode, small wavelets (i.e., instabilities) which grow in amplitude and propagate along the flame are observed. These wavelets result in flame distortion. They were not predicted by the developed model nor were they observed before under similar experimental conditions. The presence of these wavelets or instabilities may be significant and they will be further investigated in the future.

Flame radiation measurements revealed the existence of periodic radiation whose frequency was the same as that of the excited acoustic wave. Near future studies will investigate the phase relationship between the radiation and pressue oscillations in an effort to determine whether Rayleigh's criterion is satisfied by the investigated flames.

Finally, the flame visualization studies also showed that the flat flame stabilized farther away from the side wall as the amplitude of the oscillation increased. This could be due to nonlinear flow effects and it merits further study.

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2. Hegde, U. G., Chen, F. L., and Zinn, B. T., "Investigations of Reactive and Non Reactive Acoustic Boundary Layers on Porous Walled Ducts", Proceedings of the 21st JANNAF Combustion Meeting, Oct. 1984. Also, AIAA Paper No. 85-0235.

3. Narayanaswami, L., Daniel, B. R. and Zinn, B. T., "Investigation of the Characteristics of the Velocity-Coupled Response Functions of Solid Propellants", Proceedings of the 21st JANNAF Combustion Meeting, October 1984.

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7. Hegde, U. G., Chen F. L. and Zinn, B. T., "Investigations of the Acoustic Boundary Layer in Porous Walled Ducts with Flow". In preparation.

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PROFESSIONAL PERSONNEL

The following individuals contributed to the research effort described in this section:

Dr. Ben T. Zinn, Regents' Professor of Aerospace Engineering

Mr. Brady R. Daniel, Senior Research Engineer

Dr. Jechiel I. Jagoda, Assistant Professor.

Dr. Uday G. Hegde, Post-Doctoral Fellow

Mr. Julian Chen, Visiting Scholar from Northwestern Polytechnic Institute, Xian, People's Republic of China.

Mr. Subramanian V. Sankar, Ph.D Student.

Also, Mr. Lakshmanan L. Narayanaswami completed his Ph.D research entitled:

"Investigation of the Pressure-and Velocity-Coupled Responses of Solid Propellants using the Impedance Tube Technique"

in July 1984. The majority of this research was supported by the AFOSR Grant which preceded the present program.

PRESENTATIONS

1. "Investigations of Reactive and Non Reactive Acoustic Boundary Layers on Porous Walled Ducts," presented at the 21st JANNAF Combustion Meeting, Laurel, MD, October 1-4, 1984.

2. "Investigation of the Characteristics of the Velocity-Coupled Response Functions of Solid Propellants," presented at the 21st JANNAF Combustion Meeting, Laurel, MD, October 1-4, 1984.

3. "Investigations of the Acoustic Boundary Layer in Porous Walled Ducts with Flow," presented at the AIAA 23rd Aerospace Sciences Meeting in Reno, Nevada, January 14-17, 1985.

4. "Investigation of the Characteristics of the Velocity-Coupled Response Functions of Solid Propellants," presented at the AIAA 23rd Aerospace Sciences Meeting in Reno, Nevada, January 14-17, 1985.

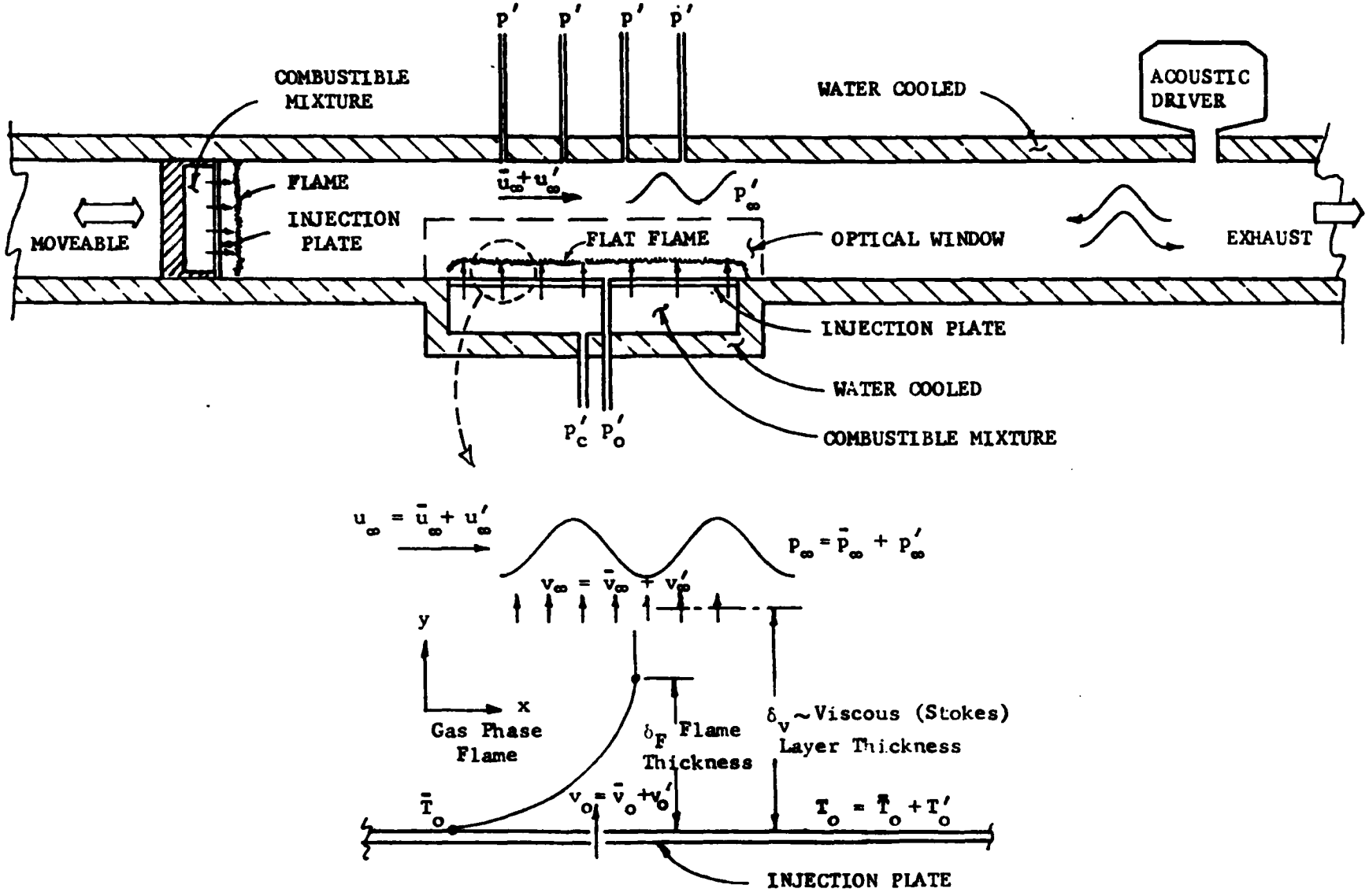

Figure 1. A Schematic of the Experimental Setup (above) and the Anticipated Flame Structure (below).

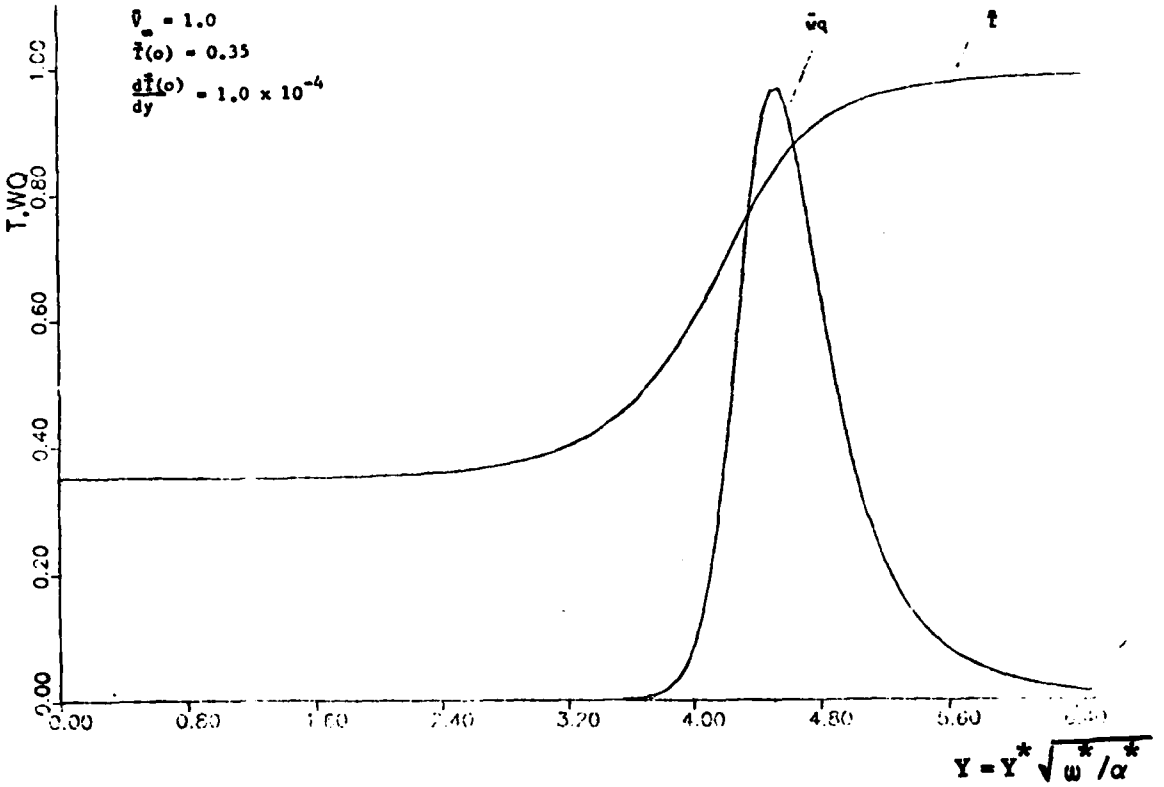

Figure (2-a). Predicted Steady State Temperature and Heat Release ($\bar{wq}$) Rate Distributions in the Flame Region.

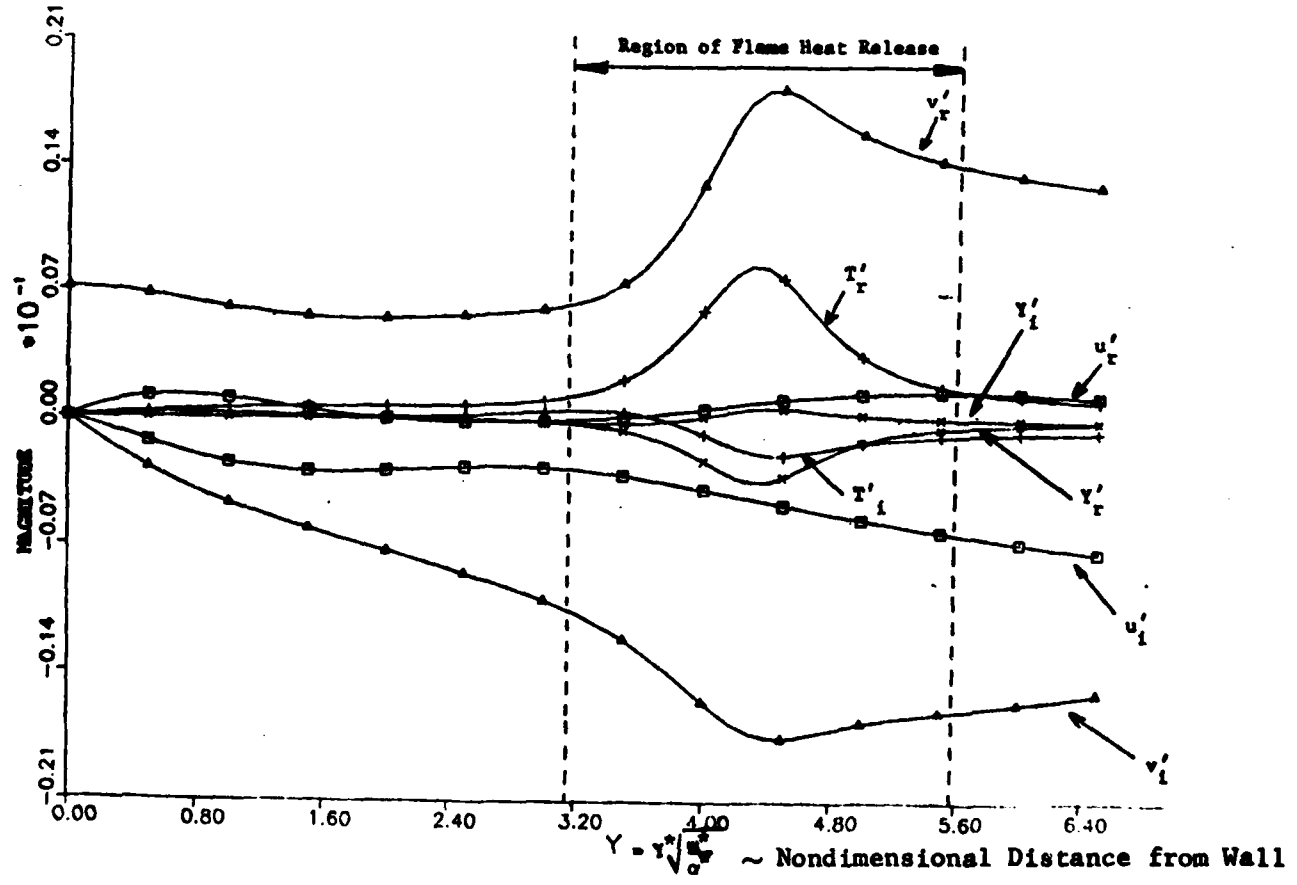

Figure (2-b). Predicted Oscillatory Solutions in the Flame Region; $\sqrt{\alpha^*/\omega^*}$ is the Thickness of the Stokes Layer.

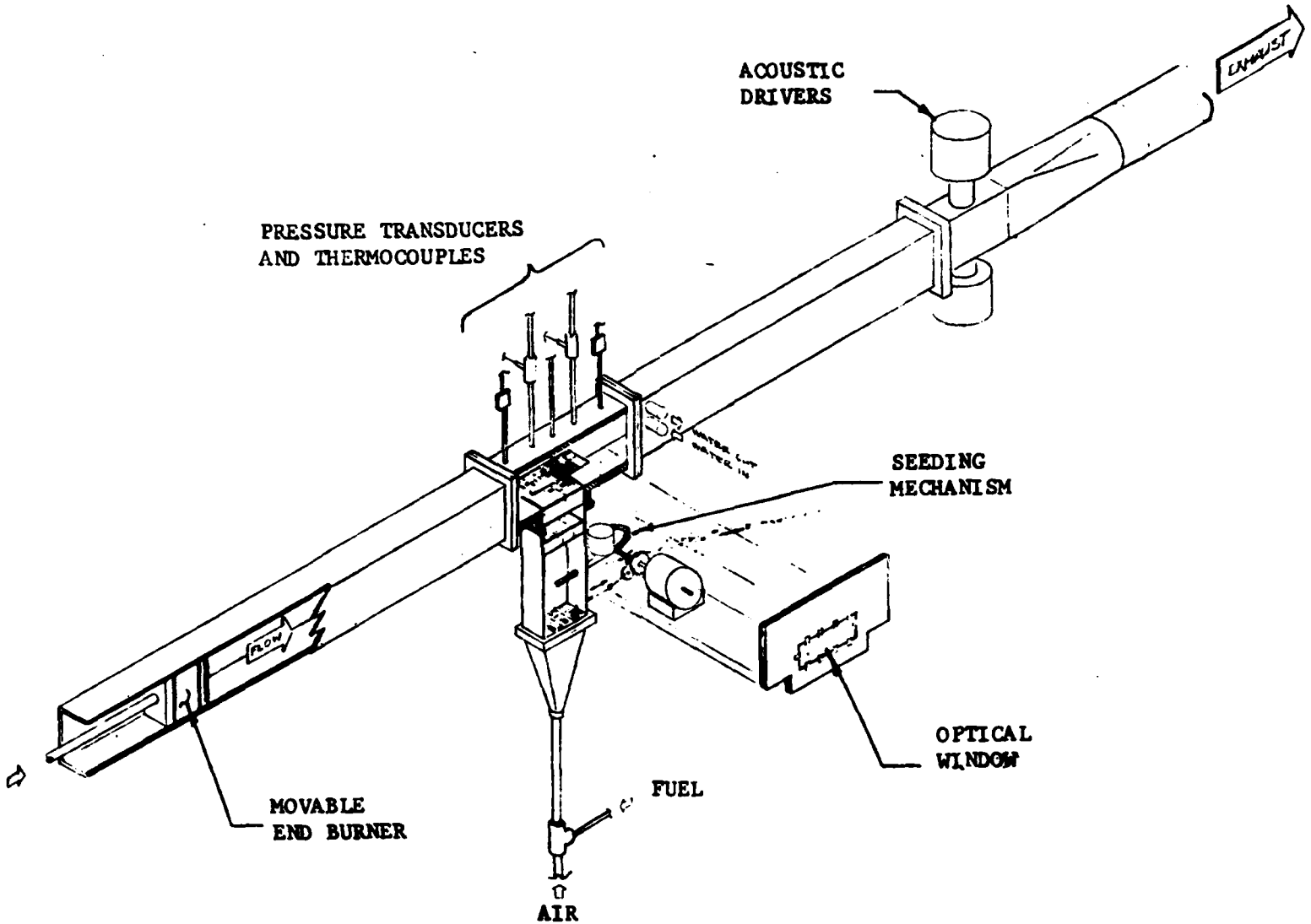

Figure 3. An Isometric of the Developed Experimental Setup.

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