CHARACTERIZATION OF A RIJKE BURNER AS A TOOL FOR STUDYING DISTRIBUTED ALUMINUM COMBUSTION

Brian R. Newbold
Brigham Young University
Provo, Utah

Abstract

As prelude to the quantitative study of aluminum distributed combustion, the current work has characterized the acoustic growth, frequency, and temperature of a Rijke burner as a function of mass flow rate, gas composition, and geometry. By varying the exhaust temperature profile, the acoustic growth rate can be as much as tripled from the baseline value of approximately 120 s^{-1}. At baseline, the burner operated in the third harmonic mode at a frequency of 1300 Hz, but geometry or temperature changes could shift operation to a second mode. During oscillatory combustion, centerline temperatures in the exhaust rose by as much as 80 K when compared to the non-oscillating case. With oscillations, the mean flow of gases in the boundary slowed with a consequent decrease in heat transfer to the walls.

The information gained in this study will aid in refining burner modeling efforts and allow interpretation of planned aluminum combustion studies in hopes of gaining a greater understanding of distributed combustion as a driving mechanism in the combustion instability of solid propellant rocket motors.

Introduction

Solid propellants and liquid propellants are the fundamental source of propulsion to space for current government and private interests. The twin boosters for the shuttle are an obvious example of solid propellant application. Solid propellant rockets offer advantages of high thrust-to-weight ratios, operational simplicity and safety, and low drag due to small frontal area (Oates, 1988). One drawback to solid propellants is their propensity to develop combustion instability which causes pressure oscillations in the combustion chamber. At the proper frequency and at a sufficient amplitude, such oscillations can modify the performance, damage the casing, disrupt the guidance system, or even cause catastrophic failure of the motor.

Combustion instability in solid propellant rockets has been studied intensely for over four decades but complete understanding remains elusive (Price, 1984). One solution to the stability problem has been the addition of fine metal particles to viscously damp acoustic oscillations (Dobbins and Temkin, 1967; Culick, 1974; Derr, 1976; Beckstead et al., 1984;). Yet consistent success in using particles as acoustic suppressants demands intimate understanding of the interactions between the particles and a motor's acoustic field.

Distributed Combustion

The predominant mechanisms usually considered as driving unstable combustion are pressure and velocity coupling (Price, 1965). A third driving mechanism is distributed combustion where a particle continues burning far from the propellant surface (Beckstead, et al., 1985). Distributed combustion is of interest since most particles used as additives (i.e. aluminum, zirconium, magnesium, etc.) will ignite and burn. Although a burning metal particle and its resultant condensed oxide will viscously damp acoustics, the burning particle will also release energy that can increase or decrease the acoustic field depending on the position of the particle relative to that field. Since particles are burning in a significant portion of a motor's volume, it is likely that some are actually positioned to contribute to the motor's combustion instability. Beckstead (1987) has highlighted a variety of examples which indicate significant distributed combustion in solid propellant motors.

Within the concept of distributed combustion, there appear to be two dominant physical mechanisms. First is the amount of energy released, and the second is the rate of that energy release which is proportional to particle size (Braithewaite, et al., Oct 1984; Beckstead, et al., 1984). A Rijke burner is being developed at Brigham Young University as a tool to clarify the relative importance of distributed combustion and these mechanisms.

Rijke Burner

In a Rijke burner, a flammable mixture of fuel and oxidizer flows through a tube, ignites in a flame zone, and exhausts out a hot section. With the proper geometry, flame, and flow rates, acoustic oscillations will couple with the flame and the convective heat transfer (Raun, Oct 1993). Diederichsen (1963) found the Rijke burner to be a useful tool in evaluating the effectiveness of particles as damping agents in solid propellants. Finlinson (1987) indicates four reasons for using Rijke burners to study combustion instability over the more conventional T-burner:

1. Distributed combustion is separated from propellant response effects.
2. Premixed combustion of standard fuels (methane, propane, etc.) instead of propellants increases safety, lowers cost, and simplifies experiments.
3. The burner can be operated continuously allowing repeated measurements.
4. Discerning effects of burning with and without particles is straightforward.

Two disadvantages are apparent. First there is the possibility that particle/propellant catalysis is overlooked, or that there is significant particle/gaseous flame catalysis in the Rijke burner. Second, the Rijke burner does not operate at the high temperatures and pressures of propellants so interactions affected by these variables may be missed.

Previous research at BYU includes: 1) validating the Rijke burner as a tool to study distributed combustion (Braithewaite, Dec 1984), 2) developing a computer code to model the phenomenon (Raun, 1986), 3) characterizing the burner at low flow conditions (Finlinson, 1988), 4) examining qualitatively the distributed combustion of several particles (Barron, 1991), and 5) improving the computer code (Brooks, 1991).

The significance of distributed combustion in a Rijke burner is illustrated in Figure 1. Braithewaite (Oct 1984) showed qualitatively that the addition of particles to his Rijke burner could double the acoustic driving over the gas alone case.

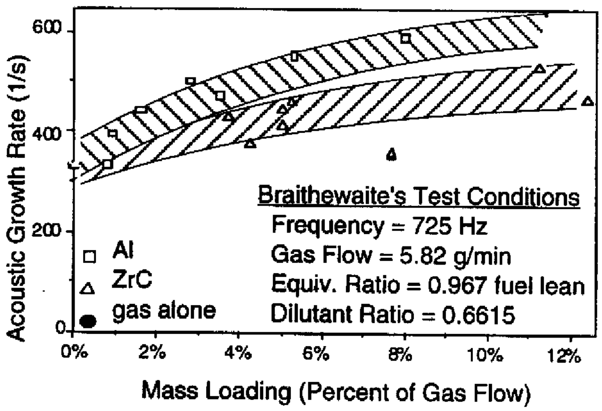

Figure 1. Braithewaite's results (Oct 1984) comparing the acoustic driving of aluminum and zirconium carbide particles in his Rijke burner.

The current work has improved the burner and experimental systems to journey from qualitative to quantitative results. Recently a detailed burner characterization of temperature and acoustic response at high flow rates was completed. After a review of the thermoacoustic phenomenon and the experimental approach, the results of the characterization will be summarized.

Thermoacoustics

Rijke (1859) was one of the first to report that a heated wire mesh placed in the bottom half of an open-open tube would sing as natural convective currents rise in the tube. The Rijke burner is a simple extension of the phenomenon with the heated mesh replaced with a flame. Early investigators (Blackshear, 1953; Putnam and Dennis, 1956; Bailey, 1957; and Tsuji and Takeno, 1965) studying the interaction between a premixed flame and an acoustic field brought the following insights to oscillating laminar flames:

1. The flame must be in a position where the product of acoustic pressure and velocity is positive. (Schimmer and Vortmeyer, 1977)
2. Higher harmonics can be excited by increased energy, but their amplitudes are less than those that appear at lower harmonics.
3. Stoichiometry is important. With proper flame position, the strongest oscillations occur when the flame temperature is maximum.
4. The flame area changes size during oscillations.

Experimental Development

The experimental apparatus and techniques for the current research are the evolutionary result of a decade of research at Brigham Young University. To obtain quantitative results, the experimental method has been significantly changed in the last three years.

Apparatus

Details of the current burner and experimental setup are found in Figure 2. A fiberglass-filled, acoustic decoupling cone is used to start and stop oscillatory combustion. With a butterfly valve open at the base of the cold section, acoustics are damped. Closing of the valve starts the growth of oscillations from a zero amplitude. The flame is over 2400 K and is stabilized on a 20 mesh steel flameholder. Particles are delivered via a fluidized-bed, drop-tube feeder. The following burner parameters can be varied: cold length, hot length, gas flow rate, gas composition, and cooling water flow rate. Particle type, size, and loading can also be varied.

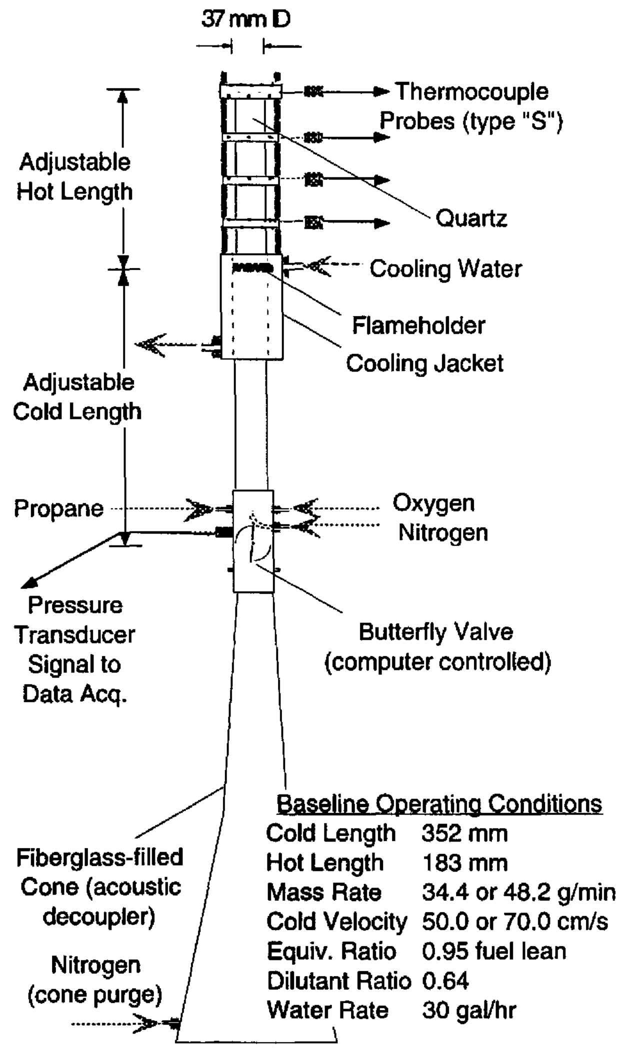

Figure 2. Schematic of the Rijke burner with baseline operating conditions indicated.

The acoustic decoupling cone, burner tube, particle feeder, gas delivery system, cooling water system, and temperature measurement system have all been improved since the work of Finlinson and Barron. The cone was doubled in size, sealed to the burner, and a nitrogen purge line installed to avoid flashbacks.

Modeling efforts by Raun (Jul 1993) and Brooks (1991) indicated that a correct temperature profile was crucial to success in modeling the Rijke burner. Finlinson determined centerline axial profiles and exit radial profiles of the temperatures in the exhaust. He did not account for radiation losses and reached the operating limits of his thermocouples. To improve upon his efforts, the exhaust portion of the burner was redesigned with quartz sections and stainless steel rings sealed with carbon gaskets. Exposed junction thermocouples (0.003 inch diameter bare wire, platinum & platinum/10% rhodium) in alumina probes (1/16 inch diameter) were inserted into the burner's exhaust via a port in each stainless steel ring. With these improvements, the radiation corrected temperature profile in the burner can be found for discrete axial locations and any radial position.

Data Acquisition and Reduction

Acoustic pressure oscillations are monitored by a transducer mounted at the base of the burner where a pressure antinode develops. After signal conditioning, a modular data acquisition system digitizes the signal for analysis with a personal computer. Following manual ignition and a 40 min warm-up period, data acquisition is nearly automated from the computer. Data are sampled at 50 KHz for 0.16 sec for a total of 8000 data points. Next, temperature measurements are recorded for the exhaust section and the cooling water. Repeated runs are made to average results and estimate data scatter.

The digitized pressure signal provided by the data acquisition system allows detailed analysis of the acoustics in the Rijke burner. Figure 3 is a typical pressure signal recorded by the system.

The first 1500 points show the noise from the butterfly valve closing. From 1500 to 3000 the pressure signal grows exponentially until the limiting amplitude begins. The growth of pressure is the primary parameter of interest and is modeled by the following linear growth equation:

$$P(t) = P_o e^{\alpha t} \sin(\omega t + \phi)$$

where $P(t)$ is the pressure signal as a function of time,
P_o is the initial pressure amplitude,
α is the acoustic growth rate,
t is the time,
ω is the frequency of the signal, and
ϕ is the phase angle.

With the exponential, this equation quickly predicts an unrealistic pressure oscillation; consequently, this equation is only valid for approximately the first half of the growth (Culick, 1974) before nonlinearities in the system begin to limit the growth and then limiting amplitude is reached.

In analyzing each data set, the only subjective action is choosing a starting point. Usually a point is chosen as soon as the transient valve noise dies; thereafter, a computer program reduces the data. The program removes any residual DC offset, performs a Fast Fourier Transform, and calculates the signal's spectral density. After picking pressure peaks, the limiting amplitude is determined and half its value is used as a cutoff point in determining the acoustic growth rate. The logarithm of the pressure peaks for the first half of the growth is a straight line. The slope of the line is the acoustic growth rate. In general the frequency determined by the FFT contains over 97% of the power spectral density.

This procedure is performed for both the top and bottom sets of peaks and then averaged. The acoustic growth rate usually has a least squares fit (R^2) above 97%. All relevant parameters concerning the growth rate, limiting amplitude, frequency, and temperatures are recorded. For each condition, five to ten runs are made; the standard deviation and average are reported as representative of the operating condition.

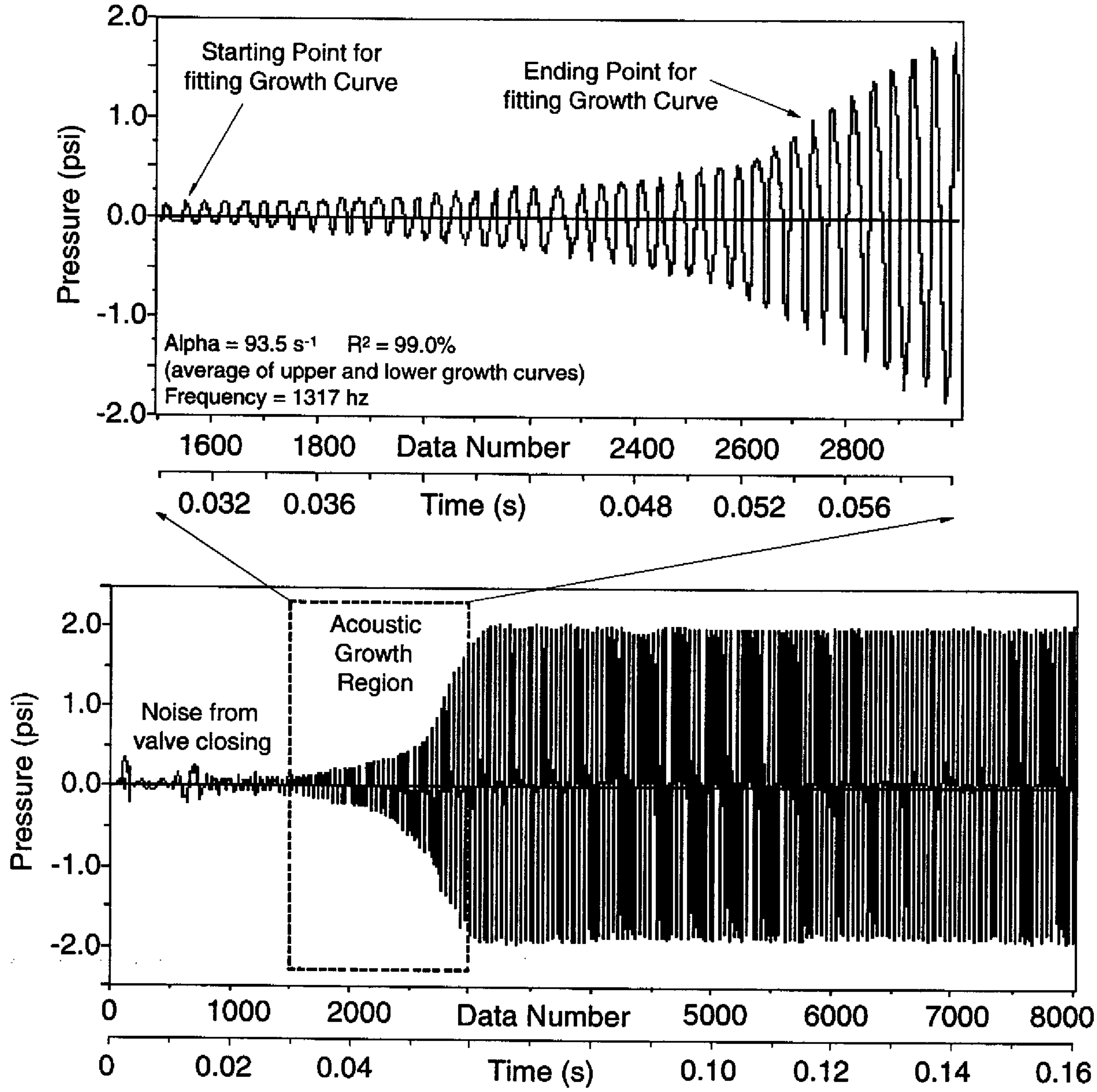

Figure 3. Example pressure signal with the acoustic growth region expanded.

Experimental Results

Four parameters were examined to characterize the Rijke burner: temperature, mass flow rate, gas composition, and geometry. Before work began, the time dependence of the dependent variables was examined.

Temperature Studies

Parallel efforts to model the Rijke burner drove the decision to investigate temperature profiles in the exhaust (Brooks, 1991). With an oscillating environment, centerline temperatures in the exhaust rose by as much as 80 K when compared to the non-oscillating case. With oscillations, the mean flow of gases in the boundary slowed with a consequent decrease in heat transfer to the walls (Hanby, 1969). Results indicated that the flame's position relative to the burner's acoustic driving regions along with the magnitude and shape of the temperature profile primarily determine which mode is driven and the extent of that acoustic driving. The results of the temperature study will not be detailed in this paper, but the study did provide substantial insight into the acoustic studies.

Acoustic Studies

Mass Flow Rate. The right half of Figure 6 shows the effect of increasing the mass flow rate from 20 to 62 g/min. The acoustic growth rate grew sharply above the baseline of 34 g/min. Increasing the acoustic driving can be explained by the tripling of total combustion energy in this study from 1.31 to 4.00 KW. The frequency drifts downward as the exhaust temperatures increase and their axial profile flattens out.

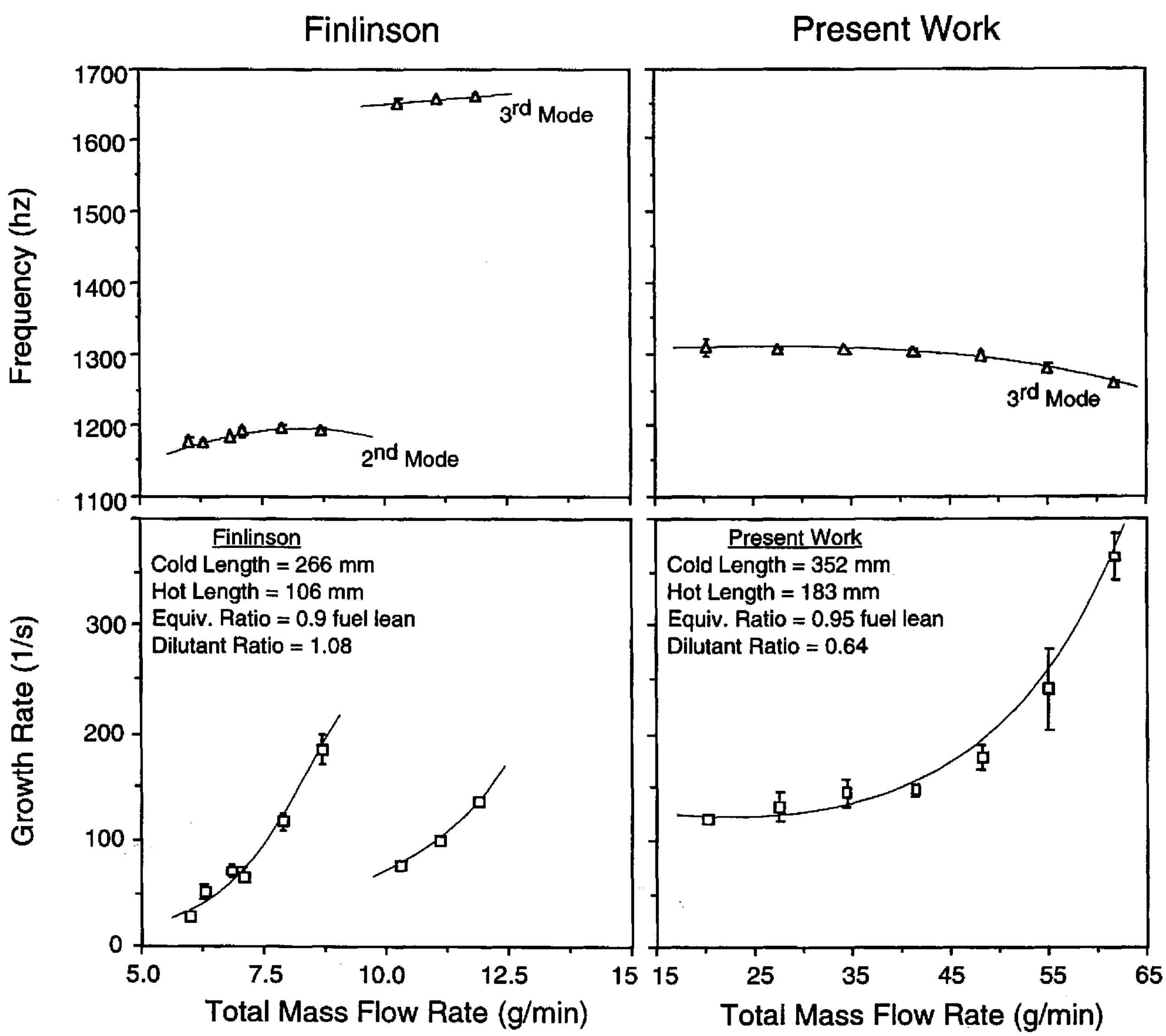

Figure 6. Comparison of Finlinson (1987) and the present work showing the effect of increasing total mass flow rate on the acoustic growth rate and frequency.

Lower flow rates were terminated by flashbacks, and higher flow rates were not possible as the decoupling cone's capacity to damp the acoustics was exceeded.

Also shown in Figure 6 is the similar study at lower flow rates completed by Finlinson. Error bars represent the standard deviation of results. Finlinson saw a jump to a higher harmonic as the axial temperature changed. It is likely that increasing the magnitude and shape of the temperature profile alters the acoustic driving regions in the hot length and shifts excitation from one harmonic to another. The studies were not plotted on the same horizontal axis because of the difference in conditions between the two studies.

Gas Composition. Two parameters were varied in Figure 7 to determine the effect of gas composition: the equivalence and dilutant ratios. The equivalence ratio defines the fuel to oxygen ratio on a mass basis referenced to the ratio at stoichiometric combustion (Glassman, 1977). In this study the baseline equivalence ratio is 0.95 fuel lean. Excess oxygen is provided to enhance aluminum combustion in future studies. Similar to the equivalence ratio, the dilutant ratio defines the dilutant to oxygen ratio referenced to the ratio found in air as shown in the following equation:

$$\Delta = \left(\frac{(D/O)_{\text{mass basis}}}{(D/O)_{\text{mass basis in air}}} \right)$$

where Δ is the dilutant ratio,
D is the mass of dilutant (i.e., nitrogen, argon, helium etc.), and
O is the mass of oxidizer. (e.g., a mixture with Δ = 0.50 would have half of the dilutant that is found in air)

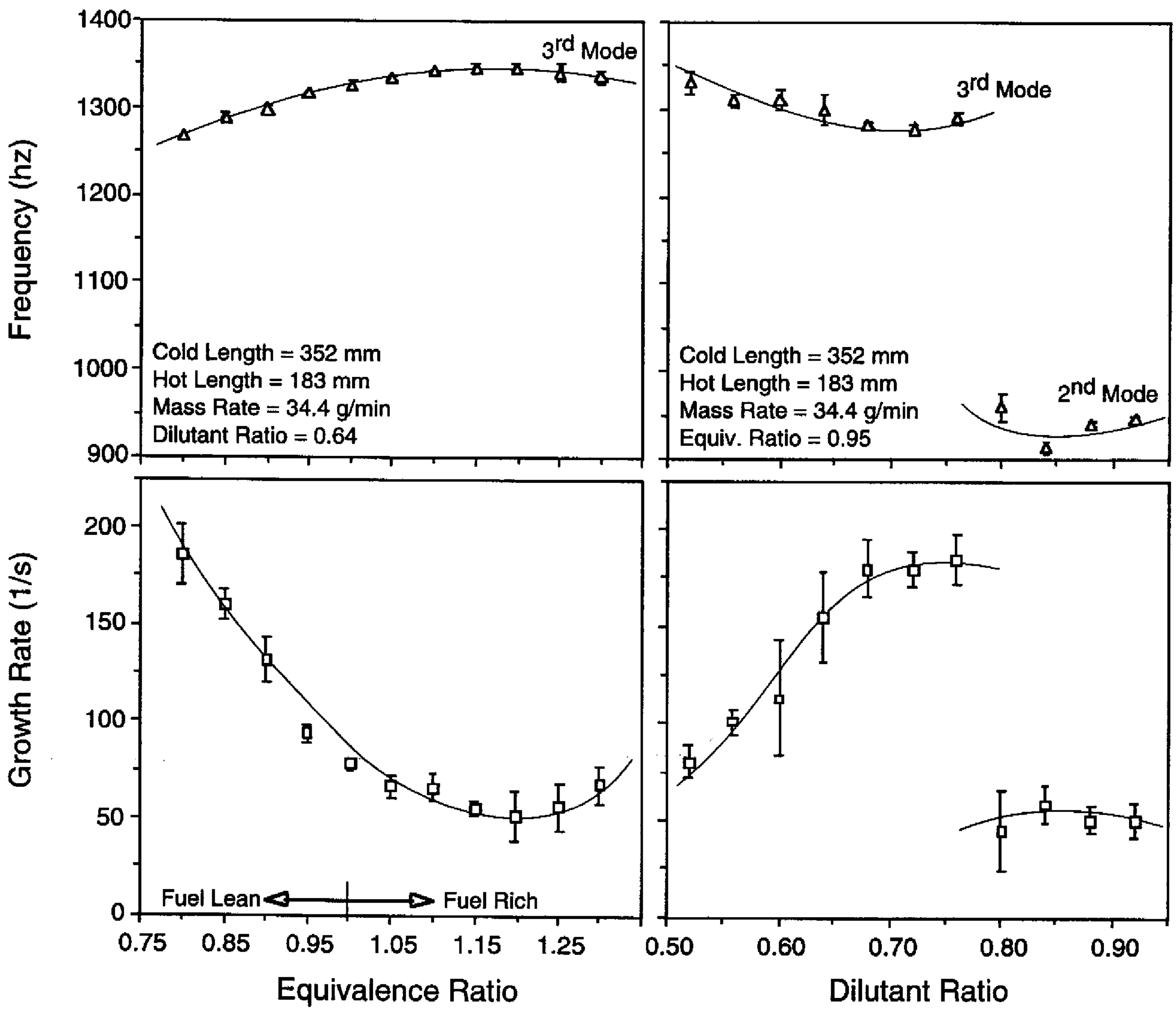

Figure 7. Effect of the gas composition on the acoustic growth rate and frequency.

The baseline dilutant ratio for this study was 0.64. When operating at this low dilutant level, a hotter flame is achieved which is necessary to ignite aluminum particles (above 2200 K, Friedman and Macek, 1962). With equivalence ratio in Figure 7, the acoustic growth rate bottoms on the fuel rich side of stoichiometric near the peaking of the adiabatic flame temperature at 2650 K. Similarly, the dilutant ratio study shows the growth rate dropping from a high at 0.72 to a low at 0.52 where the adiabatic flame temperature is 2775 K, the highest of the region studied. Besides the increase in flame and exhaust temperatures, it is possible that the acoustics were affected by the increased heat transfer to the cooling jacket and the flame shifting closer to the flameholder at the higher flame temperatures (greater flame speed). Also seen in the dilutant study was a mode shift from the third to second harmonic as the dilutant ratio approached that of air ($\Delta = 1.0$).

The decrease in acoustic growth rate in both plots with greater energy addition is contrary to initial thought. One would think that increasing the flame temperature and amount of available energy would demand an increase in the acoustic driving. This is true if the energy addition is in the proper section. For example, a burner operating in a third mode would see a decrease in acoustic growth if energy addition changed the temperature profile such that the optimum driving position moved farther away from the flameholder. One may argue that the mass flow rate study with the same geometry showed increased growth rate with greater energy addition. This is true, but in the mass flow rate study the increasing velocity in the burner also flattened the axial temperature profile significantly.

Geometry. In search of an optimum baseline condition, burner geometry was investifated extensively. Studies at two different flow rates, 34 g/min and 48 g/min, and two different cold lengths, 252 mm and 352 mm, were completed. For the 252 mm study, the hot length was varied from 102 to 254 mm in 10 mm increments. Similarly for the 352 mm study, the hot length was varied from 132 to 314 mm. Results of the low flow rate study for both cold lengths are shown in Figure 8. Both plots show resonant behavior in the acoustic growth rate and shifts from a third to a second mode in frequency. Since other variables were held constant, these phenomena must be explained in terms of temperature profiles and the flame position relative to the acoustic pressure and velocity driving regions.

In the 252 mm plot of Figure 8, one can see that at a 102 mm hot length the acoustic driving is at a peak. Increasing the hot length shifts the flame zone away from the optimum driving position for the third mode until a minimum is found at 153 mm. At the same time the frequency decreases from 1890 to 1850 Hz. From 153 mm to 163 mm there is a drop to a lower frequency and a second mode driving position. At any mode transition, it was difficult to get data since the growth rate was small or nonexistent and the Rijke burner would sometimes flip-flop modes between runs. From 163 mm to 203 mm the growth increased steeply at the new frequency of about 1200 Hz. After peaking, the growth rate dropped again to the last hot length studied, 254 mm.

The first acoustic growth curve shown in the 352 mm cold length plot was chosen as the low flow baseline condition (hot length of 183 mm). Over a 50 mm change in hot length the acoustic growth rate showed relative insensitivity to changing geometry. This indicates a stable operating region where particle combustion can be studied with minimal concern over spurious trends due to variations from the optimal driving position. As stated, a similar study at a mass flow rate 48 g/min was performed. At the higher flow rate, it is was more difficult to obtain consistent results, but plots for cold lengths of 252 mm and 352 mm were developed. They show acoustic growth peaks in the same places as the plots shown for lower flow. The acoustic growth rates are 20 to 40 percent greater than the low flow values as would be predicted by the mass flow rate study. The high flow baseline geometry is the same as that for the low flow baseline since at higher velocity there was a similar curve. Frequency curves at the higher velocity are of the same shape, mode, and magnitude as the lower velocity curves.

SUMMARY

Previous researchers have qualitatively studied the distributed combustion of metals in Rijke burners, but none of them have conducted a detailed investigation of their burner without particle combustion. Research (Putnam and Dennis, 1956; Feldman, 1968; Raun, Oct 1993) indicates that phenomena in the Rijke burner itself are complex; hence, a thorough characterization is necessary to separate burner effects from particle combustion contributions. Accordingly, the current work has improved and characterized the Rijke burner as prelude to a quantitative study of aluminum distributed combustion.

Modeling efforts found the burner's response sensitive to the exhaust temperature. As a result, the burner has been redesigned with multiple ports for thermocouple insertion so the radial and axial temperature profiles could be determined. The characterization involved quantifying the acoustic growth rate, frequency, and temperature as a function of mass flow rate, gas composition, and geometry.

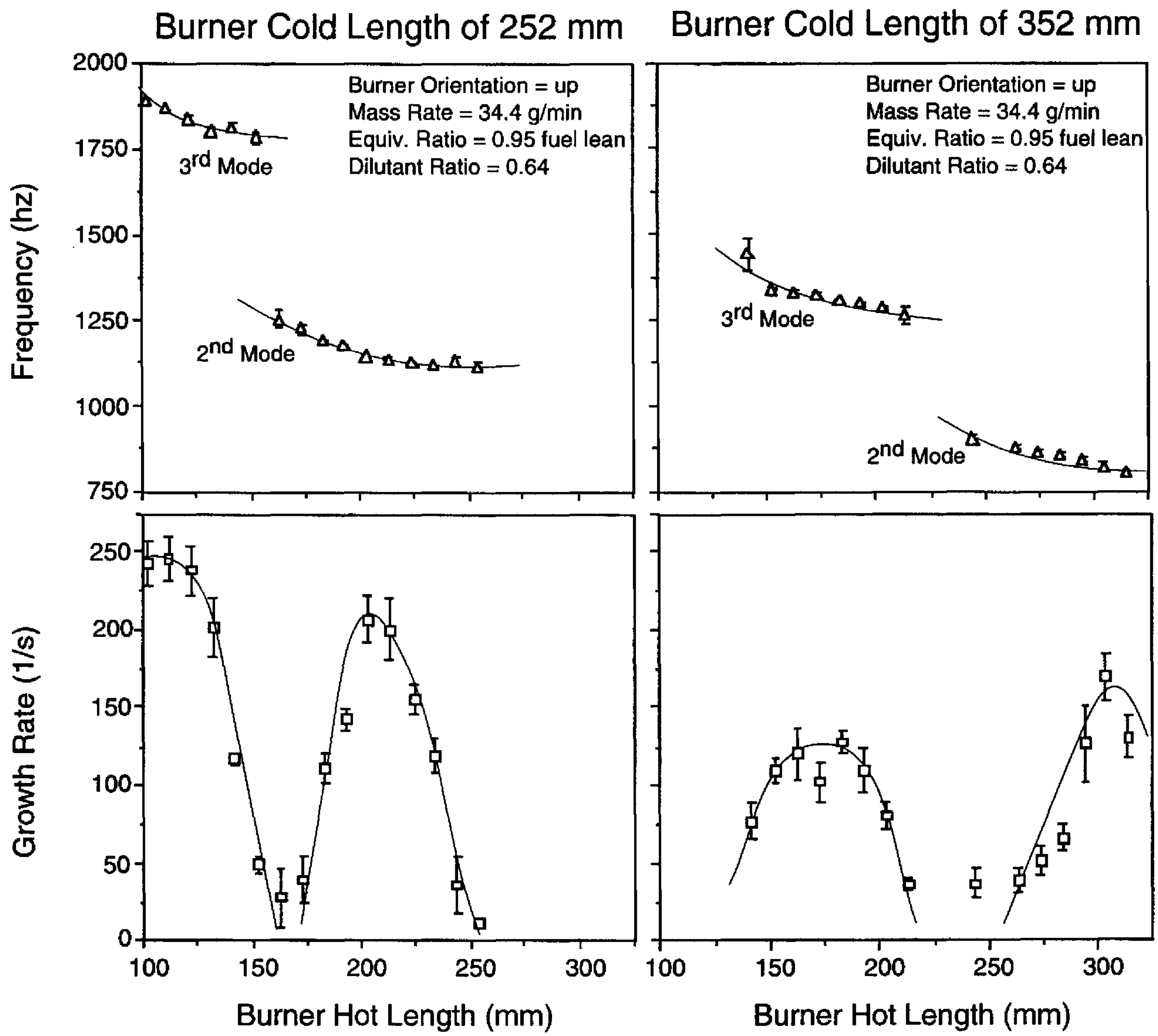

Figure 8. Effect of increasing the burner hot length on the acoustic growth rate and frequency for two different cold lengths.

Increasing the mass flow rate from 20 to 62 g/min, with a corresponding tripling of the available energy, raised the acoustic growth rate by a factor of three to 360 s^{-1}. By varying the equivalence ratio, the adiabatic flame temperature was raised from approximately 2500 K to 2700 K with an accompanying decrease in growth rate of more than half. Apparently, the changing temperature profile shifted the optimum acoustic driving region away from the flameholder. When the adiabatic flame temperature was varied over the same region by decreasing the amount of dilutant, results were similar. In the dilutant study, there was also a transition from the baseline frequency of 1300 Hz to a lower frequency as the dilutant ratio approached that of air. For two different cold lengths and velocities, the acoustic growth rate exhibited resonant behavior, and the frequency shifted from one mode to another as the hot length was increased. With a fixed cold length and mass flow rate, the growth rate increased from approximately zero up to 125 s^{-1} and then dropped again as the hot length was increased from 132 mm to 213 mm. The growth rate rose and fell again with the hot length changing from 244 mm to 314 mm. In parallel with these changes in hot length, the frequency shifted from a third mode (approximately 1350 Hz) to a second mode (approximately 850 Hz). With an oscillating environment, centerline temperatures in the exhaust rose by as much as 80 K when compared to the non-oscillating case. With oscillations, the mean flow of gases in the boundary slowed with a consequent decrease in heat transfer to the walls.

Comparisons with Finlinson's study of variations in temperature, mass flow rate, and geometry showed similar trends despite significant experimental differences. Current results indicate that the flame's position relative to the burner's acoustic driving regions along with the magnitude and shape of the temperature profile primarily determine which mode is driven and the extent of that acoustic driving. Information gained in this study will aid in refining modeling efforts and will serve as a basis for the interpretation of distributed combustion studies of aluminum.

Ultimately, the knowledge developed in this work might provide understanding of how distributed particle combustion contributes to the combustion instability of solid propellants used in government and private boosters. Such understanding may guide in the formulation of propellants and provide direction for further investigation.

Acknowledgements

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Literature Cited

Bailey, J. J., "A Type of Flame-Excited Oscillation in a Tube," Journal of Applied Mechanics, Vol. 24, No. 3, pp. 333-339, (1957).

Barron, J. T., "An Experimental Study on the Effects of Dispersed Particles on Acoustic Growth Rates in a Modified Rijke Burner," M.S. Thesis, Brigham Young University, (1991).

Beckstead, M. W., Brewster, B. S., and Richards, R. S., "Distributed Combustion Effects on Particle Damping," AIAA Journal, Vol. 22, No. 3., pp. 383-387, (1984).

Beckstead, M. W., Braithewaite, P. C., and Gordon, D. L., "Measurements of Distributed Combustion", 66th AGARD Mtg on Smokeless Propellants, Italy, (1985).

Beckstead, M. W., "Evidences for Distributed Combustion", 24th JANNAF Combustion Meeting, CPIA 476, Vol. I, pp. 1-12, (1987).

Blackshear, P. L. Jr., "Driving Standing Waves by Heat Addition," Fourth Symposium (Int'l) on Combustion, The Combustion Institute, pp. 553-566, (1953).

Braithewaite, P. C., Beckstead, M. W., and Raun, R. L., "Measurements of Distributed Combustion," 21st JANNAF Combustion Meeting, CPIA 412, Vol. I, pp. 177-186, (Oct 1984).

Braithewaite, P. C., "Measurements of Distributed Combustion in the Rijke Burner," M.S. Thesis, Brigham Young University, (Dec 1984).

Brooks, K. P. "Evaluation of a Flame Model with a Rijke Burner", 28th JANNAF Combustion Meeting, CPIA 573, Vol. II, pp. 509-517, (1991).

Culick, F. E. C., "T-Burner Testing of Metalized Solid Propellants," AFRPL-TR-74-28, AFRPL, (1974).

Derr, R. L., "Combustion Instability in Navy Rockets . . . Revisited," 13th JANNAF Combustion Meeting, CPIA 281, Vol. II, pp. 185-194, (1976).

Diederichsen, J., "A Singing Flame as a Tool for Evaluation of Damping Agents for Solid Propellant Rocket Motors," Combustion and Flame, Vol. 7, pp. 29-37, (1963).

Dobbins, R. A. and Temkin, S., "Propagation of Sound in a Gas-Particle Mixture and Acoustic Combustion Instability," AIAA Journal, Vol. 5, No. 12, pp. 2182-2186, (1967).

Feldman, K. T. Jr., "Review of the Literature on Rijke Thermoacoustic Phenomena " Journal of Sound and Vibration, Vol. 7, No. 1, pp. 83-89, (1968).

Finlinson, J. C., "Characterization of a Modified Rijke Burner for Measurement of Distributed Combustion," 24th JANNAF Combustion Meeting, CPIA 476, Vol. I, pp. 13-25, (1987).

Finlinson, J. C., "Experimental Characterization of a Modified Rijke Burner," M.S. Thesis, Brigham Young University, (1988).

Friedman, R. and Macek, A., "Ignition and Combustion of Aluminum Particles in Hot Ambient Gases," Combustion and Flame, Vol. 6, pp. 9-19, (1962).

Glassman, I., Combustion, First Edition, Academic Press, New York, p. 14-15, (1977).

Hanby, V. I., "Convective Heat Transfer in a Gas-Fired Pulsating Combustor," Journal of Engineering for Power, January, pp. 48-52, (1969).

Oates, G. C., Aerothermodynamics of Gas Turbine and Rocket Propulsion, AIAA, Washington, DC, pp. 4-5, (1988).

Price, E. W., "Experimental Solid Rocket Combustion Instability," Tenth Symposium (Int'l) on Combustion, The Combustion Institute, pp. 1067-1082, (1965).

Price, E. W., "Experimental Observations of Combustion Instability," Progress in Astronautics and Aeronautics, Vol. 90, pp. 733-790. (1984).

Putnam, A. A. and Dennis, W. R., "Survey of Organ-pipe Oscillations in Combustion Systems," The Journal of the Acoustical Society of America, Vol. 28, No. 2, pp. 246-259, (1956).

Raun, R. L., "A Numerical Model of the Rijke Burner," Ph.D. Dissertation, Brigham Young University, (1986).

Raun, R. L., "A Numerical Model for Temperature Gradient and Particle Effects on Rijke Burner Oscillations," Combustion and Flame, Vol. 94, pp. 1-24, (Jul 1993).

Raun, R. L., Beckstead, M. W., Finlinson, J. C., and Brooks, K. P., "A Review of Rijke Tubes, Rijke Burners and Related Devices," Prog Energy Comb Sci, Vol. 19, pp. 313-364, (Oct 1993).

Rijke, P. L., "Notice of a New Method of Causing a Vibration of the Air Contained in a Tube Open at Both Ends," Philosophical Magazine, Vol. 17, pp. 419-452, (1859).

Schimmer, H. and Vortmeyer, D., "Acoustical Oscillations in a Combustion System with a Flat Flame," Combustion and Flame, Vol. 28, pp. 17-24, (1977).

Tsuji, H., and Takeno, T., "An Experimental Investigation on High-Frequency Combustion Oscillations," Tenth Symposium (Int'l) on Combustion, The Combustion Institute, pp. 1327-1335, (1965).