A Fluidic Sounding Rocket Motor Ignition System

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Fluidic sounding rocket motor ignition has been found to be feasible using a system without stored energy and with the complete absence of electrical energy and wiring. The fluidic ignitor is based on a two component aerodynamic resonance heating device called the pneumatic match. Temperatures in excess of 600°C were generated in closed resonance tubes which were excited by a free air jet from a simple convergent nozzle. Using nitrocellulose interface material, ignition of Boron Potassium Nitrate ($BKNO_3$) a commonly used rocket motor ignition material was accomplished with air supply pressures as low as 0.3 MNm^{-2} (45 psi). This paper describes an analytical and experimental program which established a fluidic rocket motor ignition system concept incorporating a pneumatic match with a simple hand pump as the only energy source. This evaluation included a determination of power supply requirements, ignitor geometry and alignment, ignitor/propellant interfacing and the effects of ambient temperatures and pressure. It was demonstrated that an operator using a simple hand pump could ignite $BKNO_3$ at a standoff distance of 100 m (330 ft) with the only connection to the ignitor being plastic pneumatic tubing.

Nomenclature

A^* = nozzle area
A_v = vent area
d = excitation nozzle exit diameter
P_{amb} = ambient pressure
P_c = chamber pressure
P_i = initial pressure
P_o = supply flow pressure
R = gas constant
s = nozzle exit to resonance tube separation
t = time
T_w = endwall surface temperature
T_o = supply flow temperature
V = volume of transfer tubing
γ = ratio of specific heats (C_p/C_v)

Introduction

HISTORICALLY, the principal of aerodynamic heating of gases in resonance tubes (see Fig. 1 for symbols used) had been generally overlooked by early investigators, such as Hartmann[1] who were mainly interested in the acoustic power generation capabilities of these tubes. Sprenger[2] in 1954 was able to obtain endwall temperatures of almost 425°C in one of his air powered resonance tubes. His tube, however, was over 10 cm in length and took several minutes of steady-state operation to reach these temperatures. Thompson[3] and Kang,[4] along with Broucher and Moresca[5] have attempted with some limited success, to theoretically predict and analyze the operation of the resonance heating principles. They have, in general, been able to obtain only order of magnitude estimations of the heating which is experimentally observed.

Beginning in 1968, after preliminary independent research and developmental efforts showed promising performance, additional work was conducted toward applying this device to ignition of explosive ordnance, by Rakowsky, Miller, and Donahue, under contract to Picatinny Arsenal. In initial work the ignition of nitrocellulose was accomplished with an ignition device less than 6 cm in length called the pneumatic match. This pneumatic match, as improved by Marchese[6] under continuing programs, provides significant improvements for safe, simple, nuclear hard, shockproof, reliable and inexpensive Safing, Arming and Fuzing of components and systems. Primary explosives were ignited in less than 10 msec with helium at 1.4 MNm^{-2} (200 psig). As shown in Fig. 2 endwall gas temperatures of over 1200°C were obtained in less than 35 msec with a device 3 cm in length.[6]

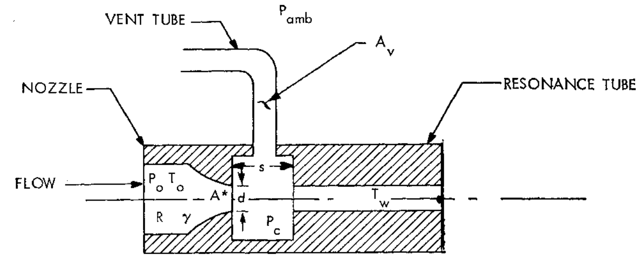

Fig. 1 Schematic of resonance tubes.

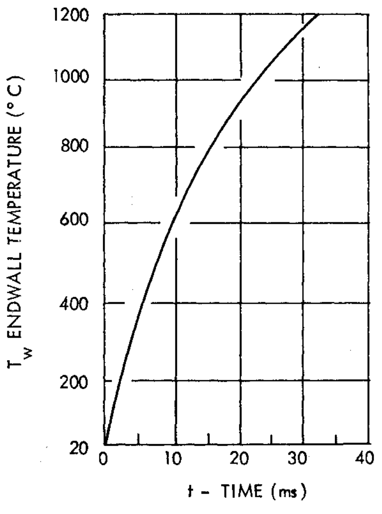

Fig. 2 Typical temperature/time data for a fluidic ignitor.

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The feasibility of adapting the pneumatic match to a restartable solid propellant rocket motor engine ignition system was demonstrated by Rakowsky and Marchese under contract to the U.S. Army's Advanced Ballistic Missile Defense Agency in early 1970. An improved resonance tube design incorporated into the pneumatic match successfully ignited an explosive/pyrotechnic train which resulted in the ignition of M-1 propellant in a simulated rocket motor ignitor. The objective of this present study was to develop and demonstrate an inexpensive, safe and foolproof ignition system concept for solid propellant rocket motors. Although first proposed for demonstration in a sounding rocket this system has broad potential applications wherever safe, nonelectrical ignitions are required. The advantages of such an ignition system would be improved safety and decreased cost without degrading reliability.

System Concept

The ignition system is comprised of a hand driven pump to pressurize a 100 m length of plastic tubing which is sealed just outside the rocket motor by a relief valve. The relief valve which allows the tubing to be used as a gas pressure reservoir remains closed until the gas pressure inside the tubing reaches the ignitor operating pressure. It then releases at a preset pressure and remains open to discharge the volume of gas in the tubing into the ignitor.

The ignitor converts the gas flow energy into thermal energy through the resonance tube heating effect. Sufficient thermal energy is generated to cause ignition of the propellant at the end of the resonance tube in less than 1 sec. Typical sizes for the nozzle-resonance tube combination is a cylinder 25 mm long by 12 mm in diameter (1.0 × 0.5 in.).

Component Development

The fluidic rocket motor ignition system can be divided into three basic components: an energy source of compressed air, the pneumatic match, and the flame producing ignitor for the rocket motor propellant. The pneumatic match, the key element of the system, has no moving parts and is powered by the flow of compressed gases.

Pneumatic Match

Basically, the pneumatic match consists of two essential parts: a resonance tube (hollow cavity closed at one end), and an excitation nozzle. The device functions when the open end of the cavity is placed in the compression region of a free jet emanating from the nozzle. When the flow emerges from the nozzle, it accelerates to supersonic speed and then readjusts to subsonic speed by compression through a shock wave. The process creates a series of diamond-shaped cells of alternate supersonic and subsonic flow. These cells or conical shock waves (Mach diamonds) intersect the jet axis throughout the length of the jet (Fig. 3).

A plot of a typical static pressure distribution along the axis of the jet is also shown in Fig. 3. It can be seen that the pressure rises in the conical fronts of the diamonds and drops in the divergent portions to a minimum at the intersections. It was discovered that by placing a cavity in certain portions of the jet a self-sustaining system of oscillations were created by driving the gas in the cavity into resonance.[1] The portions of the jet structure which have been found to give rise to these oscillations are indicated by dashed lines in Fig. 3.

Although there is continuous flow into and out of the resonant cavity, a portion of the gas remains trapped at the closed end where it is subjected to a succession of waves producing periodic compression and rarefaction of this gas. This periodic compression and expansion of the gas produces irreversible temperature increases at the endwall of the cavity sufficient to ignite pyrotechnic materials.

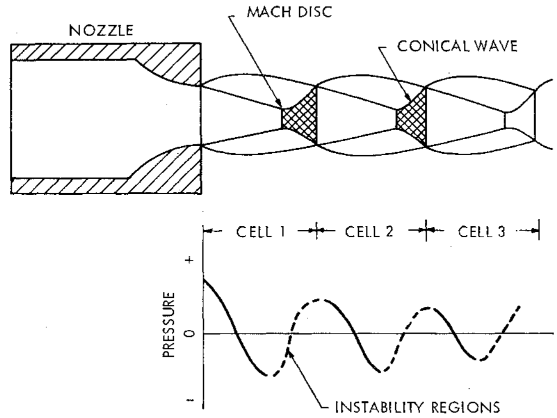

Fig. 3 Pressure variation-shock waves.

Since all explosive/pyrotechnic ignitions accomplished prior to this program utilized a resonance tube driven with high pressure helium, a new design of the pneumatic match was required to allow operation with a low pressure air supply. The use of low pressure air as the supply gas limits the maximum temperature and the time response compared to that which may be obtained with high pressure air or helium.

Nozzle

Pneumatic match nozzles are simple, convergent nozzles. Since the nozzle diameter d and pressure ratio across the nozzle influence the length of the jet cells these two parameters may be used to determine the proper separation distance s between the nozzle and the resonance tube. The minimum pressure to obtain ignition was 0.31 MNm^{-2} (45 psig) for $d = 1.2$ mm. No upper limit on pressure was found because as the pressure reduces it eventually falls into the operating range.

Resonance tube

Resonance tubes of various lengths and internal shapes were evaluated to determine the optimum configuration for this application. Several of the tubes evaluated are shown in Fig. 4. Each tube was made from a thermally insulating material in order to minimize the heat-transfer loss. Tube lengths ranged from 7.6 mm to 21.6 mm (0.30 to 0.85 in.). The internal tube diameter ranged from 1.6 mm to 0.6 mm (0.062 to 0.025 in.). Three basic resonance tube shapes were

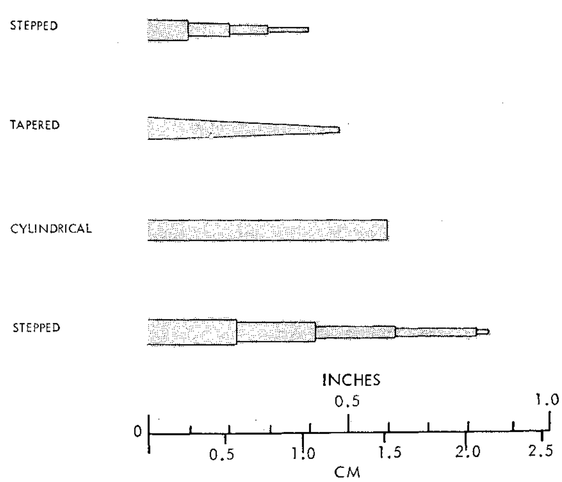

Fig. 4 Typical resonance tube configurations.

evaluated; cylindrical, tapered, and stepped. Previous comprehensive developmental efforts on resonance tube optimization indicated that the stepped tube produced very fast temperature increases and much higher endwall temperatures than the other tube configurations tested.

When the three types of tubes were tested for use with low pressure air, once again the stepped geometry resonance tube was found to be superior to the cylindrical tube in both maximum temperature attainable and minimum time to achieve the maximum temperatures (response time). The tapered tube, although it could generate steady-state temperatures almost as high as the stepped tube, was not used because its response was slower than the stepped tube. Thus, for this application, where the supply pressure drops quickly after the relief valve opens, the tapered tube does not reach its maximum steady-state temperature because the pressure falls below the operating range before the maximum temperature is reached.

Short resonance tubes (1 cm) were found to have performance characteristics comparable to the larger tubes (2 cm). Since it was required that the ignitor could not block the rocket motor nozzle after ignition, the short tube was picked for the final ignitor system. To further eliminate the possibility of nozzle blockage the ignitor has been made completely of consumable plastic.

Actual temperature/time histories at six separation distances in intervals of 0.5 mm are shown in Fig. 5. For these tests the small stepped tube, shown in Fig. 4, was supplied with a 1960 cm^3 volume with the relief valve set to discharge at 0.5 MNm^{-2} (73 psig). Figure 5 shows that the length of time that temperatures in excess of 300°C are obtained varies from 0.5 sec to 2.0 sec as a function of the separation distance with the maximum times occurring at $s = 3.5$ and $s = 4.0$ mm. Since peak temperatures occurred at $s = 3.5$ mm, the final ignitor separation distance was set there. More recent testing indicates peak temperatures in excess of 800°C may be obtained with $s = 2.5$ mm and $P_i = 0.9$ MNm^{-2} (130 psig). For this configuration with $V = 2944$ cm^3 the temperature remains greater than 300°C for 8 sec.

The effect of the initial supply pressure may be obtained with reference to the temperature/time traces shown in Fig. 6. These traces generated by the ignitor at $s = 3.5$ mm demonstrate how the time at temperatures above 300°C increases

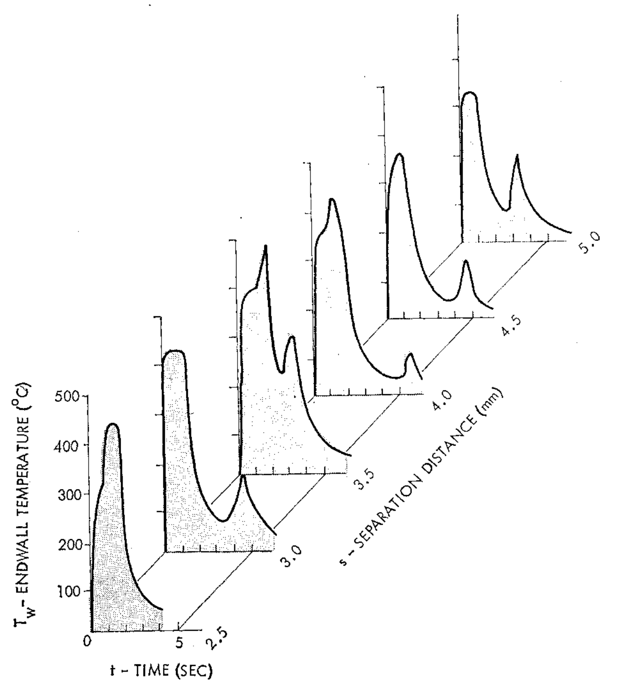

Fig. 5 The effects of separation distance on resonance tube thermal generation.

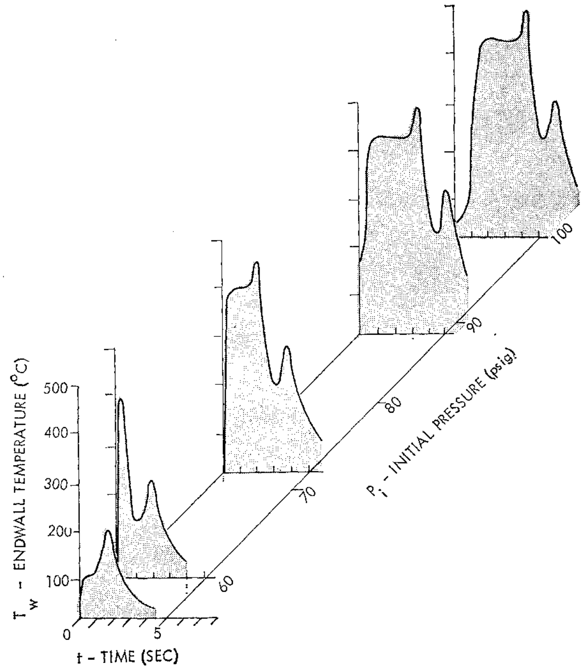

Fig. 6 The effect of initial supply pressure on resonance tube thermal generation.

with increasing supply pressure to about 3.5 sec at $P_i =$ 0.6 MNm^{-2} (87 psig). Pressures higher than 0.6 MNm^{-2} do not increase this time nor do they increase the maximum temperature. The time above 300°C remains constant with the only effect of the higher pressure being to delay the start of operation. In fact, by purposely supplying high pressures an accurate time delay may be built into the ignition system. Since it is actually the pressure ratio across the ignitor nozzle which determines the operating range the effect of operation at high elevations will be to slightly increase the delay time.

Vent tube

The vent tube allows the air being discharged to leave the ignitor. Since resonance heating is a flow phenomenon no resonance heating is possible without some means of venting One parameter which determines the location of the jet cell structure is the pressure ratio across the nozzle, P_o/P_c. With an unrestricted vent where $P_c = P_{amb}$ the ratio is simply P_o/P_{amb}. If the vent area is finite, which it must be for this system, then $P_c > P_{amb}$ and the pressure ratio is reduced. To simulate the operation of the flueric ignitor within a rocket motor, ignition tests were run with 6.4 mm ID tubing as the only vent. It was found that lengths up to 1 m could be attached to the ignitor without significantly affecting the nozzle pressure ratio.

Propellant ignitor interface-nitrocellulose

Nitrocellulose, an interface material which produces hot particulate matter, was found to be required to ignite the $BKNO_3$ pellets because they could not be ignited directly by resonance heating. Nitrocellulose has an ignition temperature of about 170°C (DTA Analysis) while the ignitor finally chosen for the system produced 600°C. An open ended tube was closed off with approximately 20 mg of nitrocellulose.

Propellant

Boron potassium nitrate ($BKNO_3$) is typically used as an ignitor in solid propellant rocket motors. Atlantic Research F-ND 2M pellets were used. Each 45 mg pellet was pressed into place against the nitrocellulose.

Energy Source

The energy source shown in Fig. 7 consists of a mechanical hand pump, check valves, an abort valve to release the supply pressure bypassing the ignitor, an in-line filter, the pneumatic tubing, and a relief valve. The energy source was designed to provide an initial gas supply pressure of 0.7 MNm^{-2} (101 psig). The hand pump selected was a simple air cylinder whose bore diameter was 35 mm (1.375 in.) and had a 51 cm (20 in.) stroke. With this pump tests indicated that it would take approximately 35 sec to obtain the operating pressure. It can be shown from the mass continuity equation and the ideal gas laws that the pressure at any time after the valve opens, P_o, may be related to the initial pressure P_i by the following

$$P_o = P_i \exp\left\{-\left[\gamma R T_o \left(\frac{2}{\gamma+1}\right) \frac{\gamma+1}{\gamma-1} \frac{A^*}{V}\right]^{1/2}\right\}. \quad (1)$$

The relief valve is not typical in that once the valve opens it does not close again until the pressure drops to below 10% of the opening pressure. Thus, it will stay open long enough to insure ignition but will automatically reset after each operational cycle.

System Development

Flueric ignitor assemblies were breadboarded and repeatably demonstrated the feasibility of the concept of flueric sounding rocket motor ignition by actually igniting $BKNO_3$ propellant over a wide range of operating conditions when powered solely by a hand pump. Acceptable operation was obtained with gas pressures as low as 0.3 MNm^{-2} (45 psig) and at ambient temperatures as low as −40°C.

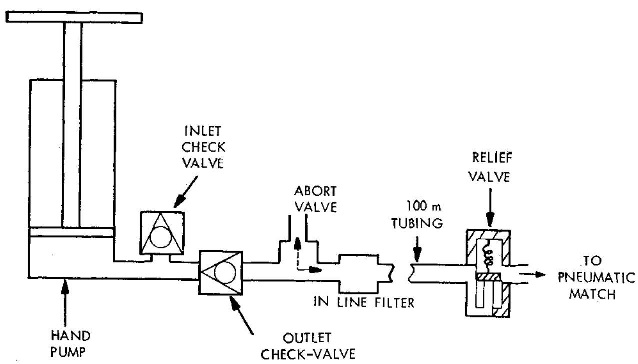

Fig. 7 Energy source schematic.

Conclusions

The objective of this program was to develop and demonstrate an inexpensive, safe, and foolproof ignition system concept for sounding rockets. A fluidic solid propellant ignitor—the pneumatic match—was developed to operate when powered by a single stage hand pump. The operation of the fluidic ignitor is based on aerodynamic resonance heating in closed tubes excited by a free air jet emanating from a simple convergent nozzle. As such it completely eliminates the need for electrical energy and wiring. Although ignition of explosives had been accomplished previously with the pneumatic match it had required a relatively high supply pressure 2.0 MNm^{-2} ($\approx$300 psig) of a specific gas (helium). The novelty of this system is the ignition of solid propellant with a man powered low pressure air supply. Hence it is concluded that fluidic sounding rocket motor ignition is feasible using a system without stored energy and with the complete absence of electrical energy and electrical wiring.

Safety is improved with this system, as compared to the commonly used electrical systems, since this system is completely insensitive to stray voltages, EMP and electrostatic voltages. The possibility of inadvertent initiation is virtually eliminated, since the probability of connecting a supply of bleeding pressurized gas with sufficient energy to achieve ignition is extremely remote. No complicated power supplied, or safe and arm devices are needed. Decreased costs can be achieved through very simple molded parts, and the ability to install the motor's complete ignition system during manufacture, decreasing motor complexity and eliminating the need for less reliable field installations.

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