Summary

A means for improving the performance of a solid fuel pulsed plasma thruster has been described and analyzed. The key to improvement is control over the mass consumed per discharge. Figures 3 and 4 show that the mass consumption can be chosen by adjusting the distance between the two side-fed Teflon fuel bars. For high mass consumption, the thruster operates in the gas-dynamic regime and provides high thrust. At low mass consumption, thruster operation is primarily electromagnetic with high specific impulse. Efficiency increases as the thrust mechanism is predominately in one regime or the other. By using side feed, the performance has been significantly increased over the conventional rear-feed design.

Carbonization of the Teflon side walls remains the one stumbling block to the full utilization of this design to flight thrusters. Geometry changes may reduce or eliminate this problem.

References

[1] Guman, W. J. and Nathanson, D. M., "Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite," *Journal of Spacecraft and Rockets*, Vol. 7, No. 4, April 1970, pp. 409–415.

[2] Vondra, R., Thomassen, K., and Solbes, A., "Analysis of Solid Teflon Pulsed Plasma Thruster," *Journal of Spacecraft and Rockets*, Vol. 7, No. 12, Dec. 1970, pp. 1042–1406.

[3] Vondra, R., Thomassen, K., and Solbes, A., "A Pulsed Electric Thruster for Satellite Control," *Proceedings of IEEE*, Vol. 59, No. 2, Feb. 1971, p. 271.

[4] Thomassen, K. and Vondra, R., "Exhaust Velocity Studies of a Solid Teflon Pulsed Plasma Thruster," *Journal of Spacecraft and Rockets*, Vol. 9, No. 1, Jan. 1972, pp. 61–64.

[5] Solbes, A. and Vondra, R. J., "Performance Study of a Solid Fuel Pulsed Electric Microthruster," AIAA Paper 72-458, Bethesda, Md., 1972.

[6] Radley, R. J., Jr., "Study of a Pulsed Solid Fuel Microthruster," M.S. thesis, 1969, Dept. of Aeronautics and Astronautics, MIT, Cambridge, Mass.

[7] Thomassen, K. I. and Tong, D., "Interferometric Density Measurements in the Arc of a Pulsed Plasma Thruster," AIAA Paper 72-463, Bethesda, Md., 1972.

OCTOBER 1972 J. SPACECRAFT VOL. 9, NO. 10

Effect of External Radiation on the Burning Rates of Solid Propellants

RALPH L. COATES* AND SOLIM KWAK†
Brigham Young University, Provo, Utah

Experimental data are presented for four different propellants burned inside an electrically heated tube furnace. Pressures ranged from 5 to 20 psia, and furnace temperatures ranged from room temperature to 1750°F. It was observed that under the influence of thermal radiation from the furnace walls, the burning rate of the propellants could be increased by as much as 100%. These data as well as data published recently by others are correlated with a simplified laminar flame theory.

Nomenclature

c_g = heat capacity of gas
F = factor for radiation exchange between nonblack bodies
E_g = activation energy, gas reactions
E_s = activation energy, solid reactions
$\dot{m}$ = mass burning rate ($\dot{m} = r\rho$)
n = burning rate exponent
P = pressure
Q = net radiant flux at burning surface
Q_s = radiant flux emitted by external source
Q_f = see Eq. (8)
r = burning rate
r^0 = burning rate under adiabatic conditions
R = gas constant
T_f = flame temperature
T_f^0 = flame temperature under adiabatic conditions
T_s = temperature of burning surface
T_s^0 = temperature of burning surface under adiabatic conditions
T_∞ = temperature of surroundings
σ = Stefan-Boltzmann constant
ρ = density of solid

Presented as Paper 72-35 at the AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17–19, 1972; submitted January 26, 1972; revision received June 19, 1972. This research was supported by the Air Force Office of Scientific Research under Grant AFOSR-70-1895.

Index categories: Properties of Fuels and Propellants; Combustion in Heterogeneous Media; Solid and Hybrid Rocket Engines.

* Professor, Chemical Engineering Department. Member AIAA.
† Research Assistant, Chemical Engineering Department.

Introduction

IF the burning surface of a solid propellant is adjacent to an insulated part of the rocket motor, the net radiant exchange of thermal energy between the two surfaces may be expected to differ appreciably from the adiabatic condition where the surface is exposed only to the combustion products and additional burning surface. Early in the burn time the insulation may be cooler and absorb radiant energy from the burning surface. Later, the temperature of the insulated surface may be substantially higher than the burning surface, resulting in a flow of radiant energy from the insulation to the propellant. In either case, it may be expected that the burning rate of the propellant would be different than when burning under adiabatic conditions.

The effect of external radiation has been reported by previous investigators. Youngberg and Horton,[1] using a simply-heated stainless-steel tube furnace, investigated the effect of the external radiant energy on the burning rate of A-13 propellant at atmospheric pressure. An external radiant flux of 2 cal/cm²/sec. was observed to increase the burning by 18%.

Using a variable thermal radiation source consisting of a shutter controlled xenon-mercury lamp, Mihlfeith, Baer, and Ryan[2] studied the effect of external radiant energy on the burning rate of several composite solid propellants. Generally, increases of 11%–31% were reported in their study for radiant fluxes in the range from zero to 14.85 cal/cm²/sec.

Ohlemiller and Summerfield[3] have investigated the effect of external radiation on the burning rate of solid propellants

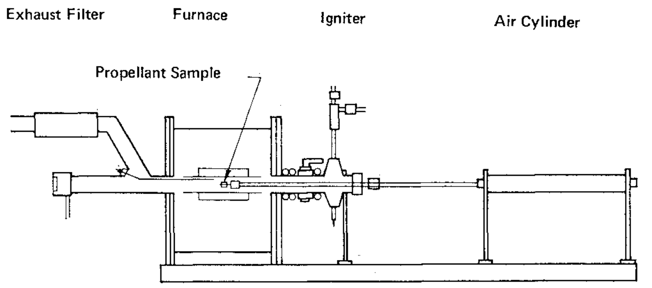

Fig. 1 Schematic diagram of apparatus for measuring effect of thermal radiation on burning rates.

using an arc image furnace. Their data indicate an increase of upwards of 100% when one composite propellant was exposed to 9 cal/cm²/sec of external radiant flux. The rate without the external flux was very low, however, being 0.021 cm/sec.

Thomson, Suh, and Woodward[4] measured the effect of external radiation on the burning rate of an M-2 double-base propellant using a shutter controlled Kanthol heating strip as the radiation source. Contrary to the other investigators, they reported that the external radiant flux did not have a significant effect on the burning rate of solid propellant. Careful study of their results indicates that this conclusion may not be valid, however, since a 17% increase in burning rate was shown to result when the external flux was increased from 0.5 to 1.5 cal/cm²/sec. Their experiments were conducted at the extremely low operating pressure of 2 in. Hg.

The objective of the present study was to obtain additional experimental data showing the effect of external radiant flux and to then attempt a correlation of the data utilizing a simplified laminar flame theory.

Experiments

The experiments were carried out with a specially constructed tube furnace, shown schematically in Fig. 1. The heated tube was a section of stainless-steel tubing with an i.d. of 2.95 in., a wall thickness of 0.14 in. and a length of 11.3 in. The tube was surrounded by two semi-circular 1200 w electrical heating elements. The heated space between the heating elements and the external pipe wall was filled with Fiberfrax ceramic fiber insulation.

A platinum/13% platinum-rhodium thermocouple was positioned inside the heated tube near the upper surface of the tube wall. This thermocouple was the sensing element for a proportioning controller which maintained the furnace temperature at any desired setting between room temperature and 1750°F.

The propellant samples were external-burning cylinders that were inhibited on both ends. The axis of the sample holder coincided with the axis of the heated tube. The time to burn a distance of 0.26 in. was measured by detecting the passage of the flame front at two radial stations. Light pipes transmitted the light emitted at these stations to photoduodiodes located inside the sample push-rod. For propellants that burn with a very nonluminous flame, it was found to be necessary to place a small amount of pyrotechnic powder adjacent to the detection stations. This powder was ignited by the passing flame front and produced sufficient luminosity to be easily detected.

The samples were injected into the tube furnace after being ignited by four oxy-hydrogen jets in the ignition chamber. Injection of the ignited samples into the furnace was accomplished with an air-actuated cylinder attached to one end of the push-rod. A more detailed description of this equipment is available in Ref. 5.

Table 1 Results of flux calibration tests

Furnace temperature °F	Radiant flux cal/cm²/sec
250	0.03
500	0.12
750	0.26
1000	0.49
1250	0.94
1500	1.63
1750	2.64

The radiant flux emitted by the furnace walls at various temperature settings was calibrated using a Model C-1104-B incident flux meter manufactured by Hy-Cal Engineering Company. The results of this calibration are presented in Table 1. The apparent emissivities of the furnace tube corresponding to these data indicate the tube radiated much the same as a blackbody. The incident flux on the burning surface of the propellant sample would be less than the measured values reported in Table 1 due to absorption by the combustion products. However, since these products do not contain metal oxides and the pressure was low, the amount of absorption would likely be small.

Four different propellants were tested in this study. These propellants are identified by the numbers A-13, TPF-1002, TPF-1006, and 10HS-891. Propellant A-13 is an ammonium perchlorate oxidized polybutadiene-acrylonitrile composite. Propellants TPF-1002 and TPF-1006 are ammonium perchlorate-fluorocarbon composites, and 10HS-891 is a double-base propellant. These propellants were tested at pressures ranging from 5 to 20 psia and at furnace temperatures ranging from room temperature to 1750°F. The experimental results are presented in Table 2. It is noteworthy that the burning rates of both TPF-1002 and TPF-1006 at 10 psia are observed to increase by more than 100% as the furnace temperature was raised from room temperature to 1750°F. The data for 10HS-891 indicate that the average burning rate apparently decreased with increasing furnace temperature at pressures of 5 and 10 psia. However, the reproducibility was rather poor at these pressures with this propellant, and only a limited number of tests were run. The uncertainty of the data therefore does not justify the conclusion that the burning rate effect was actually opposite to that observed in the remainder of the tests.

Theory

A simplified theory of solid-propellant combustion based on laminar flame theory has been recently described by Coates.[6] This theory was demonstrated to qualitatively predict the burning behavior of real propellants under a variety of different conditions, including the situation where energy is gained or lost from the surroundings. For the present considerations, the theory may be reduced to three basic equations. The first equation expresses an over-all energy balance for the combustion wave

$$T_f = T_f^0 + Q/\dot{m}c_g \quad (1)$$

The second describes the kinetics of the gas phase reactions,

$$r = r^0(P/P^0)^n(T_f/T_f^0)^{1+n}\exp[(-E_g/2RT_f^0)(T_f/T_f^0 - 1)] \quad (2)$$

and the third describes the kinetics of the gasification reactions occurring at the surface of the burning solid

$$r = r^0 \exp[(-E_s/RT_s^0)(T_s/T_s^0 - 1)] \quad (3)$$

For radiative transfer between the burning surface and the

Table 2 Summary of experimental results

Pressure psia	Furnace temp., °F	Burning rate, in./sec			
		A-13	TPF-1002	TPF-1006	10H-891
5	1000	...	...	0.011 ± 0.002	0.014 ± 0.017
	1500	...	0.010 ± 0.002	0.012 ± 0.002	0.010 ± 0.005
10	75	...	0.008 ± 0.005	0.011 ± 0.003	...
	500	0.029 ± 0.008	0.012 ± 0.003	0.011 ± 0.003	...
	750	0.033 ± 0.003	0.013 ± 0.001	0.012 ± 0.002	...
	1000	0.036 ± 0.002	0.014 ± 0.001	0.015 ± 0.002	0.015 ± 0.009
	1250	0.039 ± 0.003	...	0.016 ± 0.001	...
	1500	0.041 ± 0.011	0.017 ± 0.002	0.019 ± 0.004	0.012 ± 0.003
	1750	0.046 ± 0.006	0.019 ± 0.004	0.023 ± 0.008	...
20	75	...	0.022 ± 0.004	0.027 ± 0.014	0.009 ± 0.003
	1000	...	0.028 ± 0.009	0.028 ± 0.001	0.014 ± 0.003
	1500	...	0.031 ± 0.011	0.033 ± 0.006	0.016 ± 0.003

surroundings, the net flux Q appearing in Eq. (1) may be computed by the equation

$$Q = \sigma F(T_\infty^4 - T_s^4) \quad (4)$$

To reveal the parameters of this theory which most strongly influence the response of the burning rate to external radiation, Eqs. (1) and (2) may be differentiated and combined to yield

$$dr/r^0 = [\varepsilon/(1 + \varepsilon f)]\, dQ/Q_f^0 \quad (5)$$

where

$$\varepsilon = 1 + n + E_g/2RT_f \quad (6)$$

$$f = Q/(r\rho c_g T_f^0) \quad (7)$$

$$Q_f^0 = r^0 \rho c_g T_f^0 \quad (8)$$

For the experimental conditions of both this study, and those referenced in the Introduction, $\varepsilon f \ll 1$, so that

$$dr/r^0 = \varepsilon dQ/Q_f^0 \quad (9)$$

Thus, the important parameters appear to be r^0, ρ, c_g, T_f^0, and E_g. Values of all these parameters except E_g are usually available for a given propellant or they may be readily estimated.

To investigate the predictions of the theory for wide variations of T_∞, and hence Q, Eqs. (1–4) were solved simultaneously employing the parameters listed in Table 3. The parameters r^0, E_g, and T_∞ were varied. The results of these calculations are presented in Fig. 2. It is noted that even though r^0 was varied from 0.025 to 0.10 cm/sec, the results for these variations all fell on the same three E_g curves when plotted as r/r^0 vs Q/Q_f^0.

Correlation of Experimental Data

The theoretical results of the previous section suggest that the experimental results of both this study and those presented in Refs. 1 and 2 may be correlated by plotting the ratio of the

Table 3 Magnitude of parameters used in theoretical calculations

ρ, g/cc	1.6
c_g, cal/g°K	0.4
F	1.0
T_s^0, °K	700
T_f^0, °K	2000
E_s, kcal/mole	25
E_g, kcal/mole	25, 50, 75
r^0, cm/sec	0.025, 0.05, 0.10
T_∞, °K	300–1300

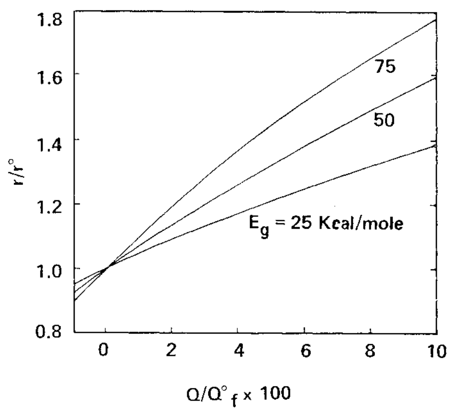

Fig. 2 Results of theoretical calculations showing the effect of net radiant flux on burning rate.

measured burning rate to some reference burning rate for the same propellant r^0 vs the ratio of the net radiant flux Q to the product $r^0\rho c_p T_f^0$. However, T_s is not known for these propellants at the low pressures under which they were tested, nor is the surface emissivity which governs the magnitude of the view factor. Consequently, it was not possible to accurately compute Q. Also, the magnitudes of T_f^0 were not known for these propellants at the test conditions. For these reasons, an attempt was made at correlating the data by simply estimating Q and plotting r/r^0 vs Q/r^0 rather than $Q/r^0\rho c_p T_f^0$.

The net radiant flux was estimated by subtracting 0.6 cal/cm²/sec from the radiant flux emitted from the radiant source. This magnitude was estimated to be the approximate radiation flux emitted from the burning surfaces of the different propellants. For a reference burning rate, the value corresponding to a surrounding temperature of 1000°F was arbitrarily selected, this rate being thought to be near that resulting from adiabatic combustion. Thus an attempt was made at correlating the data by plotting $r/r_{1000°F}$ vs $(Q_s - 0.6)/r_{1000°F}$.

Figure 3 presents the results of the present study along with those reported in Refs. 1 and 2 plotted as discussed previously. It should be pointed out that the measured burning rates from Ref. 2 range from 0.055 to 0.14 in./sec and that radiant fluxes of up to 14.85 cal/cm²/sec were employed to obtain these data. On the other hand, the present results were obtained with a maximum flux level of 2.64 cal/cm²/sec and the burning rates ranged from 0.01 to 0.046 in./sec. Also presented in Fig. 3 are lines corresponding to the theoretical calculations discussed in Sec. III.

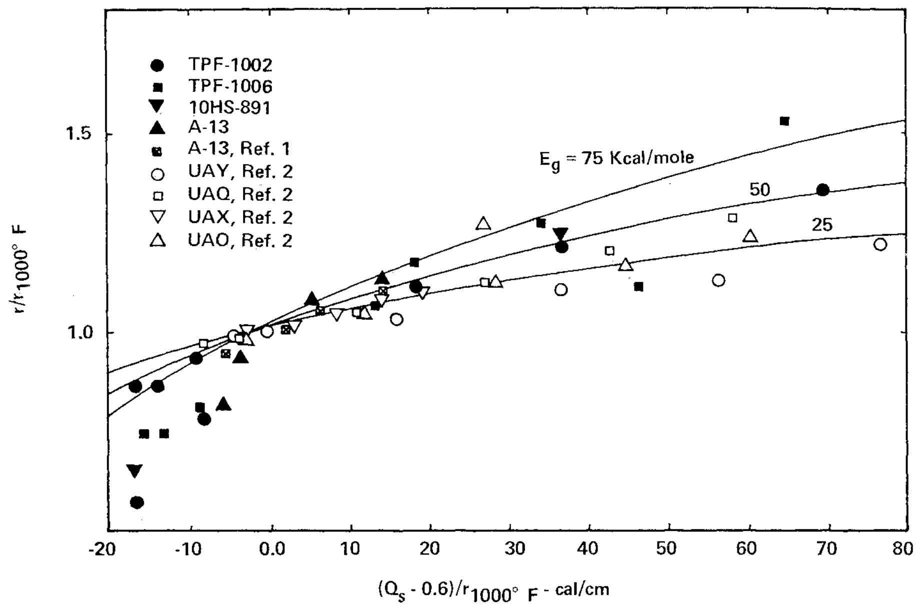

Fig. 3 Correlation of experimental data for the effect of external radiation on burning rates.

Conclusions

These data along with those reported by previous workers clearly show the importance of considering nonadiabatic combustion effects on solid propellants under conditions where the burning rates are low. They suggest that applying conventional strand burner data to make motor design calculations can be particularly hazardous if the measured strand burning rates are very low.

Considering the wide range of experimental conditions and the wide variety of different propellants represented by the data in Fig. 3, it is apparent that the approach followed to obtain this figure is a useful method of correlating experimental data and estimating the effects of nonadiabatic combustion.

The data seem to conform at least qualitatively to the predictions of the simplified theory, except under conditions in which the net radiant energy flows from the burning surface to the surroundings. Under these conditions, there is a greater reduction in the burning rate than predicted theoretically. A possible explanation for this discrepancy is that the flame temperature is reduced below the value calculated to result from the energy loss, this reduction being due to failure of the combustion reactions to go to completion. In other words, because of the energy loss, incomplete combustion may occur and the effective T_f^0 would then be less than the adiabatic value.

References

[1] Horton, M. D. and Youngberg, L. Z., "Effect of Radiant Energy on the Burning Rate of a Composite Solid Propellant," *AIAA Journal*, Vol. 8, No. 10, Oct. 1970, pp. 1738–1741.

[2] Mihlfeith, C. M., Baer, A. D., and Ryan, N. W., "The Response of a Burning Solid Propellant Surface to Thermal Radiation," AIAA Paper 71-209, New York, Jan. 1971, pp. 5–6.

[3] Ohlemiller, T. J. and Summerfield, M., "Radiation Augmented Burning of a Solid Propellant," Aerospace and Mechanical Sciences Rept. 799, 1967, Princeton Univ., Princeton, N.J., pp. 16–25.

[4] Thompson, C. L., Jr. and Suh, N. P., "The Interaction of Thermal Radiation and M-2 Double-Base Solid Propellant," *Combustion Science and Technology*, Vol. 2, Nov. 1970, pp. 59–66.

[5] Kwak, S., M.S. thesis, 1972, Chemical Engineering Dept., Brigham Young Univ., Provo, Utah.

[6] Coates, R. L., "An Analysis of a Simplified Laminar Flame Theory for Solid Propellant Combustion," *Combustion Science and Technology*, Vol. 4, Sept. 1971, pp. 1–8.