TITLE: RESEARCH ON MECHANISMS OF EXCITING PRESSURE OSCILLATIONS IN RAMJET ENGINES

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SUMMARY/OVERVIEW

An analytical and experimental study is being made of the role of combustion in large vortical structures in the mechanism of unsteady and unstable burning in air-breathing engines. A large body of experimental evidence supports the contention that these periodic fluctuations are themselves generated by the nonsteady flow over the flame holders and other surfaces. The mechanism itself is relatively independent of the acoustic configuration of the powerplant and its installation and hence constitutes the fundamental element of the combustion instability process. Whether or not the mechanism is excited does, however, depend upon the detailed acoustic properties of the combustion chamber and its environment and in many circumstances it is apparent that non-linear acoustics plays an essential role. As a consequence, the program includes detailed analytical studies of linear and non-linear acoustics in combustion configurations as a means of coupling the instability mechanism to a particular environment. The effective separation of the instability process into i) its mechanism and ii) its environment is aimed at eventually providing means of rational scaling of laboratory size experiments.

TECHNICAL DISCUSSION

The program includes both analysis and experiments. The analytical work divides broadly into two parts: (1) Studies of the basic gasdynamic phenomena in non-steady two- and three-dimensional fields with strongly exothermic chemical reactions. The emphasis is on the combustion processes in vortex structures and the fluid-dynamic stability of the flow fields generated by the interaction of non-uniform fields with acoustic waves, and (2) development of the theoretical framework for studying pressure oscillations, constructed so as to accommodate the results of item (1). We intend that the analyses should provide not only general understanding of the possible mechanisms for pressure oscillations, but also scaling laws and guidelines for experimental work and for full-scale devices. We are carrying out both linear and non-linear analysis. The first provides information about the conditions under which oscillations will occur; and the second is required to determine the amplitudes to which unstable oscillations will grow. The experimental work is concerned with unsteady combustion processes which occur in flows past steps and flameholders, and concentrates on processes which occur in the shear layers and recirculation zone regions. Tests are being carried out at Caltech in a small scale burner which has the geometry of a ramjet dump burner. In the report for this year, the experimental work will be discussed.

The process under study involves the coupling between acoustic modes of the system and unsteady heat addition which results from unsteady burning in large vortices. These vortices are formed periodically at the flame holder lip by the velocity fluctuations associated with the acoustic field. Two phenomena should be distinguished here. The first concerns the production and development of the small scale structures which have been observed in isothermal shear layers and which are not directly related to acoustic disturbances or gross fluctuations in heat release. The second concerns large structures which have been observed in flame holder as well as dump burner systems and which are related to the shedding of vortices from the recirculation zone under the influence of longitudinal pressure disturbances. We believe that these large structures play a key role in the combustion instability problem and that they are not simply connected with the small structures.

The experiments are being carried out in a small blowdown facility which supplies a metered fuel-air mixture to a combustion system which consists of a plenum chamber and a combustion chamber whose lengths can be varied so that the fundamental resonant frequencies of the system vary from 190 to 530 hz. The combustion chamber is a rectangular duct 2.55 cm high, 7.6 cm wide and can be as long as 1 m. The flame holder is a 1.92 cm high rearward facing step which extends across the 7.6 cm width of the duct. For the data discussed here the exit is not choked. The stability limits for this system allow operation at fuel-air ratios in the range between 0.7 and 1.2 of the stoichiometric value for velocities in the range between 20 and 100 meters/sec. Instrumentation includes 6 to 10 high-frequency response pressure transducers located along the combustion chamber and at various points in the supply system. Estimates of fluctuations in local values of the heat release rate are made from measurements of the intensity of light emitted from the burning gas over a volume which extends across the 7.6 cm width of the duct and has an axial extent of 3 mm. Movies of shadowgraph images taken at about 6000 frames/sec and microsecond exposure shadowgraph photographs are used to visualize the flow. The pressure and light intensity signals are digitized and then are analyzed with Fast Fourier Transforms to obtain the spectra for these signals. Cross correlations between the light and pressure signals are being analyzed to check the Rayleigh criteria for instability.

A linearized and one dimensional acoustic analysis developed earlier in this program has been used to study the acoustic modes of this system. This numerical model includes the various area changes in the duct cross section area, the contraction of the duct at the flame holder and the increased speed of sound in the combustion chamber. The model has been extended this year to allow us to study the effects of an arbitrary forcing function which crudely models the effects of nonsteady heat addition at the flame holder. This addition also allows us to understand better the relative phases of the oscillations in various parts of the system. The model also allows us to predict the amplitudes of velocity fluctuations at the flame holder lip when the pressure fluctuations are measured in the experiments.

We have developed a physical model for one of the modes of combustion instability exhibited by this system which is based on the following observations. The most dramatic changes produced by the combustion instability in question is the change it produces in the shear layer which develops in the region just down of the flame holder lip and which separates the unburnt flow from the hot recirculation zone gases. When the instability is absent, the shear layer is relatively steady and exhibits the small vortices which we have come to associate with the shear layer. In contrast, when the instability is present, the shear layer is grossly distorted by the presence of large vortices which are periodically shed from the flame holder lip at the same frequency as an accompanying large amplitude oscillation in the pressure.

The frequency of the oscillation is always one of the duct modes and thus the frequency can be modified, by changing the length of the plenum chamber or combustion chamber, over the range from 180 to 530 hz. The oscillation can be eliminated by increasing the damping of the acoustic waves in the system, e.g. by placing steel wool in the plenum chamber.

The vortices grow rapidly as they move down stream and they impinge on the lower wall of the combustion chamber at a point between 3 and 6 ducts heights downstream of the holder. The velocity of the downstream motion of the vortex is only weakly dependent on the mean velocity at the flame holder and increases as the amplitude of the pressure oscillation increases. The vortices are shed when the magnitude of the pressure fluctuation at the flame holder begins to fall from its maximum value; the vortex moves downstream and impinges on the wall when the amplitude of the pressure fluctuation is positive and is increasing. Fluctuations in intensity of the light generated by the combustion process suggest that the heat release rate reaches its maximum acceleration when the vortex reaches the wall and when the fluctuation amplitude is close to zero and is rising.

Examination of the cross correlations of the pressure and light signals suggest that the fluctuations act to feed energy into the acoustic field in the region near the flame holder, but that farther downstream the fluctuations have a damping effect.

These results suggest the following model: The acoustic field produces a large amplitude velocity fluctuation at the flame holder lip which, in turn, causes a vortex to be shed from the lip. A marked acceleration in the heat release rate is produced shortly after the vortex reaches the wall. This process generates a pressure pulse which feeds energy into the acoustic field when the phase relationship between the pulse and acoustic pressure oscillation have the proper phase. The delay between the time when the vortex reaches the the wall and the acceleration in heat release occurs is a function of the chemical properties of the fuel-air mixture and thus depends on the fuel-air ratio and a characteristic chemical time for the mixture.

During the present contract year, we have started to investigate the effects on this instability of the chemical parameters of the system mentioned in the last paragraph. We are doing this by exploring the dependence on the fuel-air ratio of the premixed gases and by changing the fuel from pure methane to mixtures of methane and hydrogen. When pure methane is used as fuel, the instability is observed to occur for fuel-air ratios between 0.78 and 1.2 of the stoichiometric mixture ratio. When a mixture of 15% hydrogen and 85% methane is used as fuel, the same instability is observed but the lower limit for instability shifts to a value of 0.57 of stoichiometric. We believe that this shift can be understood in terms of the differences in a chemical reaction time for the two mixtures. Estimates for the chemical time we are using here are based on values measured experimentally in earlier experimental work on bluff body flame stabilization.

We are continuing to investigate the influence of chemical parameters on the instability process and are also, the influence of flameholder geometry. Finally, the growth and motion of the vortices in this type of system is being examined in a separate experiments involving the motion of isolated vortices.

Several reports are available now which describe the experimental aspect of our work. For example, see the Thesis by Dr. Dune A. Smith and the condensed version which was presented at the AIAA Propulsion Conference earlier this month. A number of papers are also available concerning the theoretical aspects of our work.

Smith, Duane A., "An Experimental Study of Acoustically Excited, Vortex Driven, Combustion Instability within a Reaward Facing Step Combustor." PhD Thesis, California Institute of Technology, Pasadena California, 1985.

Smith, Duane A. and Zukoski, Edward E., "Combustion Instability Sustained by Unsteady Vortex Combustion", AIAA/SAE/ASME 21st Joint Propulsion Conference, Monterey, California, July 1985.