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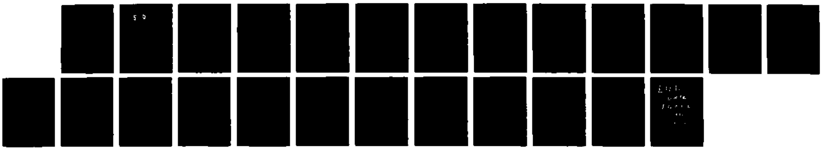

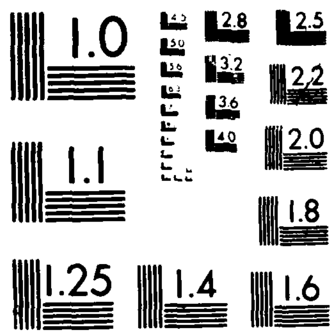

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The principle objective of this study is to identify and develop an understanding of the mechanisms whereby acoustic suppressants modify an acoustic wave. The experimental bases for the technical approach of this study is a Rijke burner which generates combustion oscillations. During the past year three major modifications were made to the Rijke burner to facilitate obtaining more reproducible data: 1) The cooling jacket was rebuilt to give better heat transfer characteristics, and a flowmeter was incorporated to allow a quantitative control of the cooling water flow. 2) A digital data acquistion system was interfaced with the burner to allow monitoring more variables, and to improve data reduction techniques. 3) A new damping device consisting of a butterfly valve and a sound absorbing cone below the burner was developed to allow greater damping. Acoustic growth rate data have been obtained a nominal frequency of 1200 Hz varying the mass flow rate, the oxidizer/fuel ratio, and the relative amount of nitrogen. In all cases, the growth rate increases as the energy release rate (or temperature) increases. These data will now be compared to the previously developed model to better understand the physical mechanisms driving the acoustic oscillations. The model is also being modified to incorporate various submodels for different types of particulates.

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CHARACTERIZING PARTICLE COMBUSTION IN A RIJKE BURNER

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TABLE OF CONTENTS

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This report is an interim report on the past year's work, and is part of the graduate work of Jerry Finlinson, Mansel Nelson, and Ron Nelson.

I. INTRODUCTION

This report summarizes the work performed during the past year on a continuing research program to study particle combustion of additives used in solid propellants for performance enhancement and acoustic suppression. The program focus concentrates on the mechanisms of particle combustion. A modified Rijke burner which had been constructed previously has been modified extensively to aid in the study of the interaction of particle combustion and acoustic suppression. The basis for the technical approach is the modified Rijke burner which has been shown and discussed in detail in previous reports. The overall approach is summarized in Figure 1. Particles are added to the burner through a gas inlet and are then ignited by the flame. Data are obtained with and without particles and with and without acoustic oscillations. The several advantages to using the modified Rijke burner have also been discussed previously. The principal advantage is that the effects of additives can be determined independent of the complex combustion experienced in solid propellants.

Acoustic suppressants have been added to low smoke and smokeless propellants for the past decade. For many years aluminum was a panacea for combustion instability. However, as the motivation to eliminate smoke in rocket exhausts increased, aluminum began to be eliminated from propellant formations. In an attempt to avoid combustion instability, ingredients were sought that would act as acoustic suppressants. For the past decade, the suppressants most often used in tactical motors have been ZrC and graphite flake. The rationale for using these additives was based on particle damping theory which in turn is based on energy dissipation by

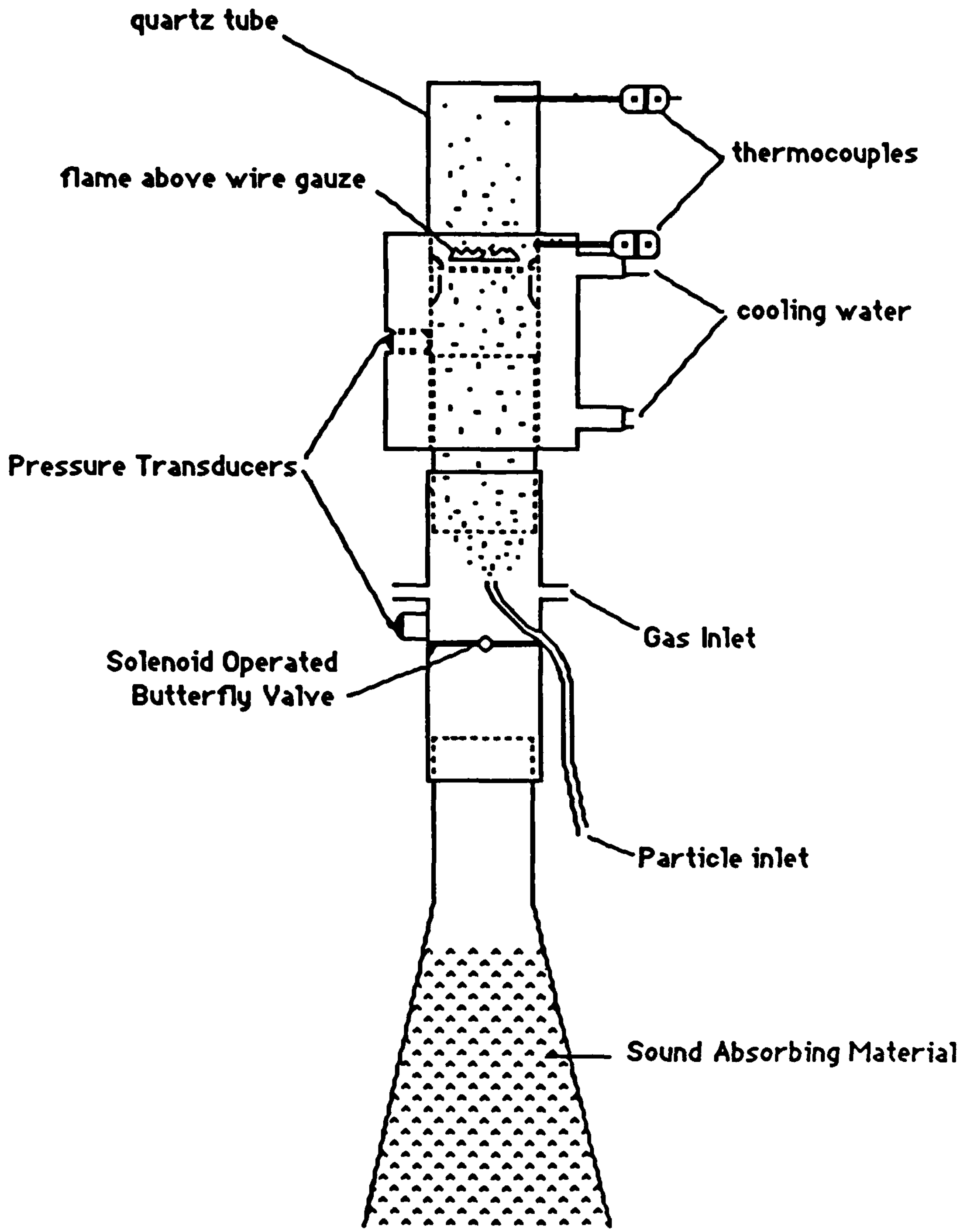

Figure 1. Diagram of the modified Rijke burner apparatus with a butterfly valve and sound absorber below the burner.

viscous drag. When ZrC was first added to propellants it was considered to be an "inert" additive. However, data obtained during the past two years in the Rijke burner show that the ZrC is burning.

The progress discussed in this report is summarized in two parts: 1) experimental improvements and 2) computer model improvements. The experimental improvements are discussed first, then the computer model improvements are discussed.

2. EXPERIMENTAL IMPROVEMENTS

The experimental apparatus and procedures were modified in four major ways:

1) a digital data acquisition system was interfaced with the equipment allowing the monitoring of more variables,
2) data reduction was improved due to the digital nature of the signal,
3) a new damping device consisting of a butterfly valve and a sound absorber below the burner was developed, and
4) the cooling jacket was modified for more consistent heat transfer.

2.1 Digital Data Acquisition System

The digital data acquisition system is described in this section. Previously, the acoustic growth rate, alpha (α), was recorded using a high speed oscillograph. The resulting plots were reduced by hand to determine the frequency, growth rate, and limiting amplitude. The major disadvantages of this system were: 1) the light sensitive oscillograph paper faded over time and was expensive, 2) the data were difficult to measure accurately due to the small plot size, and 3) data reduction was time consuming. The recently acquired Modular Data Acquisition System (MDAS) has allowed us to overcome these difficulties. The data acquisition system was purchased by the university as a cost sharing item for the contract.

The MDAS is a stand alone unit containing 1 megabyte of RAM and is capable of sampling at rates up to 540,000 Hz at 12 bit resolution. Sampling at high data rates allows data to be taken before, during, and after the acoustic growth storing the data in buffers for later analysis. The MDAS is interfaced to an HP150 personal computer through a GPIB port. The HP150 runs a TBASIC program controlling the MDAS and analyzing the data. The sampling setup is shown in Figure 2. The data are stored on a 14 MB hard disk and backed up on floppy diskettes. The MDAS is also used to perform FFT's, giving the frequency components of the acoustic signal.

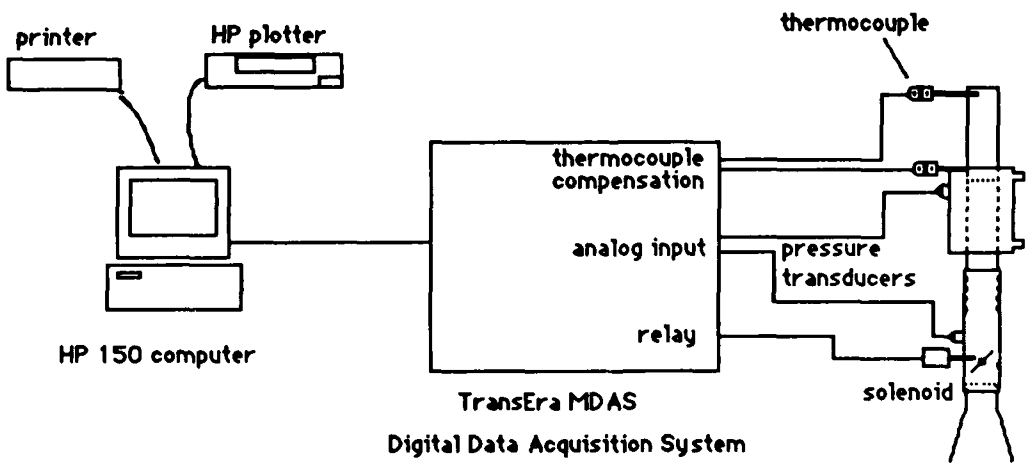

Figure 2. Digital data acquisition system and interfacing with the modified Rijke burner.

The following plug-in modules are installed in the MDAS:

4 channel, ± 10V analog input card

7 channel, thermocouple compensation card

4 channel, solid state AC relay.

The analog input card is used to measure voltages from the pressure transducer and the particle feeder balance. The acoustic mode shape can be determined my monitoring several pressure channels simultaneously. The thermocouple compensation card is used to monitor K-type thermocouples placed in various locations on and in the Rijke burner, allowing a measurement of the temperature distribution and calculation of a heat balance. The relay card controls the butterfly valve.

2.2 Improved Data Reduction

Improvements in the data reduction are discussed in this section. The digital acoustic signal from a test firing is stored in a buffer within the MDAS. The signal is analyzed by a Newton-Raphson technique, to determine the alpha (α). The Newton-Raphson technique minimizes χ^2 (chi-squared) in the following equation:

$$\chi^2 = \sum_{i=1}^{N} (A\ e^{\alpha t} \sin(\omega\ (\delta t + t)) - z_i)^2$$

where

z_i is an array with the data points of interest,

δt adjusts the phase to zero,

ω is the frequency in Hz,

A is the initial amplitude,

α is the acoustic growth rate, and

χ^2 is the square of the difference between the mathematical fit and the data points.

Figure 3 is a plot of typical data points compared to the mathematical curve fit. Noise in the data is apparently caused by the mechanical and acoustic vibrations of the butterfly paddle.

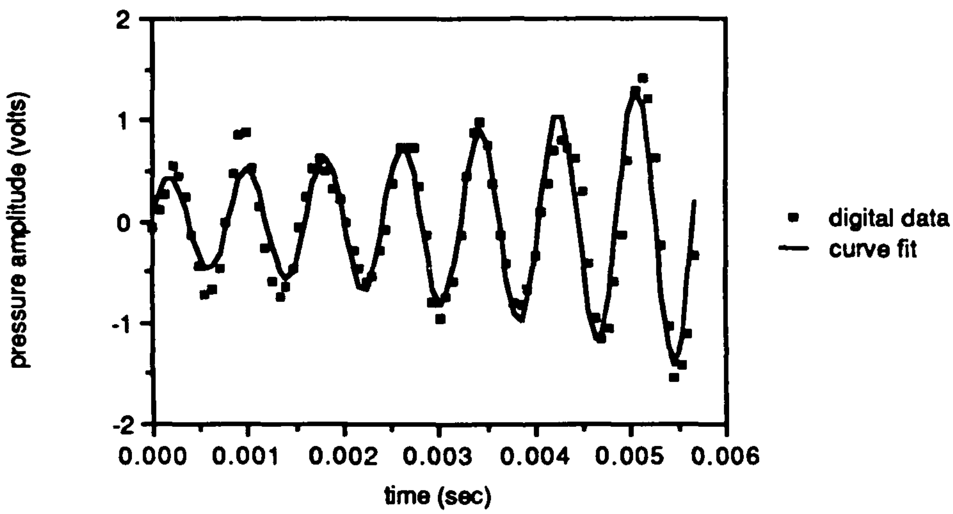

Figure 3. Pressure sample points compared with the mathematical curve fit for an acoustic growth rate of 220 (1/sec). Data was taken May 7, 1987 by Finlinson and Nelson.

The α calculated is the net growth rate of the system, which is affected by many driving and damping factors. We are currently characterizing the effects of different gas flow rates, compositions, and burner lengths on the net alpha (α_{net}). After complete characterization of the burner with respect to these variables, we will be able to characterize the effects of burning particles on the system.

2.3 Sound Damping Device

A new sound damping device was developed, consisting of a butterfly valve and a sound absorber below the burner. In order to observe and measure an acoustic growth rate, the oscillations need to grow from zero (non-oscillating) to a limiting amplitude, without significant changes in the gas and particle flow rates. For the burner to be functional, a damping device is needed which allows the oscillations to be suppressed or allowed to grow on command. The original damping device was a paddle on top of the burner. It was successful in reducing the acoustic oscillations enough to allow a reasonable measurement of α. However, there were several disadvantages in its design that prompted further investigation into alternate devices that would be more effective in damping the acoustic oscillations in the modified Rijke Burner. We were interested in a device that would provide a non-reflecting acoustic termination which could be disconnected on command.

Several different devices were tested. The most effective device was a butterfly valve with a sound absorbing chamber below the burner. The butterfly valve opens to the sound absorber chamber which dissipates the acoustic energy (see Figure 1). The non-reflecting acoustic termination is provided by a gradual expansion cone filled with sound absorbing materials. Closing the butterfly valve disengages the sound absorbing device and allows the acoustic oscillations to grow in the burner. A butterfly valve placed at the bottom of the burner has several advantages over the paddle previously used. The butterfly valve can be closed much more rapidly with less mechanical noise. Additionally, with the valve at the bottom, there is less disruption of the gas and particle flows through the burner.

After evaluating several materials, a combination of "SONEX foam" and loosely packed cotton batting were selected as the sound absorbing materials. In order to increase the sound absorbing area, a conical connection was attached below the butterfly valve. If the conical angle is too sharp, its impedance change will reflect the acoustic wave causing a standing oscillation in the burner. Transmission of sound through a conical connection is described by the following equation:

$$P_r = \frac{1}{\left(1 + \frac{[m-1]^2}{m}\frac{1-\cos\sigma}{\sigma^2}\right)^2 + \left(\frac{[m-1]^2}{m}\left(\frac{\sigma-\sin\sigma}{\sigma^2}\right)\right)^2}$$

where

P_r is the power transmitted through the cone,

$m = \sqrt{S_2/S_1}$, with S1 and S_2 the smaller and larger diameters,

s = 2kl', with l' as the slant length of the cone and

k = 2p/l.

Using this equation a conical connection was designed with power transmission greater than 99 percent at frequencies above 800 Hz. A plot of the sound power transmission of the current cone, which has an angle of 2.87^o is shown in Figure 4.

Increasing the water flow rate from 200 to 900 ml/min causes an additional heat transfer of 700 cal/min, which is 16 percent of the total energy. Surprisingly this did not affect the acoustic growth rate in an obvious way. This could be due to offsetting changes in the heat transfer through the quartz tube.

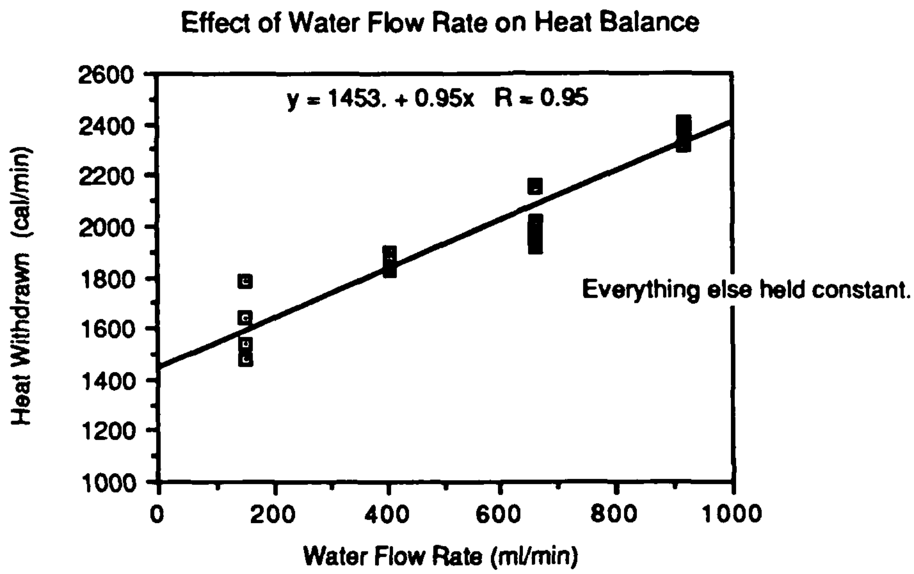

Figure 5 Effect of water flow rate on the heat withdrawn by the cooling water.

The heat loss through the quartz tube above the burner is estimated to be several hundred calories. The result of the heat losses is that less than fifty percent of the heat of combustion exits the burner in the combustion products. Naturally, these heat losses affect the temperature profile and the resulting frequency of the acoustic oscillations. These heat losses need to be controlled, or at least measured, to obtain consistent data. We have added a flow meter and a constant pressure feed system for the cooling water. Initially, large fluctuations in the cooling water exit temperature were noted and determined to be caused by air pockets in the cooling jacket. The cooling jacket was redesigned to eliminate air pockets and make the heat transfer more uniform.

We are currently investigating the effect of acoustic oscillations on the heat transfer through the wire gauze and quartz tube. The temperature of the combustion products leaving the burner has been observed to drop over fifty degrees in some experiments as the oscillations grow from zero to the limiting amplitude. This effect is apparently due to increased convective heat transfer caused by the disruption of the gas boundary layer along the quartz tube. Further experiments will be required to confirm this hypothesis.

3. Computer Model Improvements

The present status of modeling particle combustion for the BYU Rijke burner is presented in *this report*. The combustion of several types of particles in a Rijke burner is considered. The modifications are being developed for use in a computer program written previously, that calculates the properties and growth rate of acoustic oscillations in the Rijke burner. By including these particle models, the influence of particle combustion on combustion instability can be studied from a theoretical as well as an experimental view.

A review of the literature was conducted to determine the mechanism by which different types of particles burn. The review focused on aluminum and zirconium carbide, but other types of particles were also included. It was found that metals such as aluminum and magnesium burn by a diffuse vapor flame. Boron, in a wet environment, and carbon burn at the surface of the particle. Zirconium may burn as a liquid that dissolves it's oxide. Zirconium carbide is a porous particle with evidence that the reaction takes place in the pores. Other particles also appear to burn by one of these four mechanism. Therefore, modeling particle combustion processes can be divided into four general groups:

1) a vapor phase diffusion flame,
2) a shrinking core surface reaction,
3) a reaction of a liquid that dissolves it's oxide or absorbs the oxidizer before reacting, and
4) a porous solid.

Each of these groups may be subdivided into subgroups. Any burning particle should be approximately described by one of these models. Each type of particle also has features that are unique to itself, so a general model from one of the groups may not exactly describe its combustion rate and process. For purposes of including the particle models in the computer program *for the* Rijke *burner, equations for the reaction rate of the* particle have been derived.

3.1 Vapor Phase Diffusion Flame

Particles that burn by a vapor phase flame have been studied extensively because of their importance in the combustion of liquid fuels such as gasoline and liquefied hydrogen. In the development of the computer program for the BYU Rijke burner, Raun (1985) included Glassman's model (1977), of a vapor phase diffusion flame. Assumptions that are included in Glassman's model are Lewis number equal to unity, constant transport properties in the gas phase, constant heat capacity, and no radiation effects. Raun modified the the model to account for radiation effects and a correction for variable heat capacity. Raun's modification of

Glassman's model yields the following equations for the reaction in the Rijke Burner.

$$r_p = \left(\frac{6k_t}{\rho_{sp} C_{pg} d_p} \right) N_u \ln(1 + B_T)$$

3.2 Shrinking Core Model

Levenspiel (1972) outlines the shrinking core model. In this model the particle reacts at a sharp boundary between the reactant solid and the products or surrounding fluid, the unreacted core shrinking as the reaction proceeds. An oxide film of product surrounding the unreacted core may form. The reaction may be diffusion controlled, kinetically controlled, or a combination of both. It does not matter whether the particle and the ash layer are liquid or solid, as long as they form distinct phases and the reaction takes place only at the surface of the unreacted core. This will approximate some liquids and all nonporous solids, as diffusion into them will be much slower than the reaction rate. The equations for the reaction with no oxide formation is given first, then the equation that includes an oxide layer.

$$r_p = \frac{b M_b}{a M_A} \pi d_p^2 \frac{\rho_{gA}}{\frac{1}{k_g} + \frac{1}{k_r}}$$

$$r_b = 4\pi \frac{M_B}{M_A} \frac{b}{a} \frac{r_s^2 r_c^2 \rho_{ga}}{\frac{r_s r_c (r_s - r_c)}{D_e} + \frac{r_c^2}{k_g} + \frac{r_s^2}{k_r}}$$

3.3 Liquid Drop Model

For reactions in which the reactant metal is a liquid and there is no distinct product layer or the reaction takes place homogeneously in the particle, a model which takes into account diffusion in the particle is necessary. However, there are some simplifications that can be made. Danckwert (1970), discusses the theory of reactions when the reactants are in different phases, usually gas and liquid. For the case of a gas reacting with a liquid, as the liquid phase reactant concentration is increased the reaction tends to become either gas phase diffusion or kinetically controlled. If the kinetics are fast, the reaction will take place at the surface of the particle. If the kinetics are slow and the gas is soluble in the liquid the reaction will take place throughout the particle. Since the particles in the Rijke burner are very small the concentration differences in them should also be small. Also, the liquid reactant concentration is several orders of magnitude greater than the gas phase oxidizer concentration, so the reaction rate will be more sensitive to the oxidizer concentration than the liquid reactant concentration. For these reasons the liquid drop model assumes that the liquid phase concentrations are uniform across the particle. The first equation gives the reaction rate for a liquid drop reacting at the surface. The second gives the reaction rate for a reaction taking place in the particle.

$$r_b = \frac{b}{a}\frac{M_B}{M_A}\pi d_p^2 \frac{\rho_B \rho_{ga}}{\frac{M_B}{k_r} - \frac{\rho_B}{k_g}}$$

$$r_b = \frac{b}{a}\frac{M_B}{M_A}\frac{1}{6}\pi d_p^3 k_r C_{ac} C_b$$

3.4 Porous Solid

The reaction of a porous solid is very complicated due to the internal structure of the particle, which is not known. Models of reactions in porous solids are therefore roughly divided into two groups, the idealized pore models, and the empirical fit models. The empirical fit models have a form like the equation for the shrinking core models, except that the resistance for the pore diffusion and kinetics are lumped into terms that are correlated with experimental data for a particular type of particle. These terms have no physical meaning, and have values such that the equation works. The idealized pore models replace the real but unknown pore structure with a simple and mathematically tractable structure. Empirical factors such as effective pore lengths or average pore diameters are still required, but all the terms in the model represent actual physical properties.

The single pore model was developed by several workers over a period of time. The Ramachandran and Smith (1977) model is used in this study. This model looks at a single pore of an idealized cylindrical shape. The equations for species conservation are solved for an average pore. The total change for the particle is the change for the average pore multiplied by the number of pores per particle. The effective pore radius and diameter are calculated from the porosity and total surface area of the particle. The equations for the reaction rate, and pore size are listed below.

$$n_{pore} = \frac{m_o}{\pi \, l \, (\lambda_p^2 - r^2)\, \rho_{sp}}$$

$$n_p = \frac{6}{\pi d_p^3} \frac{\rho_p}{\rho_{sp}}$$

$$r_b = n_p \, n_{pore} \, 2 \frac{b}{a} \frac{M_b}{M_{ox}} \int_0^l \frac{\rho_{ap}}{\dfrac{1}{k_r\,(\lambda_p + \delta_2)} + \dfrac{\mathrm{Ln}\left(\dfrac{\lambda_p + \delta_2}{\lambda_p - \delta_1}\right)}{D_e}} \, dz$$

$$D_{ap}(\lambda_p - \delta_1)\, 2 \frac{d^2 \rho_{ap}}{d^2 z} + 2D_{ap}(\lambda_p - \delta_1) \frac{d\delta_1}{dz} \frac{d\rho_{ap}}{dz} = \frac{2\rho_{ap}}{\dfrac{1}{k_r\,(\lambda_p + \delta_2)} + \dfrac{\mathrm{Ln}\left(\dfrac{\lambda_p + \delta_2}{\lambda_p - \delta_1}\right)}{D_e}}$$

$$(\lambda_p - \delta_1) \frac{d\delta_1}{dx} = (\gamma - 1)(\lambda_p + \delta_2) \frac{d\delta_2}{dx}$$

$$\gamma = \frac{\rho_b}{M_b} \frac{M_{ox}}{\rho_{ox}\,(1 - \varepsilon_{ox})} \frac{o_x}{b}$$

$$\frac{d\delta}{dx} = \frac{1}{v_p} \frac{o_x M_{ox}}{\rho_{ox}\,(1 - \varepsilon_{ox})} \frac{\rho_{ap}}{\lambda_p + \delta_2} \frac{1}{\dfrac{1}{k_r\,(\lambda_p + \delta_2)} + \dfrac{\mathrm{Ln}\left(\dfrac{\lambda_p + \delta_2}{\lambda_p - \delta_1}\right)}{D_e}}$$

$$\delta = \delta_1 + \delta_2$$

An important consideration of the different types of combustion models listed above is the change of reaction rate with time. In the case of the shrinking core without an oxide layer and the vaporization burning model, the reaction rate increases with time if the reaction is diffusion controlled. Just the opposite is true for the other types. This is important because it may indicate that the ability to drive acoustic oscillations will increase as the particles burn for the vaporizing and shrinking core type and will decrease for the other models. This is due to the fact that the heat transfer to the gas from the burning particle will increase as the reaction rate increases.

Nomenclature

a	stoichiometric coefficient for the reactant gas species
b	stoichiometric coefficient for the liquid or solid reactant
o_x	stoichiometric coefficient for the liquid or solid product
C_a	concentration of gas species
C_{ap}	concentration of oxidizer in pore
C_p	heat capacity
B_T	Spalding number for heat transfer
D_{ap}	diffusivity of oxidizer in pore
D_e	diffusivity of oxidizer in oxide product
d_p	diameter of particle
h_v	heat of vaporization
h_r	heat of reaction
k_g	gas phase mass transfer coefficient
k_r	reaction rate constant
k_t	thermal conductivity
l	effective pore length
M_a	molecu' weight of gas species
M_b	molecular weight of liquid or solid reactant
M_{ox}	molecular weight of liquid or solid oxide product
m_o	initial mass of particle
n_p	number of particles per volume of burner
n_{pore}	number of pores per particle
Nu	Nusselt number
r	pore radius
r_b	mass reaction rate of solid of liquid reactant
r_p	mass reaction rate of particle
r_c	radius of unreacted core
r_s	radius of particle with ash layer
v_p	particle velocity in burner
x	distance in burner
z	distance in pore measured from particle surface
g	constant in pore model defined by equation
ε	porosity of solid product
ρ_{sp}	material density of solid or liquid
ρ_{ag}	density of oxidizer in gas
ρ_{ap}	density of oxidizer in pore
ρ_p	density of particle

δ thickness of solid product in pore

δ_1 distance from initial pore radius to solid surface in pore

δ_2 distance from initial pore radius to interface of solid product and reactant

λ_p initial pore radius

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PUBLICATIONS AND PRESENTATIONS RELATING TO AFOSR CONTRACT DURING CONTRACT PERIOD

PUBLICATIONS

Beckstead, M.W., Braithwaite, P.C., and Gordon, D.L., "Measurements of Distributed Combustion," AGARD Conference Proceedings No. 391, Jan. 1986, paper 21.

Beckstead, M.W., and Braithwaite, P.C., "Measurements of Distributed Combustion" submitted for publication.

Raun, R.L., and Beckstead, M.W., "A Survey of Rijke Burner Models" in preparation.

Raun, R.L., and Beckstead, M.W., "A Numerical Model of a Rijke Burner", in preparation.

PRESENTATIONS

"Combustion Mechanisms of Solid Propellants" presented by M. W. Beckstead, Tokyo, Japan, Oct. 1986 to Japan Defense Agency Rocket Propulsion Laboratory (N. Kubota).

"The Effects of Distributed Combustion on Solid Propellant Combustion Respose Measurements" presented by M.W. Beckstead, Milan, Italy, March 1987 to the Politechnic University of Milan (L. deLuca).

"Combustion Mechanisms of Solid Propellants" presented by M.W. Beckstead, Palaiseau, France, March 1987 to ONERA (G. Lengelle).

"A Numerical Model of the Rijke Burner" presented by R.L. Raun as Paper 87-21, Western States Section/, Combustion Institute 1987 Spring Meeting, Provo, Utah, April 1987.

"Evidences for Distributed Combustion" presented by M.W. Beckstead at AFRPL, Edwards Calif. April 1987 to the Aerothermochemistry Branch (L. Quinn).

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