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6. AUTHOR(S)
T.Y. Toong

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology
Department of Mechanical Engineering
Cambridge, MA 02139

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Examination of low-frequency instability in ramjet dump combustors shows that the oscillations are triggered and sustained by interactions between non-uniform entropy zones and pressure waves. Pressure waves are produced as entropy waves convect through a choked nozzle and entropy waves are generated as the pressure waves perturb the combustion zone. A linearized stability theory is developed for the case of near blow-off which corresponds to maximum rumble. Both oscillation frequencies and amplification rates are obtained. The theory is used to analyze the effects of combustor configuarations (including combustor-to-inlet area ratio, nozzle-to-combustor area ratio, combustor diameter, presence of flameholder and mode of fuel injection), inlet stanation temperature, and fuel-air ration on stability. Both predicted frequencies and stability characteristics agree well with the experimental observations. One prossible mechanism of turbulcnce-combustion interactions has been examined by studying the development of Tollmien-Schlichting waves in a reacting shear layer. Analysis shows that the growth rates of these waves depend on the order, the thermicity, and the activation energy of the Arrhenius-type chemical

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reaction as well as the disturbance wavelengths and Damkohler's similarity parameters. Two papers have been published and two are in preparation.

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ANNUAL TECHNICAL REPORT ON RESEARCH

SUPPORTED BY GRANT AFOSR-78-3662

(September 30, 1981-September 29, 1982)

Basic Instability Mechanisms in Chemically Reacting Subsonic and Supersonic Flows

T. Y. Toong

Massachusetts Institute of Technology

Summary of Progress

Examination of low-frequency instability in ramjet dump combustors shows that the oscillations are triggered and sustained by interactions between non-uniform entropy zones and pressure waves. Pressure waves are produced as entropy waves convect through a choked nozzle and entropy waves are generated as the pressure waves perturb the combustion zone. A linearized stability theory is developed for the case of near blow-off which corresponds to maximum rumble. Both oscillation frequencies and amplification rates are obtained.

The theory is used to analyze the effects of combustor configurations (including combustor-to-inlet area ratio, nozzle-to-combustor area ratio, combustor diameter, presence of flameholder and mode of fuel injection), inlet stagnation temperature, and fuel-air ratio on stability. Both predicted frequencies and stability characteristics agree well with the experimental observations.

One possible mechanism of turbulence-combustion interactions has been

examined by studying the development of Tollmien-Schlichting waves in a reacting shear layer. Analysis shows that the growth rates of these waves depend on the order, the thermicity, and the activation energy of the Arrhenius-type chemical reaction as well as the disturbance wavelengths and Damköhler's similarity parameters.

Two papers have been published and two are in preparation.

RELEVANCE TO USAF

This research on instability mechanisms involved in the mutual influence among sound, entropy, and vorticity modes in chemically reacting subsonic and supersonic flows will aid in the design and the development of advanced power and propulsion systems, in the alleviation of noise pollution, and in the effective control and prevention of explosions.

I. Objective and Scope of Work

The main objectives of this work are to determine the major mechanisms governing the efficiency, power output, stability, and pollutant emission of propulsion devices as well as safety against explosions. Two problems have been studied during the past grant period: (1) Triggering and sustenance of low-frequency instability in dump combustors and (2) temporal development of turbulence-combustion interactions. The following section summarizes briefly the results obtained.

II. Results and Discussion

(1) Triggering and Sustenance of Low-Frequency Instability in Dump Combustors

One major problem related to the use of dump combustors in propulsion devices is to eliminate the low-frequency oscillations. Figure 1a shows the configuration of a coaxial dump combustor, used in the facility of Aero Propulsion Laboratory, AF Wright Aeronautical Laboratories. Here, the flame is stabilized by the use of a flameholder or simply a recirculation zone. Figure 1b shows a transition from low-frequency instability at high equivalence ratio to high-frequency instability at lower equivalence ratio. Such a trend has been predicted by a theoretical analysis conducted during the past grant period.

The low-frequency instability is believed to be triggered and sustained by interactions between non-uniform entropy zones and pressure waves. Figure 2,shows the generation of pressure waves as an entropy wave is convected through a choked nozzle and the generation of the entropy wave as the pressure waves interact with the combustion zone.

A linear perturbation analysis has been conducted to study the instability behavior. Figure 3 shows a comparison of the predicted frequencies with the observations obtained at the AF Aero Propulsion Laboratory for three combustor lengths and diameters with and without a flameholder. The general agreement is quite satisfactory.

The theory is also used to predict the effects of combustor configurations (including combustor-to-inlet area ratio, nozzle-to-combustor area ratio, combustor diameter, presence of a flameholder, and mode of fuel injection), inlet stagnation temperature, and fuel-air ratio on the amplification rates. Figure 4 shows the effect of combustor-to-inlet area ratio for wall injection at different fuel-air ratios together with the corresponding combustion efficiencies. As the combustor diameter increases for a given inlet area, the flow tends to be more stable with accompanying increase in the combustion efficiency. The amplification rates are smaller at lower fuel-air ratio, suggesting possible domination of high-frequency instability under such conditions as observed in the experiments (cf. Fig. 1b). The solid symbols in Fig. 4 indicate stable flows in the experiments. Note that the corresponding predictions show negative amplification or attenuation.

Similar trend is also observed for uniform injection. Theory also shows that the flow is more stable at higher inlet stagnation temperatures, smaller nozzle-to-combustor area ratios (although the reverse trend is also predicted for some conditions), larger combustor diameters, and with a flameholder. These findings are found to be in qualitative agreement with the APL observations.

(2) Temporal Development of Turbulence-Combustion Interactions

One possible mechanism of turbulence-combustion interactions has been examined by studying the growth of Tollmien-Schlichting disturbance waves in a reacting shear layer. It is known that non-reacting, inviscid, shear layers are always unstable to normal-mode disturbances when the mean velocity profile has an inflection point. Figure 5 shows schematically the development of instability in such a flow where vortices are formed due to the growth of the disturbance waves.

Analysis shows that the growth rates of these waves depend on the order, the thermicity, and the activation energy of the Arrhenius-type chemical reaction as well as the disturbance wavelengths and Damköhler's similarity parameters. In the case of quasi-steady situation, the chemical effect is represented by the product of Damköhler's third similarity parameter and the non-dimensional activation energy. Figure 6 shows this effect of the activation energy on the growth rates for different wavelengths. The chemical effect is smaller for smaller α^* or longer wavelength. In other words, the chemical kinetics has different effects on eddies of different sizes. Regardless of the wavelengths, however, one observes in general that exothermic reaction increases the growth rates.

III. Publications and Reports

See attached Enclosure I.

IV. Professional Personnel

Professor T. Y. Toong and Dr. G. E. Abouseif.

CAPTION TO FIGURES

Figure 1 (a) A typical coaxial dump combustor

(b) Transition from low-frequency instability to high-frequency instability resulting from a decrease in equivalence ratio

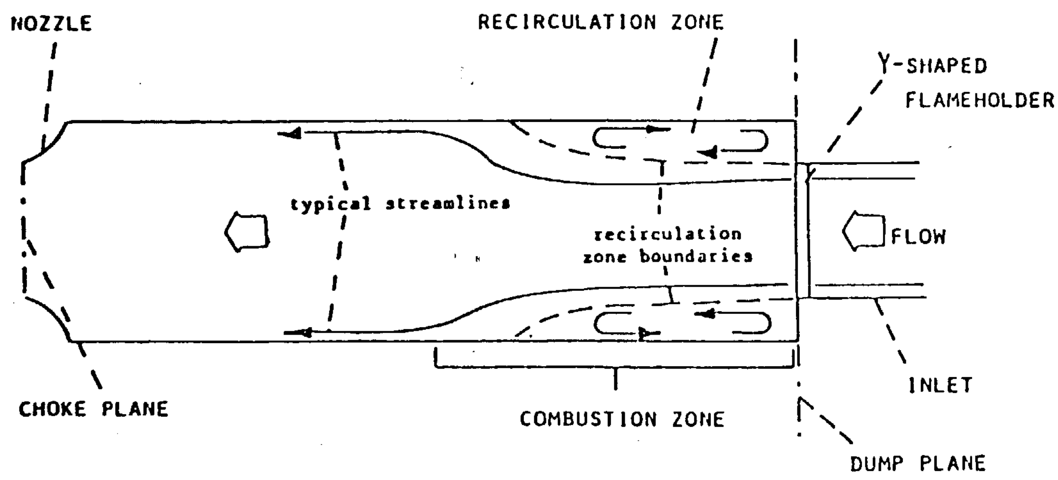
Figure 2 Illustrating low-frequency instability mechanism

Figure 3 Comparison between predicted and observed frequencies for low-frequency instability; three combustor lengths and diameters with and without a flameholder

Figure 4 Effects of combustor-to-inlet area ratio on amplification rate and combustion efficiency for wall injection at different fuel-air ratios

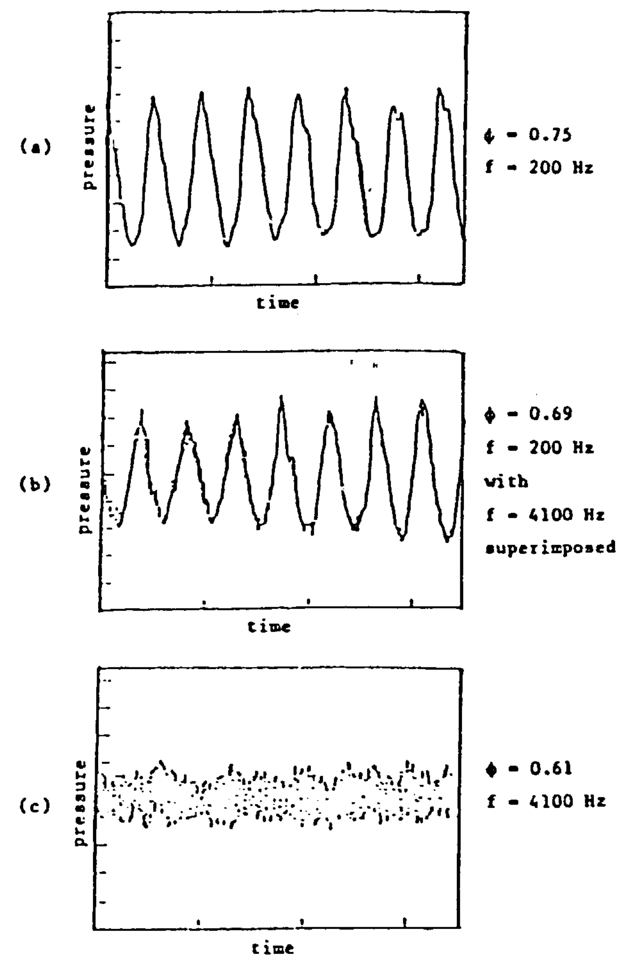
Figure 5 Development of instability in a shear flow showing the formation of vortices due to the growth of Tollmien-Schlichting disturbance waves

Figure 6 Effects of activation energy on growth rates of disturbance waves of different wavelengths



CONFIGURATION OF A TYPICAL COAXIAL DUMP COMBUSTOR

(a)



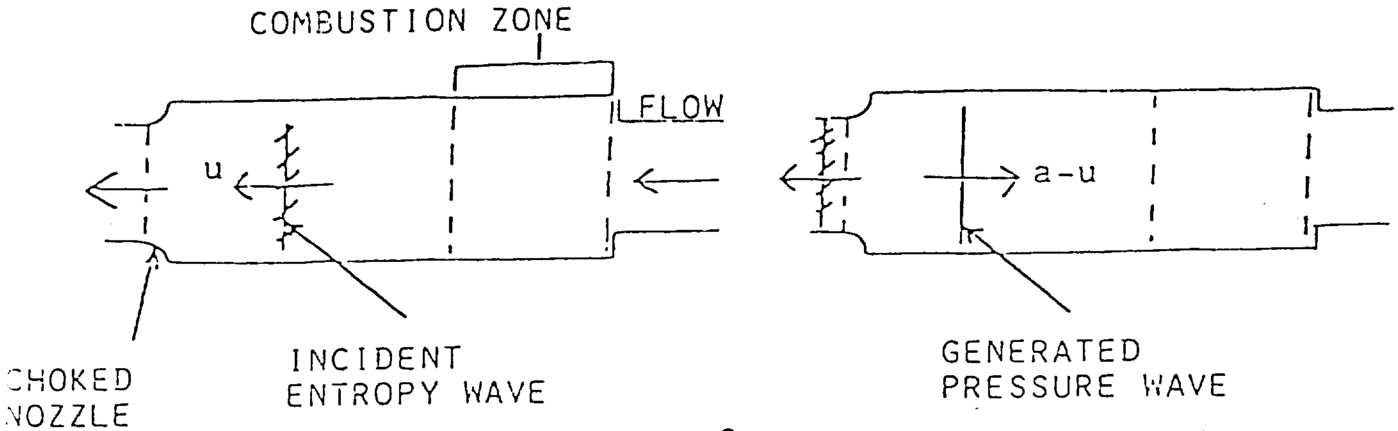
TRANSITION FROM THE LOW-FREQUENCY INSTABILITY TO THE HIGH-FREQUENCY INSTABILITY RESULTING FROM A DECREASE IN EQUIVALENCE RATIO

(b)

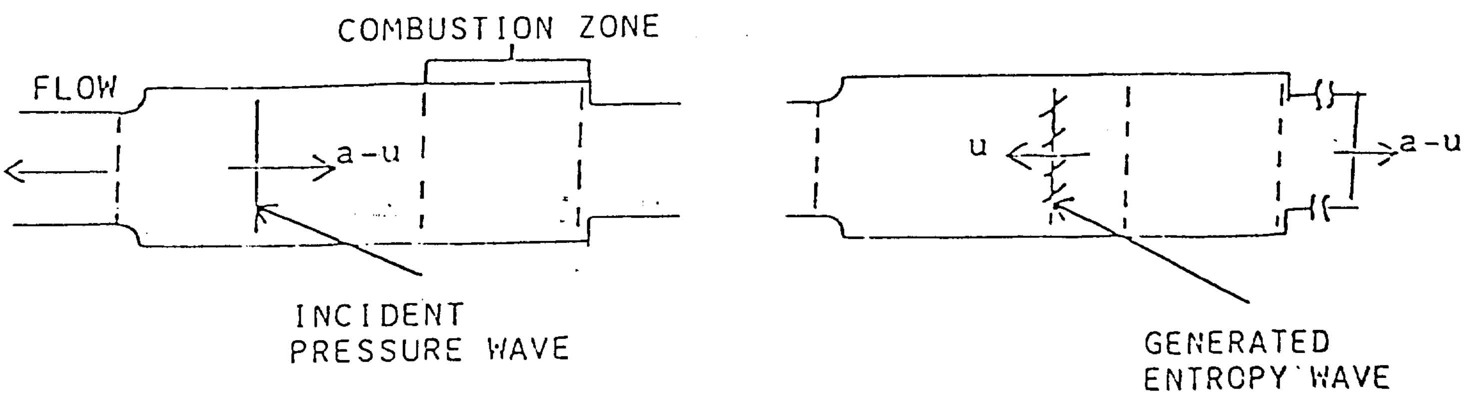
Figure 1

Fig. 2a Generation of Pressure Waves by Convection of Entropy Waves through a Choked Nozzle

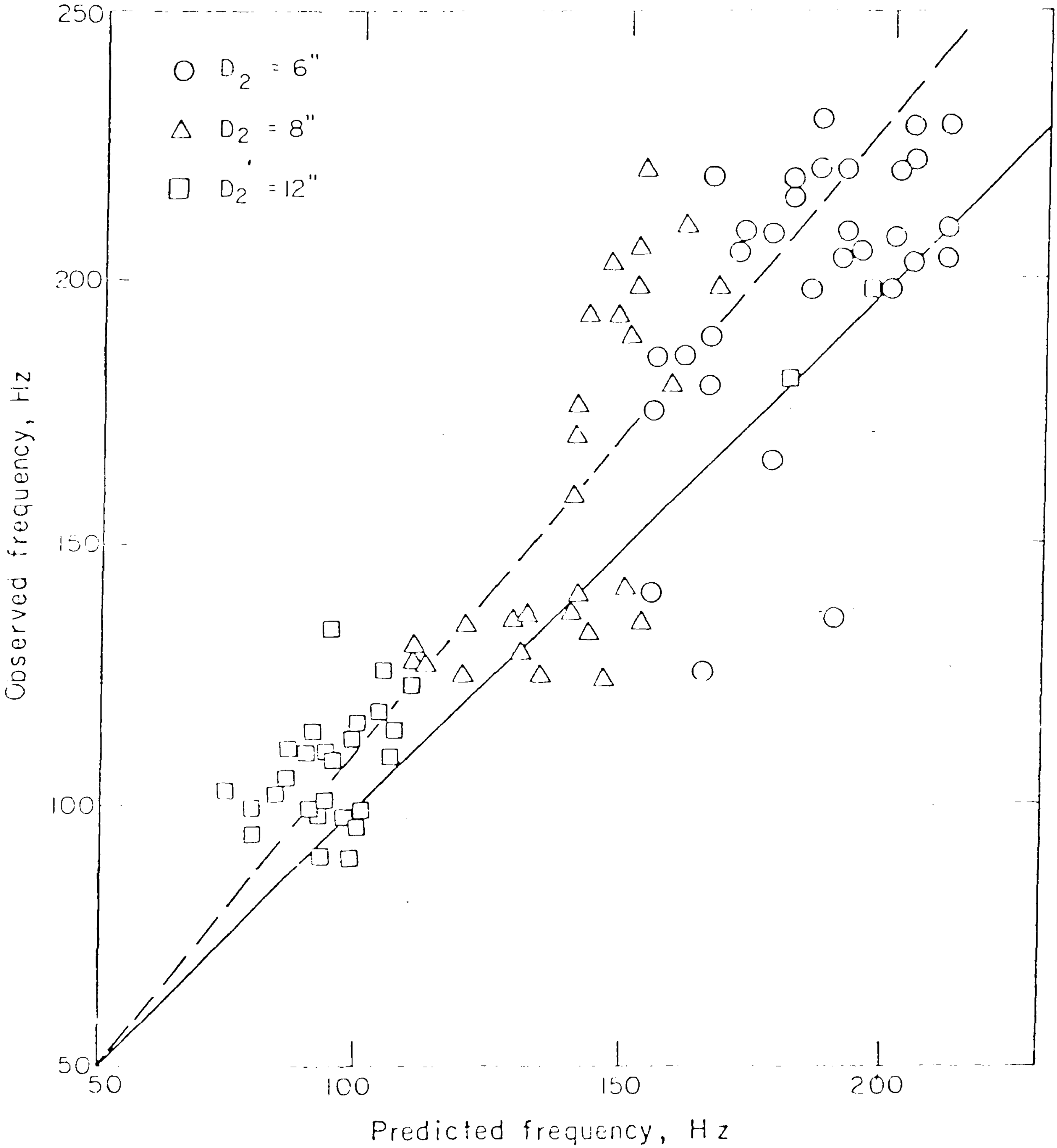
Fig. 2b Generation of Entropy Waves by Pressure Waves Incident on Combustion Zone



2a

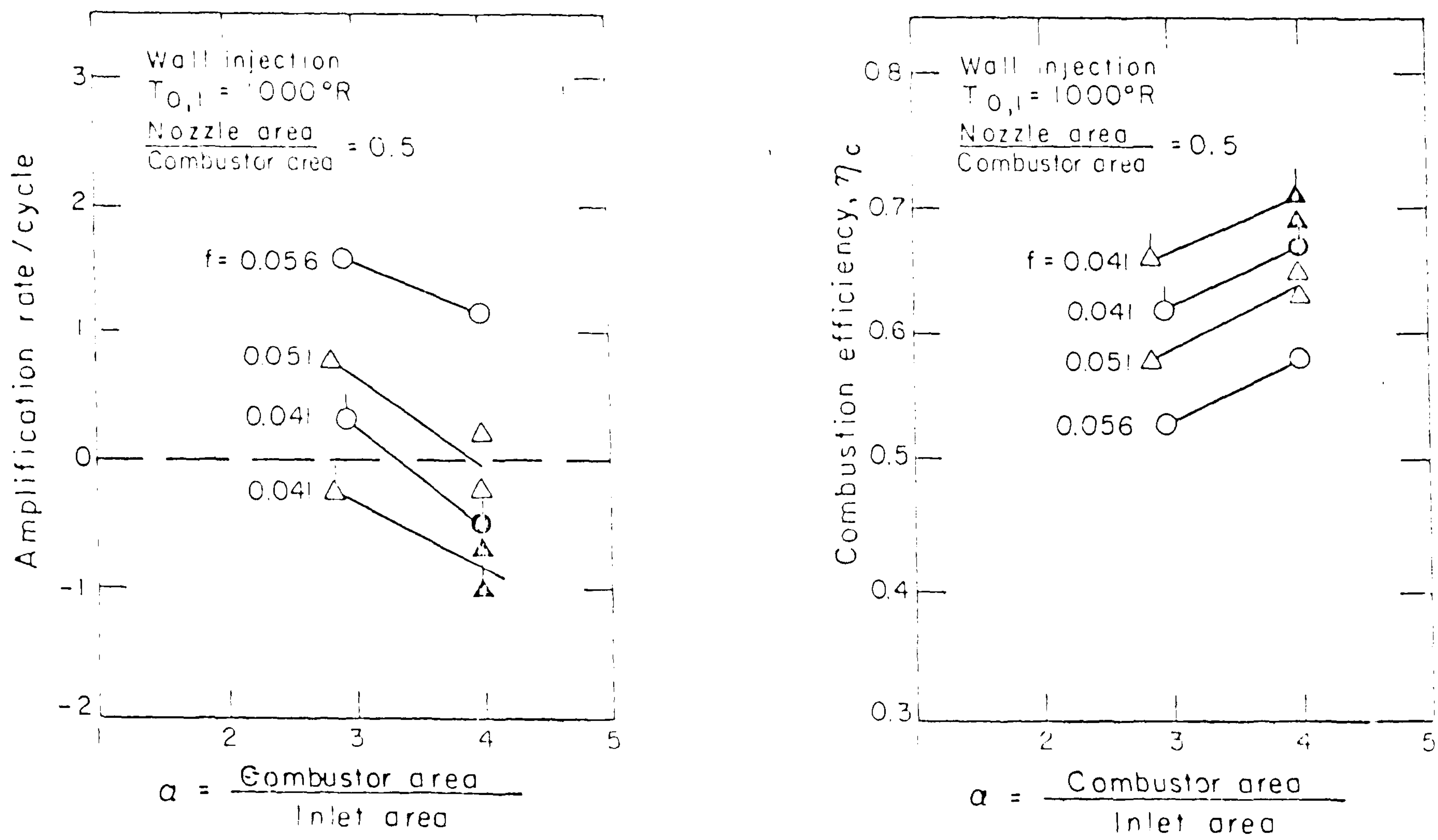


2b



250
200
150
100
50
Observed frequency, Hz
D2 = 6"
D2 = 8"
D2 = 12"
50
100
150
200
Predicted frequency, Hz

Figure 3



Wall injection
$T_{0,1}$ = 1000°R
Nozzle area / Combustor area = 0.5
Amplification rate / cycle
3
2
1
0
-1
-2
f = 0.056
0.051
0.041
0.041
2
3
4
5
a = Combustor area / Inlet area
Wall injection
$T_{0,1}$ = 1000°R
Nozzle area / Combustor area = 0.5
Combustion efficiency, η_c
0.8
0.7
0.6
0.5
0.4
0.3
f = 0.041
0.041
0.051
0.056
2
3
4
5
a = Combustor area / Inlet area

Figure 4

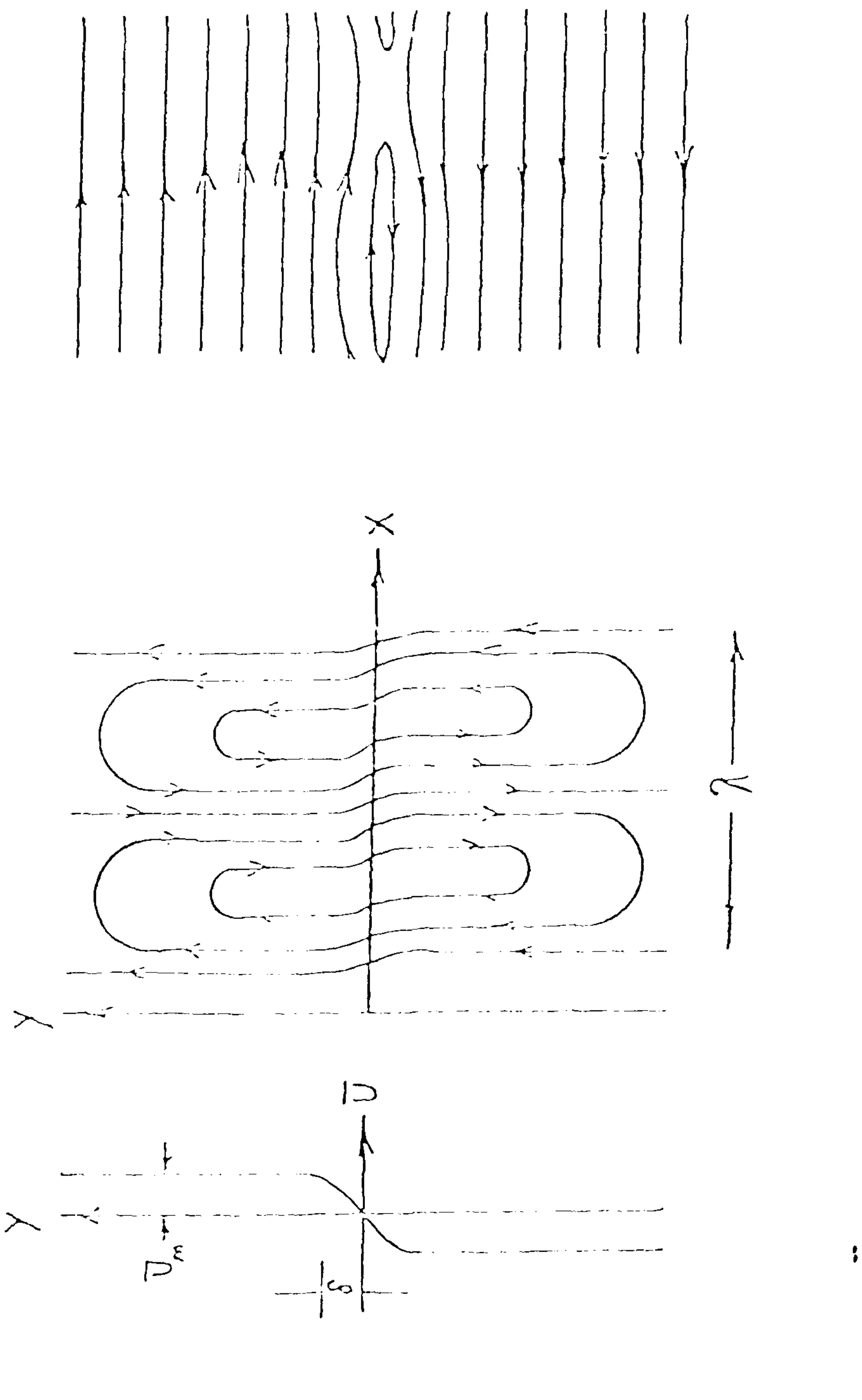
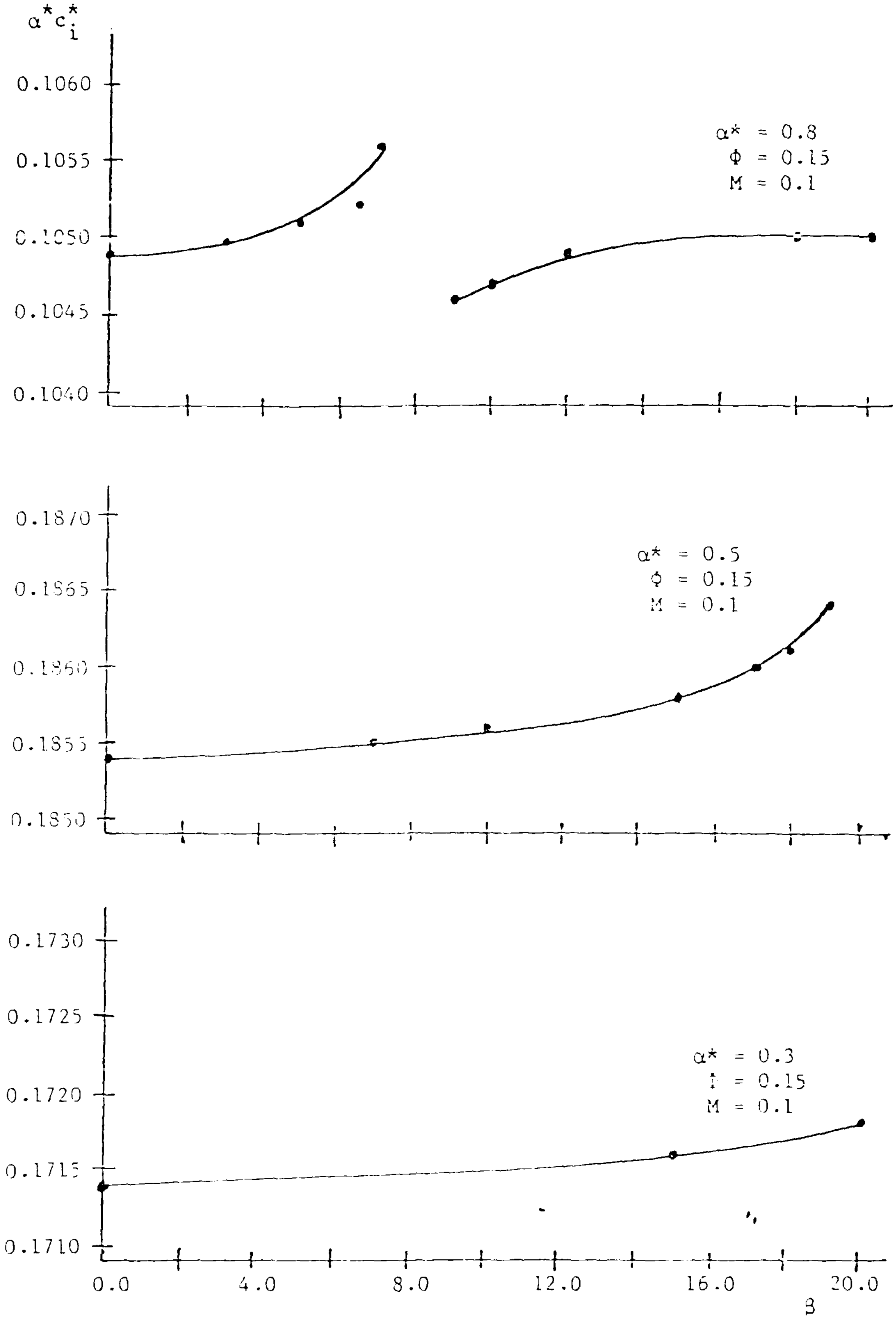


Figure 5



EFFECTS OF ACTIVATION ENERGY ON GROWTH RATES OF DISTURBANCE WAVES AT DIFFERENT WAVE NUMBERS

Figure 6

ENCLOSURE I

Basic Instability Mechanisms

in Chemically Reacting Subsonic and Supersonic Flows

Publications and Reports

(Grants AFOSR-74-2619 and AFOSR-78-3662)

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