Feasibility of a Fluidized Powder Demand-Mode Gas Generator

Morton Shorr* and Thomas F. Reinhardt†
Bell Aerospace, Division of Textron, Buffalo, N.Y.

Spark ignition tests were made on a fluidized powder bipropellant demand-mode gas generator. The propellants were ammonium perchlorate and polyethylene, fluidized with air and hydrogen gas, respectively. Spark ignition of the mixed fluidizing gases released enough combustion energy to ignite the bipropellant powders. A detailed description of the concept, performance calculations, static tests, and ignition and combustion under flow conditions are presented.

Introduction

FLUIDIZED powder propellants are an outgrowth of prior attempts to increase the energy density of liquid propellants through gelation and addition of powdered solids. It was reasoned that, since the objective of maximum density was achieved by using the highest possible solids loading, the ultimate solution was to eliminate the liquid carrier and concentrate on ways of transporting solid powders alone. In previous investigations of fluidized powders,[1,2] effective transport of powdered solids through typical propellant feed system components, when fluidized with less than 1% by weight of a carrier gas, such as nitrogen has been demonstrated. It was also observed that, unlike gelled liquids, the fluidized powder flow characteristics were essentially Newtonian, and were unaffected by changes in temperature. Discharge coefficients were found to be lower than for liquids, being in the range of 0.40 to 0.45. The maximum practical packing density for the powders was found to be about 75%, even with carefully graded powder sizes and with mechanical aids such as ball milling and vibration. (The space between the powder particles is not lost, however. It can be used very effectively to store the fluidizing gas under pressure, and makes possible a blowdown system without an external pressurization source.)

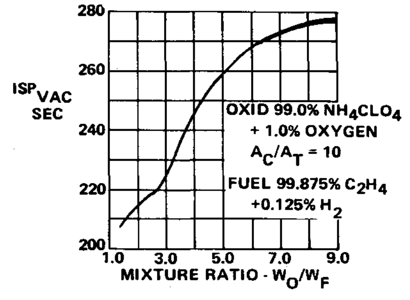

Fig. 1 Specific impulse vs mixture ratio shifting equilibrium.

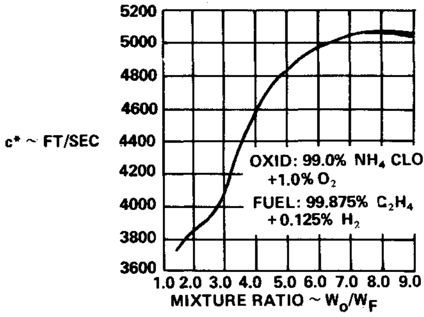

Fig. 2 Characteristic exhaust velocity vs mixture ratio shifting equilibrium.

The ignition and combustion of fluidized powders in a typical liquid propellant type reaction chamber was the subject of the investigation leading to the present paper. For the initial experiments, a propellant combination was selected that was available at low cost, and that had good theoretical performance and bulk density. Performance calculations for the selected propellants (ammonium perchlorate and polyethylene) are shown in Figs. 1–5. For a gas generator application, an O/F mixture ratio of 3.0 was selected, leading to a combustion temperature of 2700°R, a molecular weight of 18.5, and a characteristic velocity of 4130 fps. The exhaust products, shown in Fig. 5, consist of mainly H_2 and CO, with traces of HCl, CO_2, N_2, and solid carbon.

Ignition Concepts

On other projects at Bell, fluidized powders have been ignited with pellet-type igniters and with hypergolic liquids. On this program, however, repeatable start-stop operation was

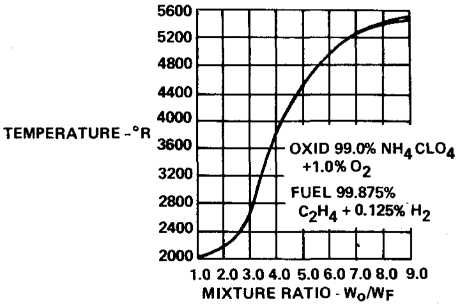

Fig. 3 Combustion temperature vs mixture ratio shifting equilibrium.

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Index categories: Combustion Stability, Ignition and Detonation; Fuels and Propellants, Properties of.

* Development Engineer, Advanced Missile Propulsion. Associate Fellow AIAA.

† Staff Scientist, Propulsion Systems and Components Directorate.

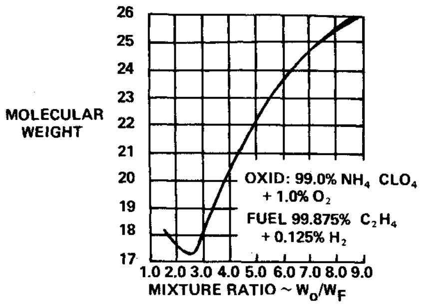

Fig. 4 Molecular weight vs mixture ratio shifting equilibrium.

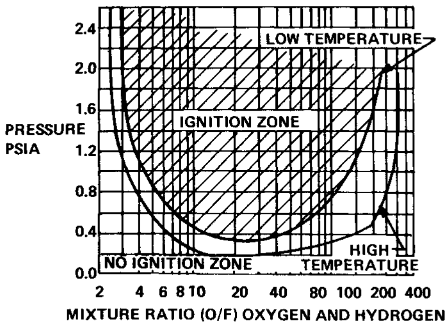

Fig. 6 Ignition—no ignition zones as a function of pressure, temperature, and mixture ratio.

required, therefore spark ignition was investigated. The amount of spark energy required to ignite and sustain combustion in fluidized powders is unknown. In nonmathematical terms, it can be stated that the spark must deliver enough energy to the solid fuel and oxidizer to vaporize sufficient quantities of each so that their combustion will liberate energy in excess of the spark energy. Quantitatively, this would depend on the temperature to which the grain surface must be heated, the grain size, the spacing between grains, the spark intensity, and the heating time available. Rather than attempting a mathematical analysis of this phenomenon, it was decided to conduct a series of experiments to establish an adequate (though not necessarily minimum) spark energy level. The first experiment consisted of packing a mixture of powdered fuel and oxidizer around the electrodes of a spark plug. The second consisted of flowing streams of ammonium perchlorate and polyethylene fluidized with nitrogen gas into a mixing chamber containing a spark plug. The third experiment was the same as the second, except that reactive fluidizing gases were used; air for the ammonium perchlorate, and hydrogen for the polyethylene. The theory of the latter experiment was that the spark would ignite the gases, which would in turn ignite the solids. This proved to be correct, as will be discussed in connection with the test program.

Use of reactive fluidizing gases introduces a requirement to control the mixture ratio of the fluidizing gases as well as that of the powders being transported. The mixture ratio of the fluidizing gases should be controlled to achieve minimum ignition energy rather than maximum performance. Fortunately, as shown in Fig. 6, the ignition energy for hydrogen/oxygen shows a very broad minimum.[3] The energy release per unit weight of fluidizing gas is shown in Fig. 7 for both H_2/O_2 and H_2/air. Although these numbers are fairly large, it should be remembered that the fluidizing gas constitutes only about 1% of the total flow. Consequently, if the ignition mechanism consisted of bulk heating of the powder by the fluidizing gas, the temperature of the powder would only be increased by about 20°C. However, a more probable mechanism is that the reactive gases inflame rapidly and expose the surfaces of the solid particles to a high temperature. The particles tend to sublimate and decompose on their surfaces, producing enough additional gases to sustain the combustion. With this combustion mechanism in mind, it might be concluded that to achieve high combustion efficiency, the particle size should be as small as possible. However, as particle size decreases, ignition will become more difficult, as the heat from combustion of the fluidizing gases will be absorbed more rapidly by the powder. A compromise on powder size is thus indicated. In the experiments to be described, the powder sizes were 55 μ for the ammonium perchlorate and 177 μ for the polyethylene. These were probably larger than the optimum sizes.

Test Program

A series of test demonstrations was conducted to ascertain the ignitability and subsequent combustion of the powder combination, ammonium perchlorate (AP) and polyethylene (PE).

Initial ignition tests revealed some qualitative data which were used as a guide for determining the spark ignition energy necessary to burn the powder mixture. A Mallory Electric Corporation Model 28050 exciter was used to drive a Champion annular-surface-gap spark plug, model number FHE 146-7A with a 12-v d.c. source. This combination delivered 5 mjoules at a rate of 200 sparks/sec. The spark plug was submerged in a mixture of AP and PE powders. Table 1 summarizes the results of these initial tests. The 4:1 mixture ratio was easier to ignite than the lower mixture ratios. Also, ignition with the higher powder mixture ratio occurred on the first spark pulse which is indicative of the adequacy of low energy for this

Table 1 Spark plug ignition test

AP/PE	Mixture ratio	Spark rate, sec	Spark energy, mjoules	Input voltage, v d.c.	Results
70/30	2.33	200	4.0	14.0	Delayed ignition
60/40	1.50	200	4.0	14.0	No ignition
80/20	4.0	200	4.0	14.0	Fast ignition

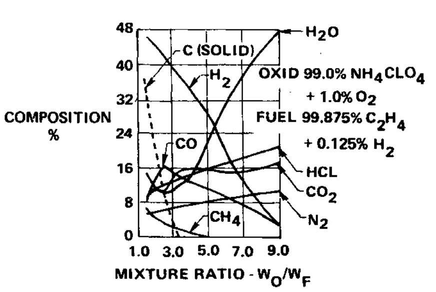

Fig. 5 Percent compounds vs mixture ratio shifting equilibrium.

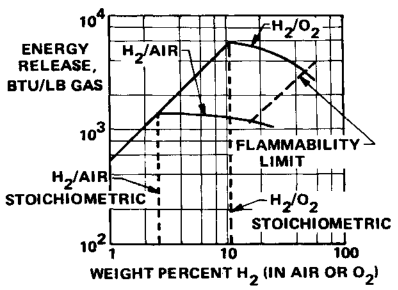

Fig. 7 Energy release from combustion of hydrogen.

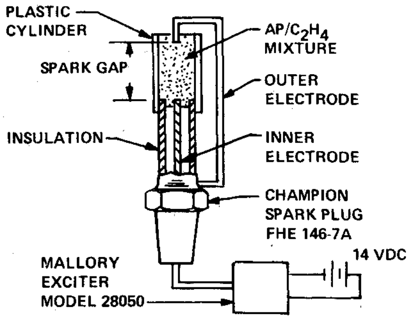

Fig. 8 Initial powder ignition test arrangement.

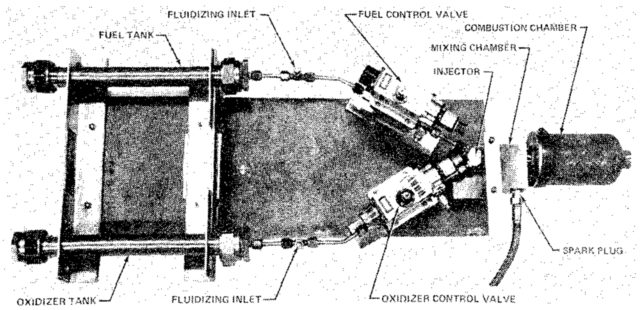

Fig. 9 Test hardware arrangement.

system. Figure 8 shows the test arrangement. The purpose of the outer electrode was to ensure passage of the spark through the powder mixture so as to circumvent the possibility of having stratified fuel or oxidizer powder particles at the spark plug tip. Ignition was followed by rapid burning until all of the powder was consumed, leaving essentially no residue.

In the next series of tests, attempts were made to ignite a flowing mixture of AP and PE powder fluidized with nitrogen. The flow test equipment consisted of fuel and oxidizer storage tanks made from 1½-in.-diam stainless steel tubing 12-in. long. The oxidizer and fuel feed lines each contained a solenoid actuated ball valve. The feed lines contained orifices sized to approximate flow rates such that the AP/PE mixture ratio would be between 3.0 and 4.0, based upon the preliminary static ignition test results. The oxidizer and fuel lines discharged into a premix chamber which formed the injector assembly where the powders impinged. The premix chamber contained the spark plug and the combustion chamber was attached to the premix chamber. The test hardware arrangement is shown in Fig. 9. A cross section of the injector, premix chamber, spark plug and combustion chamber is shown in Fig. 10. The retainer screen was added after initial flow tests showed that the fluidized powder stream was not dispersing through the combustion chamber.

As a safety precaution, it was decided to use an oxygen-acetylene torch located at the powder discharge port to assess ignitability. If the powder mixture would ignite outside the mix chamber and flash back would occur, then the powder mix velocity was less than the flame velocity and this condition would be hazardous. In all tests, however, no flash back occurred and the torch apparently did not contribute to ignition. One incident did occur, however, during run number 23. The AP valve plugged and apparently some GH_2 fluidizing gas for the PE diffused into the ox valve and ignited. This localized burn caused sufficient pressure to burst the valve seats.

Seventeen test runs were made and are summarized in Table 2. The early tests used nitrogen gas (GN_2) for fluidization of both AP and PE powders. Ignition of the powder mix in a flow

Table 2 Record of gas generator ignition tests

Run no.	Duration sec	Flow rate g/sec	Mixture ratio O/F	Feed Pressure PE psia	Feed Pressure AP psia	Type of ignition	Remarks
14	0.92	187.5	5.6	172	393	Torch	N_2 fluidization; no ignition
15	1.48	171.6	6.45	132	229	Torch	No ignition
16	1.0	...	...	133	234	Torch	Ran out of AP; no ignition
17	1.32 1.02 ox	249.4	6.48	259	404	Spark plug	Air fluidization; no ignition, ran out of AP; used semiconductor surface gap spark plug
18	0.95 fuel 0.98 ox	149.6	6.26	142	264	Spark	H_2 fuel fluidization; air ox fluidization; gas burned, but powder did not
19	0.88	189.5	4.65	261	399	Torch, spark	Same fluidization; torch lit outside; spark lit inside; powder not burning efficiently
20	0.65 fuel 1.22 ox	167.4	5.35	181	307	Spark	Momentary start; fuel line plugged. Same fluidization, combustion chamber added
21	1.40	...	...	130	247	Spark	Same, throat diameter enlarged; H_2 and air burn, no powder ignition
			...	261	405	Spark	Delayed start; ox line and ox stand valve exploded. Apparent AP buildup in premix chamber
24	1.35		...	261	398	Spark and torch	H_2 and air fluidization. Some gas burning, fuel orifice plugged
25	1.32	190.6	7.10	262	401	Spark and torch	Same conditions H_2 and air burning
26	0.97	...	...	259	402	Spark and torch	Same conditions, screen mounted in combustion chamber. Fuel line plugged
27	0.94	...					
28	0.95 ox 0.70 fuel	196.5	...	262	402	Spark and torch	Same conditions, pressure spike, plugged fuel orifice
29	0.60 ox 0.52 fuel	...	3.14	337	402	Spark and torch	Good firing. Shutdown and reignited. Clean burn
	1.75	...	...	350	404	Spark	Long ignition delay
30	1.75	...	...	350	403	Spark and torch	Fuel line plugged, no ignition
31	1.75 ox	170.6	3.78	351	404	Spark and torch	Same condition, 5 pulses, excellent burning

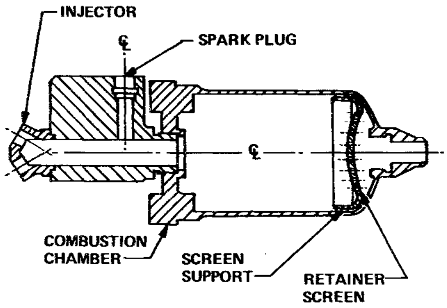

Fig. 10 Powder propellant gas generator test arrangement.

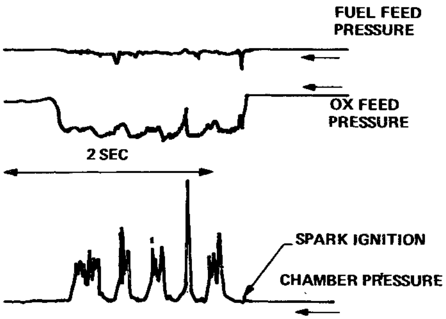

Fig. 11 Pressure traces—run no. 31.

regime was not obtained with a spark until reactive fluidizing gas and the retainer screen were used in run number 28.

Figure 11 shows the pressure vs time traces for test run number 31. The fuel and oxidizer feed pressure were measured just upstream of the ball valves, and the combustion pressure was measured in the mixing tube opposite the spark plug. The ignition due to the spark is quite evident on the chamber pressure trace. The electrical ignition system for the flow tests consisted of the Champion spark plug driven with a 120-v, 60-cycle transformer yielding approximately 120 sparks/sec. The transformer exciter was used instead of the Mallory exciter because a d.c. converter was not available during the test. However, the energy of the spark was approximately equivalent to the Mallory system; (5 to 10 mjoules), the lower spark rate of the transformer apparently did not effect ignitability.

Examination of the pressure traces in Fig. 11 show five distinct pulses separated by periods of no combustion, looking superficially like the combustion chamber-feed system interaction phenomenon which often occurs in liquid propellant rockets and is known as "chugging." Inspection of feed system pressure traces showed, however, that propellant flow remained steady during the pulses; hence, the pulsing must have been due to action wholly within the combustion chamber. A possible explanation is that a combustible inventory of propellant vapors builds up in the chamber, is ignited by the H_2/O_2 flame and burns at a rate more rapid than the vaporization rate. When there is no longer sufficient combustible vapor in the chamber, the flame extinguishes and the process repeats itself. This may be akin to the "chuffing" phenomenon observed in solid rocket motors.

Conclusion

Ignition and combustion of fluidized powders entails some unique problems, unlike either solids or liquids. The evidence of the previous tests shows ignition and combustion to be surface phenomena, similar to that of conventional solid propellants, but complicated by the hydrodynamics of flow and mixing. Useful ignition-promoting techniques were found to be a) a screen to break up and diffuse the momentum of the injected powders, and b) the use of reactive pressurizing gases.

References

[1] Fricke, H. D., Burr, J. W., and Sobieniak, M. G., "Fluidized Powders—A New Approach to Storable Missile Fuels," Paper presented at the 12th JANAF Liquid Propulsion Meeting, November 17–19, 1970, Las Vegas, Nev.

[2] Fricke, H. D., Berman, K., and Sobieniak, M. G., "Flow Studies of Dense Phase Gas/Solid Suspensions with a Positive Expulsion Fluidization Tank," Paper presented at the ASME/AICHE/SIME/ASCE Second Symposium on Storage and Flow of Solids, Chicago, Ill., September 17–20, 1972.

[3] Chamberlin, J., "Development of RL10 Torch Ignition System," Rept. PWA FR-303, Nov. 1961, Pratt & Whitney Aircraft, East Hartford, Conn.