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Measurement System for Determining Solid Rocket Propellant Burning Rate Using Reflection Microwave Interferometry

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A method has been developed for direct and continuous measurement of the instantaneous burning rate of solid rocket propellants at different pressures, under conditions similar to those of a solid rocket motor, and with no disturbances of the combustion gas flow. The method is based on microwave reflection interferometry. The system consists of an experimental motor, microwave installation, hardware, and software for measurements. The system operates in the Ka-band (35 GHz). The burning rate data are available immediately after test runs because of the special software for data reduction. The principle of the measurement method and data reduction, together with a description of the test motor and installation, are given. Also, the most characteristic results of base burning rate are given, as obtained for different double-base and composite rocket propellants at different temperatures. The results show that the microwave system can be used for precise determination of the base burning rate of solid rocket propellants under different pressures during only one test at defined initial temperature, in laboratory conditions similar to those in a real rocket motor.

Nomenclature

b = coefficient of pressure in the Saint-Robert's law of burning rate
n = pressure exponent of burning rate in the Saint-Robert's law
n_r = index of refraction
P_c = combustion pressure
r = propellant burning rate
ΔQ = standard deviation of the burning rate in comparison with Saint-Robert's law
σ_p = coefficient of temperature sensitivity

Introduction

SOLID propellants are used in a variety of applications and the most important one is in rocket motors. Accurate knowledge of the burning rate of a solid propellant is a prerequisite in the design of new solid propellant rocket motors. Also, exact values of burning rate are necessary for the quality control of propellants during production. Numerous methods have been developed for burning rate measurements of solid rocket propellants, but generally, they can be divided into two main groups: 1) indirect and 2) direct. A method is termed indirect if the burning rate is determined by the calculation of data obtained during motor work, mostly from analysis of the pressure-time-charge size data, taking into account any nonneutral burning geometry of the grain. Charges used in these test motors are usually small. A method is called direct if the burning rate is determined by the measurement of a propellant burning surface motion during combustion. They can be divided into two groups: 1) laboratory sample and 2) direct motor firing methods. Laboratory sample methods can be used only on laboratory test motors and include probes,[1] γ-ray[2] and x-ray,[3] photographic,[4,5] ultrasonic,[6] and microwave interferometry. Direct motor firing methods can be used on real motors, although they can be used also on test motors. This group involves methods of interrupted burning,[7,8] and conductivity, ionization,[9] and thermocouple probes.

The burning rate of solid propellants depends on a number of parameters: the pressure and initial propellant temperature, crossflow velocity, propellant type, fuel-to-oxidizer ratio, and oxidizer particle size in the case of composite propellants. Generally, the burning rates of solid propellants may be described by the empirical equation (Saint-Robert's law):

$$r = bP_c^n \tag{1}$$

The aim of this experimental work was to develop a method for fast, direct, and continuous measurement of the base burning rate of solid rocket propellants at different pressures and initial temperatures, under laboratory conditions of test propellant similar to those of typical solid rocket motor operation, and with no disturbances of the combustion gas flow. The method is based on microwave reflection interferometry. A complete burning rate vs pressure curve can be obtained with a single experiment in a wide range of pressures.

Previous Investigations

Among the direct burning rate measurement methods developed during the past 40 years, the microwave technique is probably the most attractive. The first paper in which the use of microwaves was mentioned is probably the paper by Koch in 1953,[10] in which using microwaves to measure detonation velocities in explosives was described. In this period, microwaves used for determining detonation velocity are described in other papers.[11,12] The first paper on the microwave measurement of regression rates in solid propellants is that by Johnson.[13] There are further contributions to microwave burning rate measurements.[14–17] Gittings et al.[18] describes the change in quasistationary regression rates introduced by the presence of acoustic modes in a rocket motor. A report

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by Gould et al.[19] describes in detail K-band experiments with the objective of studying the regression rate of propellant ANB 3066 under steady and oscillatory conditions. The report by Alkidas et al.[20] describes measurements with carboxyl-terminated polybutadiene/ammonium perchlorate (CTPB/AP) propellants imbedded in an undersized waveguide, which supports only a single mode when filled with propellant as dielectric. Several papers by Strand et al.[21,22] at the Jet Propulsion Laboratory (JPL) at the California Institute of Technology, deal with the subtle subject of microwave determination of propellant acoustic response functions. This group used an apparatus originally developed at JPL, which was subsequently modified and improved. Several composite propellants were examined and the complex response functions were determined as functions of the acoustic frequency.

Experimental investigations aimed to develop a method for determining solid rocket propellant burning rate using reflection interferometry have been carried out at JPL by the Faculty of Mechanical Engineering in Belgrade for over 15 years. In this period, different microwave installations and different methods of data reduction were developed for calculating burning rates of solid rocket propellants.

Principle of Microwave Reflection Interferometry

The principle of the burning rate microwave reflection measurement technique is illustrated in Fig. 1. Electromagnetic radiation from a generator is divided by a microwave installation into two parts. One part of the electromagnetic radiation is propagated through a branch of the microwave installation without changes in phase. This part of radiation is called the reference signal and the part of installation is called the reference branch. The other part of electromagnetic radiation propagates through a propellant sample enclosed in a waveguide, where it is both reflected and transmitted at each material interface. This part of microwave installation is called the measurement branch. The signal of interest is the reflection from the burning surface of propellant sample (transition from solid propellant to gas products of burning). This signal changes continuously in phase during the regression of burning surface. The reflection signal could be merged with a reference signal to form a new wave. The reflection and reference signals alternatively reinforce and destroy each other when they are superposed, and this process is generally termed interferometry. This new wave is received by a detector, which transforms microwave power into electric current and voltage. The detector signal is a sine wave (Fig. 2), and the phase of this sine wave is changed with reduction in length of the burning sample. The voltage signal is steady in the absence of burning. The distance between two adjacent maxima or minima in this signal represents the half-wavelength of the signal in the propellant. It defines the position of burning surface in time, and using appropriate methods of data reduction makes the calculation of the value of the burning rate possible.

The various reflections that appear (see Fig. 1) introduce higher-order harmonics in the interferograms. To keep this effect to the minimum, we have selected a plastic support with dielectric properties similar to the propellant (see Fig. 3, item 7), and also introduced an absorber at the far wall (see Fig. 3, item 9).

The reduction of data was based on the fact that the interferogram proved symmetric within the half-period, so that both minima and maxima of the fringe pattern were used. This directly yields the thickness of the unburned propellant at a particular time in terms of the propellant wavelength, known from the propellant refractive index that was separately measured. To avoid the accumulation of error that would result if differences of the primary data were formed, a polynomial regression through several adjacent points was run to fit the thickness–time curve, and the burning rate was determined as the derivative of the polynomial using the Savicky and Golay method.[23]

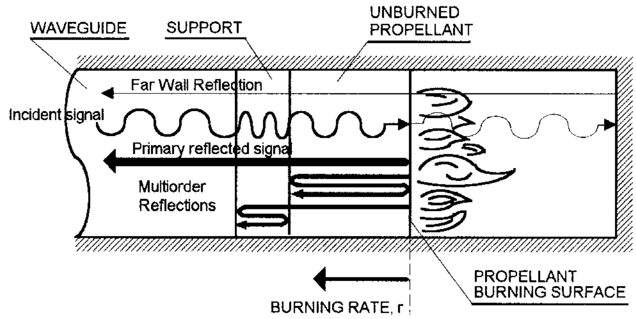


Fig. 1 Microwave burning rate measurement technique.

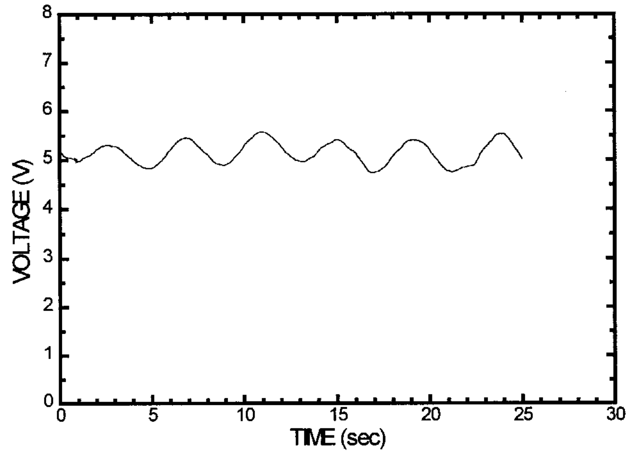


Fig. 2 Interference pattern from one test.

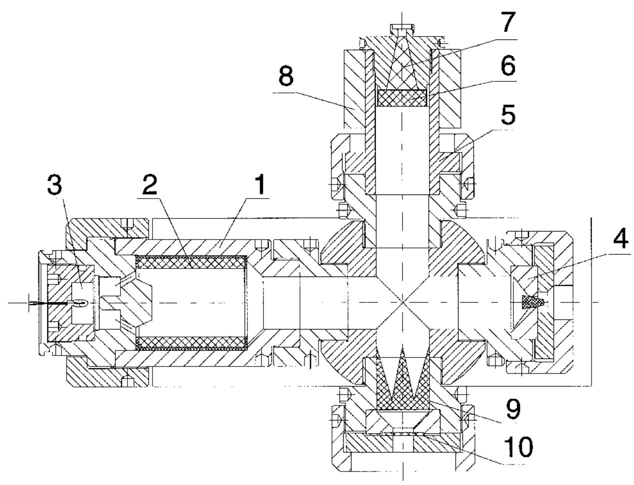


Fig. 3 Test motor assembly. 1, Chamber of the gas-generating section; 2, gas-generating charge; 3, igniter; 4, nozzle section; 5, chamber of the measuring section; 6, propellant sample; 7, horn antenna; 8, heat exchanger; 9, microwave absorber; and 10, membrane section.

The results are dependent on many factors: roughness of burning surface, grain compressibility, and transient flame ionization level. Possible effects of the transient flame zone ionization level on the burning rate determined by the microwave technique have been investigated experimentally with transmission experiments.[24] When a flame of laterally inhibited charge is introduced into the focus of two horn lens antennas, the detector electric current exhibits no significant changes in intensity. A metal plate of the same width blocks the transmission path almost completely. These experiments show that the flame of the propellant does not reflect or absorb a large part of the microwave power back, and that it has no significant effect in microwave burning rate measurements. The reflection signal is really formed from the propellant/gas phase interface, not from the flame plasma during propellant burning.

The accuracy of the burning rate measurements depends on the knowledge of the microwave wavelength in the solid propellant. The frequency of the microwave radiation was measured with an accuracy of $\pm 0.25\%$, and index of refraction of propellant was determined with an accuracy of $\pm 1\%$. Total error is equal to the sum of these two errors. Waesche and O'Brien[25] have studied the operation of nozzleless motors and have also discussed the relative merits of microwave measurement.

Experimental Test Apparatus

The microwave installation is shown in block diagram form in Fig. 4. A continuous microwave signal is generated from a Gunn microwave oscillator with Gunn bias regulator. It produces approximately 100 mW of microwave power with a 10 V, 1.7 A dc input. The oscillator is set at 35 GHz. A ferrite isolator is placed immediately after the oscillator. As it allows signal propagation in the forward direction only, it serves to prevent unwanted reflections of microwave radiation from other parts of the installation. The direct reading frequency meter placed behind the isolator serves to measure the frequency of the input signal before each test. Passing the frequency meter, this signal comes to a variable attenuator, which allows control of microwave power by movement of a resistive vane. The signal with an adjusted level of radiation enters the H arm of a hybrid tee junction (magic tee). In the magic tee, it is divided into two equal signals with half the power and with the same phase, one in each arm. One signal is directed to the experimental motor by a waveguide section. It comes to the microwave inlet that consists of tapered transition from rectangular to round waveguide and a horn. The signal passes from the horn to the propellant sample, where it is reflected from the burning surface and propagates back through the same waveguide system to the magic tee. This signal carries the relevant information about burning rate, along with multiorder reflections that travel several times through the propellant between the burning surface and elements of the horn.

The other signal in the second arm of the magic tee, the reference signal, comes into another branch of the installation, which is terminated with a tunable short. The tunable short serves to reflect the wave back to the magic tee with minimum losses and to regulate its phase. A precision level-set attenuator, placed behind the magic tee, allows control of the microwave power level of the signal that leaves this part of the installation. The tunable short and precision attenuator are set before each test. This setting brings both waves to constructive interference, which makes the microwave interference signal start from a maximum. In this way we are certain that all subsequent points will stay within the data acquisition range. This yields good measurement, and later, easier data reduction.

The magic tee is used again to couple and superpose the reflection signal and the referential signal from both arms. These two signals exit from the E arm of the magic tee. This

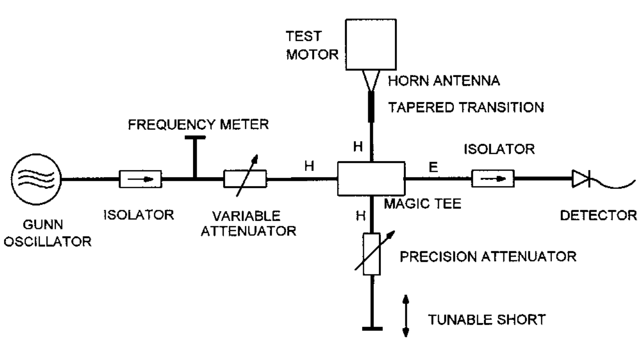


Fig. 4 Block diagram of the microwave measurement system.

combined signal passes through an isolator (which serves to prevent possible unwanted reflections), to the tunable broadband detector with silicon whisker contact diode. It converts microwave power into electric current and voltage that exhibits minimum sensitivities of up to 1500 mV/mW across full waveguide bandwidth. All of these elements of the microwave installation are connected with a standard rectangular Ka-band waveguide made of copper.

The detector voltage is amplified 100 times and sent to the A/D converter and computer, where it is recorded and stored on the computer's disk together with pressure-time data. In this way all of the data are in digital form convenient for recording, analysis, transfer, and storage. Also, microwave signal (burning rate) vs time data are coordinated with pressure vs time data.

A personal computer-based data acquisition system, used in experiments, consists of pressure transducers, charge amplifiers, microwave signal amplifier, elements for transfer of signals, A/D converter, personal computer (IBM PC or compatible), control section, and pyrotechnic device controller. Complete starting of a test, monitoring, acquisition, and data reduction are performed on the personal computer. Appropriate programs for test control and data acquisition are specially developed for this type of test.

The test motor is so designed to yield combustion product gas temperature, pressure, and freestream velocity for the burning of a propellant similar to that surrounding combustion of a typical solid propellant motor for end-burning. All basic elements are made of steel, capable of sustaining a number of tests. A schematic diagram of the test motor is presented in Fig. 3. The test motor consists of a central section and four additional sections: gas-generating, measuring, nozzle, and membrane. The gas-generating section is the chamber that forms a high-pressure hot combustion gas flow needed to provide working pressure and temperature in the measuring section by burning a special gas-generating charge. This hot combustion gas simulates actual rocket conditions. The propellant grain has progressive surface spread because it has a cylindrical form inhibited at both ends and the outer lateral surface. This geometry makes the continual burning of propellant samples at different pressure with a ratio between lower and top pressure up to 1:4 possible.

Preliminary Results

The index of refraction of the examined propellants at microwave frequency is a basic physical quantity that determines the wavelength in propellant, and in this way influences in the first degree the obtained value of burning rate. Although this quantity can be obtained from experiments with mechanical changes of propellant thickness and from burning at constant pressure, a special microwave method is developed for measurement of the index of refraction of all of the examined propellants at 35 GHz. Measurement is based on the method of substitution and reflection interferometry. The phase shift introduced by the propellant is counteracted by a calibrated phase shifter to reset destructive interference. Measurements were performed with a minimum of three different thicknesses of propellants. Calculation is performed including multiorder reflections. The indexes of refraction for all examined propellants are given in Table 1. The largest value of standard deviation is obtained during examination of composite propellant F-79, and it was 2% from three measurements.

Before a test in the real motor was conducted, testing with laboratory equipment had been performed to determine the viability of the whole system. The first tests were performed with the complete microwave installation, and the test apparatus consisted of a motorized metal plate-reflector placed in front of the microwave horn. The motion of reflector toward the waveguide was similar to propellant regression during burning in test motor. After these experiments, a number of quasisteady regression rate measurements were done to check the accuracy

Table 1 Propellant data

Propellant	Type	Composition	Weight percent	Average particle size of filler, μm	Index of refraction
A	D.B.	Nitrocellulose/nitroglycerin	55.7/30	——	1.887
B	D.B.	Nitrocellulose/nitroglycerin	54.8/38.15	——	1.887
C	D.B.	Nitrocellulose/nitroglycerin	53.4/33.2	——	——
F-79/1	Comp.	PVC binder/AP/Al	24.5/75/0.5	242	1.96
F-79/3	Comp.	PVC binder/AP/Al	24.5/75/0.5	695	1.96
F-81 L/2	Comp.	PVC binder/AP/Al	29.5/69/0.5	778	1.967

of the instrumentation, hardware, and software for these measurements. The propellant sample was replaced with a column of liquid that has an index of refraction close to that of a propellant. Carbon tetrachloride with an index of refraction n_r = 1.84 was used. Surface regression of the column of liquid was obtained by leakage through a hole at the bottom of the vessel, which also serves as a waveguide. These tests prove that reflection interferometry and data reduction software can determine the moving rate of reflection surface; in this case a liquid surface.

Burning Rate Results

After the preliminary experiments had been completed, several burning rate measurements were performed at atmospheric pressure. Tests were performed with different types of propellants, with the combustion chamber widely open to the atmosphere. Under these conditions the regression rate is constant because the propellant samples burn at a steady pressure, and the interferograms can be interpreted to yield propellant properties. The average burning rate at the ambient pressure in these tests can also be calculated by directly dividing the web by the burning time determined from measured microwave signal history. The results from these experiments for different types of propellants are shown in Fig. 5. These results are also compared with results obtained by direct measurements and show good agreement. The largest difference between the average value of burning rate measured with microwaves and measured directly is obtained with double-base propellant A; it was 4.2%.

On the basis of the successful results of all previous experiments, the burning rates of several different propellant formulations, double-base (D.B.) and composite (Comp.), at different temperatures were measured using the described equipment. The burning rates of the examined propellants are presented in Figs. 6–10. All of the data were correlated with the Saint-Robert's law. The characteristics of propellants that were examined are listed in Table 1.

The burning rates vs pressure obtained for double-base propellant A are shown in Fig. 6. Burning rate was measured in a pressure range from 3 to 20 MPa at three temperatures: four tests at 248 K, 10 tests at 293 K, and eight tests at 323 K. Separate tests are represented with different symbols. The first experiments were done with a gas-generating charge made from the same propellant A, and then numerous problems appeared with ignition and stable burning, especially at low pressure and temperature. After using gas-generating charges made from double-base propellant B or composite propellant F-79/1, the propellant samples had stable burning in all conditions. Although the flame temperature in experiments with the new gas-generating charge was different from the flame temperature of the test propellant, comparable results between measurements with old and new gas-generating charges at the same conditions had shown that changes of composition in gas-generating charge had no influence on the value of burning rate. The results indicated that there existed differences in burning rates from batch to batch under the same conditions. From the obtained results, the coefficient of temperature sensitivity at pressure P_c = 10 MPa is $\sigma_p = 0.0051\ K^{-1}$.

The double-base propellant B was examined in a pressure range from 3 to 18 MPa at three temperatures: three tests at 248 K, nine tests at 293 K, and seven tests at 323 K. The measured burning rate vs pressure is shown in Fig. 7. Separate tests are represented with different symbols. The initial experiments were done with gas-generating charges made from the same propellant B, and then problems appeared with stable burning at low pressure and temperature. These gas-generating charges were replaced with gas-generating charges made from the composite propellant F-79/1, and then test samples attained stable burning in all conditions. Comparative results between measurements with these two compositions of gas-generating charges at the same conditions have shown that the change of composition has not influenced the actual value of the burning rate. However, the regularity of the pressure curve was better with the composite propellant. From the obtained results, the coefficient of temperature sensitivity at pressure P_c = 10 MPa is $\sigma_p = 0.0033\ K^{-1}$.

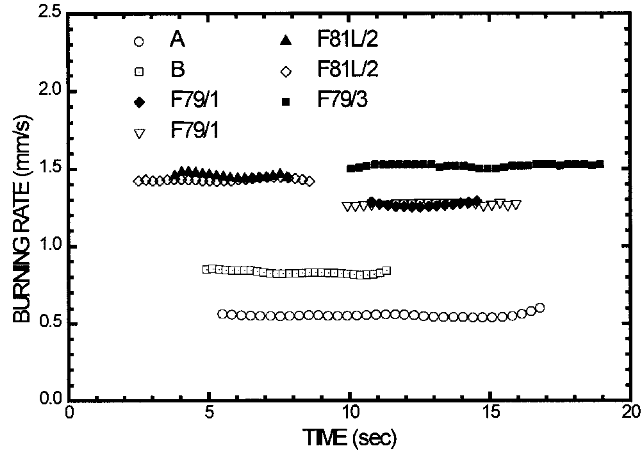
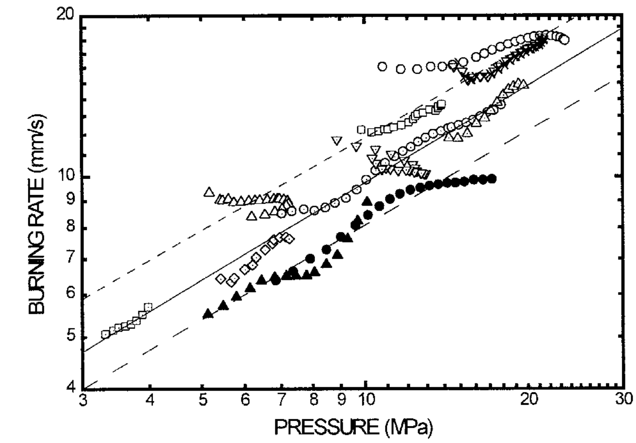


Fig. 5 Burning rate results at atmospheric pressure.

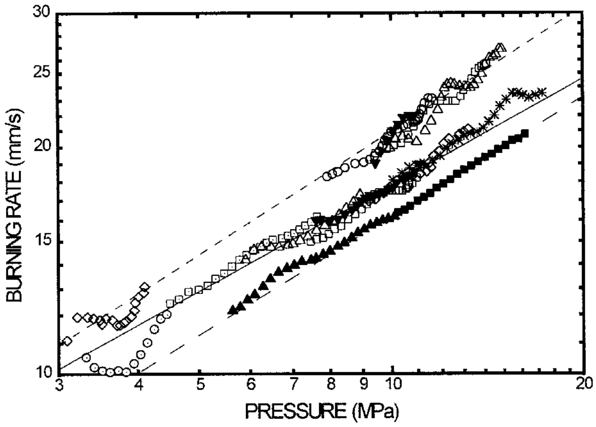


– – T=248 K n=0.587 b=6.30 10^{-7} ΔQ=3.98 %

—— T=293 K n=0.605 b=5.66 10^{-7} ΔQ=5.48 %

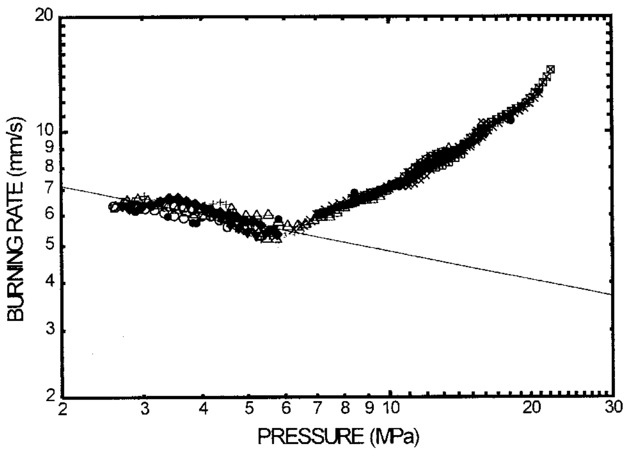
...... T=323 K n=0.577 b=1.08 10^{-6} ΔQ=6.09 %

Fig. 6 Burning rate results of double-base propellant A.



– – T=248 K n=0.491 b=5.93 10^{-6} ΔQ=0.90 %
—— T=293 K n=0.517 b=4.34 10^{-6} ΔQ=2.60 %
······ T=323 K n=0.542 b=3.37 10^{-6} ΔQ=2.77 %

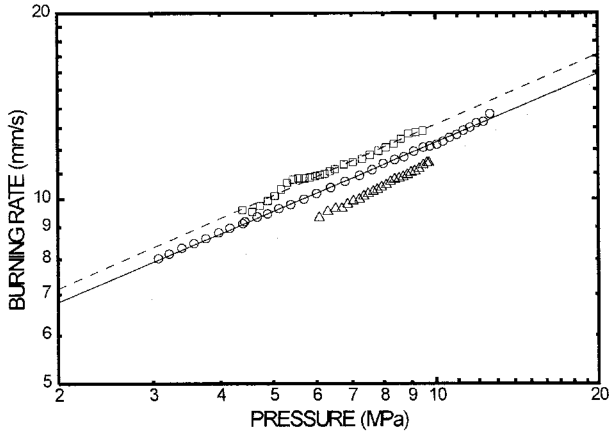
Fig. 7 Burning rate results of double-base propellant B.



• - burning rate results obtained in 2" test motor

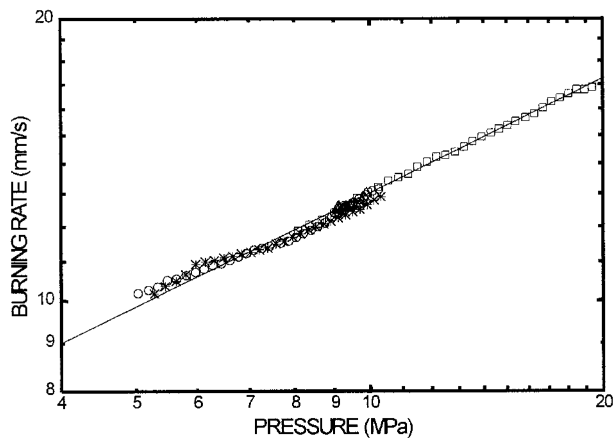
—— P_c<6 MPa n= -0.253 b=2.86 10^{-1} ΔQ=4.62 %
– – P_c>6 MPa n= 0.593 b=5.21 10^{-7} Q=3.07 %

Fig. 8 Burning rate results of double-base propellant C.



– – T=248 K n=0.427 b=1.18 10^{-5} ΔQ=0.33 %
—— T=293 K n=0.366 b=3.41 10^{-5} ΔQ=0.47 %
······ T=323 K n=0.379 b=2.91 10^{-5} ΔQ=1.04 %

Fig. 9 Burning rate results of composite propellant F-79/1.



—— T=293 K n=0.392 b=2.32 10^{-5} ΔQ=1.28 %

Fig. 10 Burning rate results of composite propellant F-79/3.

The burning rate of double-base propellant C was examined in a pressure range from 2.6 to 20 MPa. All experiments were performed at 293 K. The measured burning rate vs pressure is shown in Fig. 8, where results of separate tests are represented with different symbols. As this propellant cannot be fired below a pressure of 2.5 MPa and has stable burning only over 6 MPa, gas-generating charges were made from composite propellant F-79/1 and were used to obtain stable burning for all experiments. Seventeen experiments in total were performed, mainly in pairs of propellant samples that belong to different propellant series. The results show that two types of burning rate data can be distinguished, separated by a breakpoint. The burning rate exponents and coefficients for the two different regions are marked in Fig. 8. The agreement between test samples that belong to the same propellant series was excellent, although there were differences between different pairs of propellants. Results are also given in Fig. 8, which have been obtained during measurement in 2-in. test motor for comparison with results obtained with microwave interferometry.

The burning rate of composite propellant F-79 was examined with two samples with different dispersion grade of ammonium perchlorate as oxidizer. The composition F-79/1 was examined in a pressure range from 3 to 12 MPa at three temperatures. The results are shown in Fig. 9: two tests were run at 248 K (represented with triangle symbol), three tests were run at 293 K (represented with circle symbol), and two tests at 323 K (represented with square symbol). From these results, the coefficient of temperature sensitivity at pressure P_c = 9 MPa is σ_p = 0.0022 K^{-1}. The burning rate of propellant F-79/3 was measured in a pressure range from 5 to 19 MPa only at 293 K. In total, four tests were performed and the results are shown in Fig. 10. Results of separate tests are represented with different symbols. For both propellants, gas-generating charges were made from the same propellant as test samples. The results indicate that this composite propellant is much more homogeneous and of better quality than the previous double-base propellants, and attains better ignition and burning. This was the reason to use this composition of propellant for gas-generating charges for tests with all double-base propellants.

Conclusions

An experimental apparatus for measuring the base burning rates of solid propellants under wide ranges of pressures has been designed, and numerous tests have been performed on composite and double-base propellants. The test motor design and microwave installation have proved to be capable of sustaining a large number of tests at different temperatures over a wide range of pressures. The whole microwave installation, except for the microwave inlet in the test motor, is removed from the test zone and in this way protected from possible destruction during tests. The base burning rates of three types of double-base and one type of composite propellant are presented in this paper. From the previously mentioned work, the conclusion can be made that accurate knowledge of the burning rate of a solid rocket propellant in a wide range of pressures is obtained during only one test. The results have demonstrated that the method is at least as accurate as more classical methods and can be used to determine quasisteady burning rate curves over wide pressure ranges in a single test. Compared with the Crawford bomb or small motors measurements, a regression rate vs pressure curve is obtained with minimum 20 points, in a range of minimum 2 MPa in a single experiment. Apart from this increase in efficiency, the conditions in the combustion chamber are closer to those prevailing in a rocket chamber, as the high pressure is generated by hot combustion gases, which simulates the heat loss conditions in a real rocket motor.

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