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Recent Developments and Current Status of Hybrid Rocket Propulsion

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Efficient, high-energy hybrid motors can be designed for specific applications. High impulse and variable thrust capabilities have been proved. New propellant systems and improved motor designs have led to impulse efficiencies ≥ 93%, nearly total fuel utilization, and burning rates approximating those of conventional solid propellants. Improved throttling techniques can provide efficient performance over a thrust range of 10:1. The good combustion efficiencies and fuel utilization have resulted from studies of the gas-flow behavior in the combustion zone and application of the results to the design of injectors, grains, and combustion chambers. The rapid-burning fuels have been developed by examining the mass- and heat-transfer mechanisms inherent at the fuel surface and by formulating fuels containing advanced ingredients to increase decomposition and vaporization of the solid. Although random throttling over an extensive thrust range is of no concern for on/off or programed modulation of thrust levels, it is expected to become a critical requirement for future applications. This problem has been resolved experimentally by injecting make-up oxidizer downstream of the fuel grain, thus maintaining high performance over the entire thrust range. In addition, analyses of combustion phenomena have shown which mechanisms and parameters must be controlled to allow complete random throttling with only head-end injection of the oxidizer.

Introduction

THE name "hybrid" has been applied to almost every type of propulsion system that is not entirely homogeneous in character. However, the concept that is of most current interest uses a combination of a single liquid (usually the oxidizer) and a solid (usually the fuel) that does not burn without the addition of the liquid component. The essential features of this concept are shown in Fig. 1. The liquid component is contained in a tank entirely separated from the solid. The driving force for the liquid flow is provided by gas pressurization, and thrust is controlled by a simple valve that regulates the liquid flow rate. Ignition is usually accomplished by hypergolic reaction between the solid phase and either the main liquid or a starting charge of a secondary, more reactive fluid. The solid phase of the propellant is normally in the form of a simple internal-burning cylinder. This may be bonded to the case for convenience, but such a structure is not required for mechanical support because of the inherent strength of the fuel composition. Finally, the nozzle and general chamber construction is consistent with standard solid-propellant technology. No regenerative cooling is necessary, and the nozzles are fabricated of lightweight metal or fiberglass for structural strength and lined with ablative-type insulation.

The advantages of the hybrid engine concept are derived from the following two basic features: 1) the complete separation of fuel from the principal oxidizer, and 2) the capability to use an optimum combination of propellant ingredients regardless of whether these are solid or liquid or mutually incompatible because of chemical reactivity. The hybrid concept may be described, therefore, as a means for providing greatly increased design flexibility that can be used to avoid a number of the limitations of both solid and liquid propulsion systems.

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In fact, this flexibility permits the use of an essentially unlimited choice of chemical materials in the propellant system. This choice covers the range in solids from ordinary rubber to complex mixtures employing very advanced polymers specially adapted to the hybrid application together with reactive metals and recently developed high-energy compounds. In the fluid phase the choice is nearly as broad, again covering the range from common oxidizers such as nitrogen tetroxide to cryogenics such as oxygen and fluorine depending upon the requirements and environmental limitations of the application.

Some contemplation of the versatility of the hybrid approach leads quite directly to the recognition that with appropriate designs almost any known material with sufficient stability to be handled can be in some way employed in a propellant system. The potentials, therefore, are limited primarily by basic thermodynamics and not by engine design. At the present time, approximately 360 sec is the maximum theoretical impulse for hybrids, but future research may disclose more energetic systems.

A general comparison of the performance capabilities and growth history of hybrids with the other forms of chemical propulsion systems is presented in Fig. 2. This figure is based on the history of development of established propellant

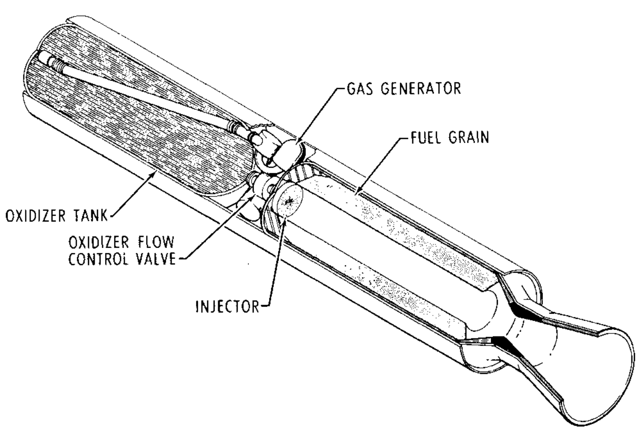

Fig. 1 General design concept for hybrid engines.

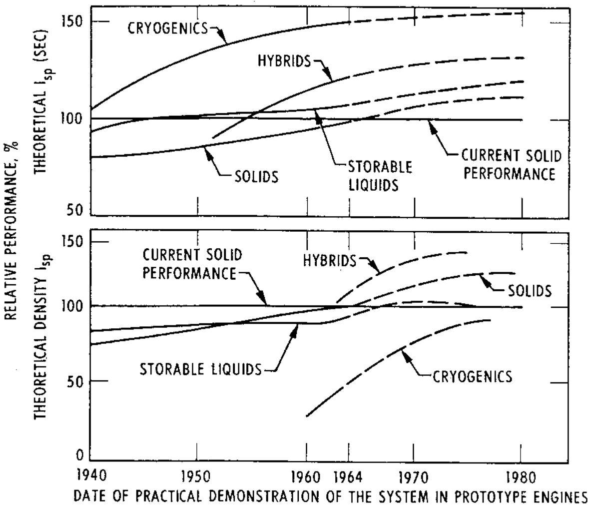

Fig. 2 Comparison of present and predicted performance capabilities of hybrids with solids and liquids.

systems, current developments, and the potential for future growth. It is shown that in all aspects, hybrids exceed solids both in specific impulse and impulse density. Storable liquids are essentially competitive with hybrids at the present time; however, the growth potential currently recognized for the hybrids is somewhat greater than for the liquids. Also the classic limitations of liquids, particularly the cryogenics, in energy per unit volume is readily apparent from this illustration. Although the cryogenics provide the highest performance of all systems considered, it is noteworthy that they also provide less impulse per unit volume than either of the other methods. It is indicated, therefore, that where volume limitation is a critical factor, the hybrid or the solid has a distinct advantage.

Combustion Analysis

The basic problems encountered with hybrid systems have involved a generally low recovery of theoretical specific impulse, uneven burnout of the fuel along the length of the combustion chamber, a decay in thrust level with time that has been unpredictable, extreme loss of efficiency with thrust modulation, and burning rates low enough to make design particularly difficult for short-duration engines. Logically, the major objectives of the research and development work over the past several years have been to understand and control the processes occurring in a hybrid combustion chamber so as to overcome these basic problems.

A fundamental study established under Advanced Research Projects Agency sponsorship led very quickly to the conclusion that no real solution to any of the recognized difficulties in the development of hybrid engines would be achieved without a fundamental understanding of the combustion process involved. Furthermore, it was recognized that this process was so different from those occurring in either solid or liquid engines that the rules evolved from previous design technology could not be generally applied. However, it was found that the problems in hybrid engine combustion were amenable to analysis by scientific techniques, and once a fundamental investigation was attempted, very rewarding progress was achieved. As a result, the basic phenomena are now generally understood, and many of the processes have been reduced to description by mathematical equations. An illustration of the flow and diffusion processes is shown by the two Schlieren photographs presented in Fig. 3. These pictures show a bar of polymethyl methacrylate burning in the flow of oxygen under controlled conditions, using a laboratory wind tunnel. The upper photograph was taken at an exposure of 3 sec and shows average steady-state diffusion zones. The lower picture was taken using only 5 μsec exposure and shows the violent turbulence that is characteristic of the process. It has been well established that the actual combustion occurs in a relatively narrow zone a significant distance (approximately $\frac{1}{10}$ of the distance to the aerodynamic boundary layer) from the surface of the solid fuel. This combustion zone is fed by vaporized fuel and gases from decomposition of the solid and by vaporized or gaseous oxidizer from the fluid phase. Heat from the combustion zone is conducted or radiated to the surface of the solid and to the incoming fluid or gaseous phases of both fuel and oxidizer. Where these gasified materials meet combustion takes place, and diffusion of the products proceeds away from the combustion chamber.

It is a major factor in the operation of hybrid engines that the surface of the solid fuel is actually relatively cold in the usual sense of a combustion temperature. This is because the surface temperature is controlled, not by the combustion reaction, but by the decomposition or vaporization of the solid. Measurements have shown this temperature to be in the region between 200 and 400°C for most conventional fuels. Similarly, the temperature through the center of the port area is also relatively low. Initially, this temperature is determined by the vaporization of the liquid or by the temperature of the incoming gas. As the products from the combuston zone diffuse into the port area, they actually drop in temperature by expansion and by mixing with the relatively cool unreacted material flowing in this region. Since the liquid or gas phase coming from the injector does not contact the surface of the solid (after the first initial reaction), the task of the injector in a hybrid engine is, not to place the oxidizer on the surface of the fuel, but to diffuse and vaporize the liquid phase so that it can mix readily with the material in the active combustion zone.

Analysis of the process described leads to a solution of the problems of design including the grain, the injector, and the combustion chamber in general. Further combustion analysis also leads to a definition of ideal characteristics for hybrid, solid, and liquid phases. Further treatment of these processes is technically complicated and beyond the scope of this paper. However, the major factor in controlling the performance efficiency of a hybrid engine is designing to promote effective mixing of the vaporized fuel and oxidizer, so that unreacted material does not escape from the motor. The testing of experimental designs has conclusively demonstrated that this mixing is critical, but it can be accomplished in a practical manner. Also, proper matching of the injector characteristics with the design of the solid phase can and has actually been demonstrated to achieve essentially complete fuel utilization. In addition, specific impulse efficiencies comparable to those achievable in efficiently designed liquid or solid systems have been demonstrated.

The third major problem, very low combustion rates, has also been largely solved by analysis of the nature of the hybrid combustion processes. Quite clearly, since no oxidizer is present in the solid phase of a true hybrid, the burning process is quite different from a normal solid propellant. The rate of consumption of the fuel is dependent primarily upon the rate

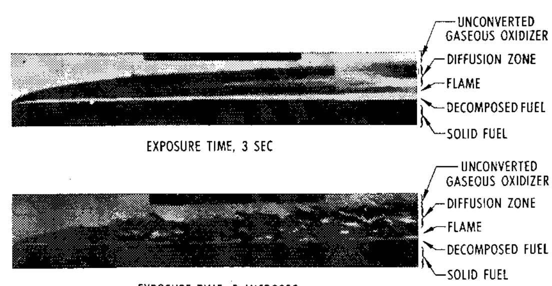

Fig. 3 Schlieren photographs of the hybrid combustion process.

of heat input and the amount of energy required to cause vaporization. An ideal fuel should therefore have the lowest possible latent heat of decomposition or vaporization, and the products formed should be readily convertible to reactable gases. An additional important consideration is, that if it is possible to promote nearly self-sustaining chemical reactions in the surface, substantial rate increases can be derived. Research work directed along these lines has been quite successful, and at the present time systems are being studied that have burning rates (or regression rates, as they are now called) approximating those obtainable in a low-energy solid propellant.

Regression-Rate Correlation

One of the most significant of the fundamental developments coming from the current research work is that the burning rate, or regression rate, of a hybrid depends on the flow of the oxidizer (or fluid phase) in very much the same way that the burning rate of a solid propellant depends upon pressure. As might be inferred, the predominance of the controlling effect of mass flux overrides all of the other rate-modifying effects to the extent that for many systems the regression rate has only a very slight dependence on temperature, and, in general, nonmetallized fuels have no dependence on pressure. This provides some very attractive advantages for operation in an extreme environment.

The dependence of the hybrid fuel regression rate on mass flux has a profound effect on the design of the solid-fuel configurations. The thrust is dependent upon the rate of fuel flow, if the liquid flow is held constant. The fuel flow in turn is dependent on mass flux, or flow per unit area. As the solid burns away, it is inevitable that the port area increases. Therefore, if constant thrust is to be maintained, the surface area must increase to compensate for the corresponding loss in regression rate. Where the surface is held constant, as in a conventional internal burning star, the thrust will decrease significantly with time. The geometry required can be defined by the regression-rate equation, $r = aG^n$, or, more particularly, by the exponent n on the mass flux, G. If $n \simeq 0.5$ (which is conventional), a tubular shape is found to be essentially ideal for most systems. If the $n > 0.5$, a progressivity greater than that provided by a tubular shape is required. Fortunately, most of the systems of interest have $n \simeq 0.5$. It can be shown by this type of analysis that the principal cause for the decaying thrust experienced in early tests of hybrid engines was attributable to the use of neutral surface configurations. When tubular charges or other versions of designs providing progressive surfaces have been used, constant thrust has been achieved with no serious difficulties.

Throttling

When demand thrust with throttling over a wide range is required, the achievement of efficient operation becomes a complex problem. The problem is caused mainly by the fact that for many propellant systems the fuel flow from the grain does not vary in direct proportion with the flow of the oxidizer injected at the lead end. As a consequence, the oxidizer-to-fuel flow ratio will not remain constant over the throttling range. Because optimum performance occurs at a single given value of O/F, it follows that a performance loss results from such throttling.

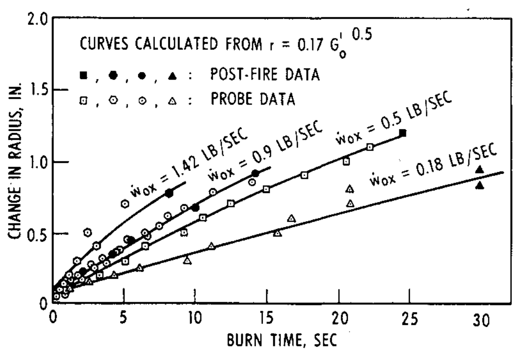

Fig. 4 Total regression vs burning time for constant values of oxidizer flow rate.

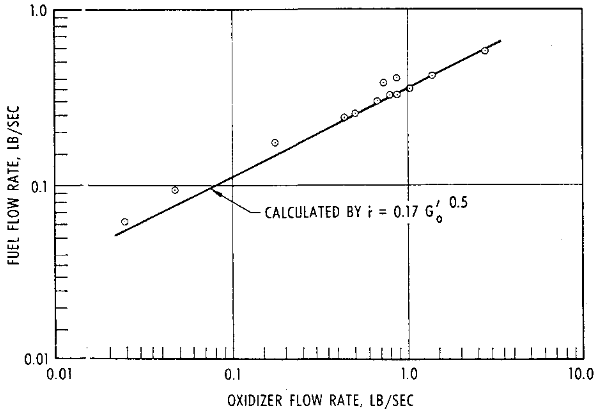

Fig. 5 Fuel flow rate vs oxidizer flow rate.

The extent to which fuel flow varies with oxidizer flow can be determined from the relationship between fuel regression rate and oxidizer flow as defined by $r = aG^n$. From this expression, it can be seen that the value of the exponent n is the factor that determines how fuel flow varies with head-end injection oxidizer flow. Where $n = 1.0$, fuel flow varies directly with oxidizer flow, and no mixture ratios shift would occur during throttling. For most hybrid systems under investigation, however, the value of n is between 0.5 and 0.8, so that some shift in mixture ratio occurs when the oxidizer flow is varied.

A typical hybrid propellant combination currently under study has a burning (or regression) rate described by a simple empirical correlation

$$\dot{r} = 0.17\ G_0^{0.5} \tag{1}$$

This correlation was determined by means of numerous motor firings in the 5.0-in. diam size. Total fuel regression was determined as a function of burn time and oxidizer flow rate. A portion of these data are shown in Fig. 4. The lines that appear to have been fitted to the data are in fact independent data calculated by means of

$$R^2 = R_0^2 + 0.34(\dot{w}_{ox}/\pi)\ t \tag{2}$$

which is the integrated form of Eq. (1) for the internal-burning cylinder fuel grain configuration used in the test. The validity of Eq. (1) is shown by the excellent agreement between calculated and experimental data shown in Fig. 4. This relatively simple correlation provides the means for calculating regression rate and hence, fuel flow rate as a function of oxidizer flow rate and time for a variety of fuel grain shapes and sizes.

Fuel flow rate varies as the square root of oxidizer flow rate for this system as shown in Fig. 5; thus, variations in motor thrust in a given configuration cause the motor mixture ratio to vary as shown in Fig. 6. Since

$$O/F \propto \dot{w}_{ox}^{\ 1-n} \tag{3}$$

the mixture ratio likewise varies as the square root of oxidizer flow rate for this fuel system.

For applications with a specified thrust-time profile, very little performance penalty is imposed by this phenomena. The mixture ratio shift can be minimized by proper grain design, and good fuel utilization can be achieved because the required oxidizer and fuel weights have been accurately de-

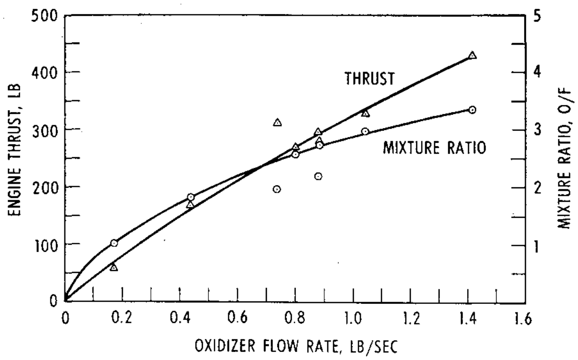

Fig. 6 Thrust and mixture ratio vs oxidizer flow rate.

fined. However, for demand thrust applications, a severe weight penalty is imposed by using only head-end throttling because the mixture ratio will vary as a function of thrust. Head-end throttling is best accomplished by operating at a higher than optimum O/F at the maximum thrust level and at a lower than optimum O/F at the minimum thrust level. For applications requiring throttling from 2000-lb thrust down to 250-lb thrust with a propellant system having a value of $n = 0.5$, O/F values and performance vary as shown in Fig. 7. It is apparent that the specific impulse is not drastically degraded through the range of O/F values encountered. However, since the system must operate on demand, one must, in effect, provide enough oxidizer and fuel for performance at both ends of the O/F curve. Such a situation will leave a quantity of unconsumed oxidizer at the low thrust condition and unconsumed fuel at the high thrust condition. In comparing the total propellant weight for this approach with one operating at a constant optimum O/F condition throughout, approximately 30% additional propellant is required.

From the previous discussion, it is apparent that increasing weight penalties are associated with demand thrust requirements as the value of n becomes less than 1.0. In addition to the obvious approach of modifying the value of n to approach 1.0, a promising solution to this problem is the injection of supplemental quantitites of oxidizer at the aft end of the grain (upstream of the nozzle) to maintain constant O/F ratios. This concept is similar to that described in early hybrid designs, using an oxidizer deficient solid fuel and injecting oxidizer downstream to achieve a degree of throttleability. In the current approach the oxidizer is injected into the head-end of the fuel grain in such a manner that the mixture downstream of the grain is always fuel rich. Then, additional oxidizer is added downstream of the grain such that the total flow can be held to the required proportions (O/F) to maintain the optimum system performance.

The feasibility of aft-end injection has been demonstrated in 5.0-in. motor firings. The major disadvantages to aft-end injection with this propellant combination are:1) an additional liquid flow circuit, with associated weight and reliability penalties, is required, and 2) 8:1 thrust modulation requires a 64:1 variation in head-end oxidizer flow, which is difficult to achieve with simple valving.

Another possible solution to the problem of maintaining constant O/F over a wide throttling range is the development

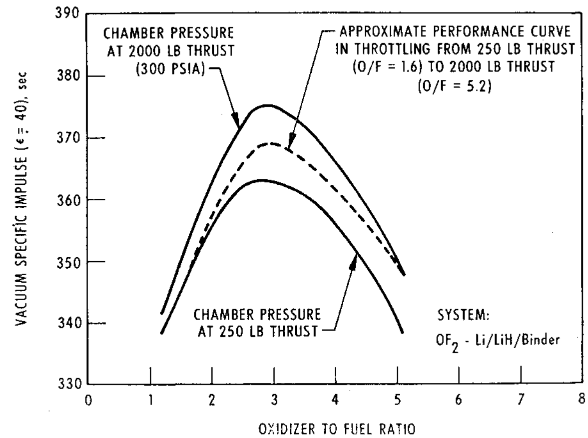

Fig. 7 Estimated delivered specific impulse as a function of O/F ratio.

of a pressure-sensitive hybrid fuel. When the regression-rate behavior of a fuel is defined by the G_0 relationship previously stated, regression rate is not significantly affected by combustion pressure because most conventional hybrid fuels are not pressure sensitive. For pressure-sensitive fuels, the regression-rate correlation is in the form of

$$\dot{r} = a\,P_c{}^m\,G_0{}^n \tag{4}$$

A preliminary evaluation of the implications of this relationship to hybrid throttling has indicated that when $m + n = 1.0$, no mixture ratio shift occurs during throttled operation. Furthermore, for the circular fuel grain configuration, the optimum values of these exponents are $m = 0.5$ and $n = 0.5$. At these values, constant mixture ratio operation is inherent to the design for any value of time or oxidizer flow rate.

Conclusions

In brief, the development status of hybrids at the present time can be summarized as follows:

1) The feasibility of most of the outstanding features that have been predicted for hybrid engines has been demonstrated. This includes high impulse, start/stop operation, modulated thrust, and insensitivity to temperature and pressure. Efficient throttling up to thrust levels of 10:1 is practical.

2) Knowledge of the combustion process has been established to the point where grain and engines can be designed to achieve efficient performance. Fuel utilization and impulse efficiency comparable with those of solids and liquids have been demonstrated.

3) Basic improvements in the low burning rates have been accomplished, and no major restriction remains in the ability to design for normal applications.

4) Existing technology is at the point where model studies and feasibility demonstrations can be undertaken for specific applications.