necessary, as is generally the case, to consider all subsystems simultaneously when searching for an optimum system design.

Using the aforementioned computer simulation as a basic tool, a design methodology has been formulated which will provide a spacecraft developer with a means to optimize the design of an electric propulsion system (and, therefore, to maximize mission performance) for any given application.

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A Vortex Valve for Flow Modulation of 5500°F Gas

A. Blatter* and T. W. Keranen†
Bendix Research Laboratories, Southfield, Mich.

The results of developing a fluidic, no-moving part vortex valve capable of modulating the hot gas generated by a typical solid propellant are presented. The developed vortex valve has the capability of controlling a 16% aluminized, 5500°F gas flow of 1.0 lb/sec at 750 psi and for durations up to 50 sec. Seven hot gas tests were performed during the development. A materials selection was made based on an elasto-plastic thermal analysis of the vortex valve geometry. The final vortex valve demonstrated a 3.46/1 flow modulation range at a control pressure to supply pressure ratio of 1.7. A 2000°F gas was used to control the vortex valve, and it is concluded that a higher temperature control gas would improve the vortex valve modulation range.

Introduction

SOLID-PROPELLANT rockets have evolved rapidly in the last twenty years from simple uncontrolled devices to more complex units capable of thrust modulation, start-stop, and thrust vector control. The demand for more accurate control, more life and reliability and, finally, lower cost and less weight. In the effort to obtain maximum power from the solid propellant, combustion temperatures are increasing, and the combustion products are highly corrosive and erosive. Valves capable of operating in this severe environment are needed. By bleeding controlled quantities of gases from the combustion chamber, various control functions may be accomplished. Valving techniques for such purposes have been the subject of many investigations. This paper describes the development of a fluidic, no-moving-part vortex valve which has the capability of modulating the flow of solid-propellant hot gas. The vortex valve has certain operating limitations and, provided that these characteristics are acceptable to the system under consideration, the vortex valve can offer certain system advantages.

Received June 2, 1969; presented as Paper 69-424 at the AIAA 5th Propulsion Joint Specialist Conference, U.S. Air Force Academy, Colo., June 9–13,1969; revision received October 9, 1969. The authors wish to thank the NASA Langley Research Center for permission to publish results from the work sponsored under Contract NAS1-5199. They also thank the Bendix Research Laboratories for assistance in the preparation of this paper, and the many individuals who contributed to the effort while it was in progress.

* Staff Engineer, Dynamic Controls Laboratory.

† Engineer, Vehicle Controls Department, Dynamic Controls Laboratory.

Vortex Valve Concept

The vortex valve (Fig. 1) functions by the interaction between properly introduced control and supply flows. The supply flow is introduced radially into a cylindrical vortex chamber. In the absence of control flow, it proceeds radially toward the center outlet orifice whose size establishes maximum valve flow. Supply flow is modulated by tangential control flow that imparts a rotational component to the supply flow. Conservation of angular momentum causes the tangential velocity to increase toward the center of the valve. This generates an impedance or pressure buildup

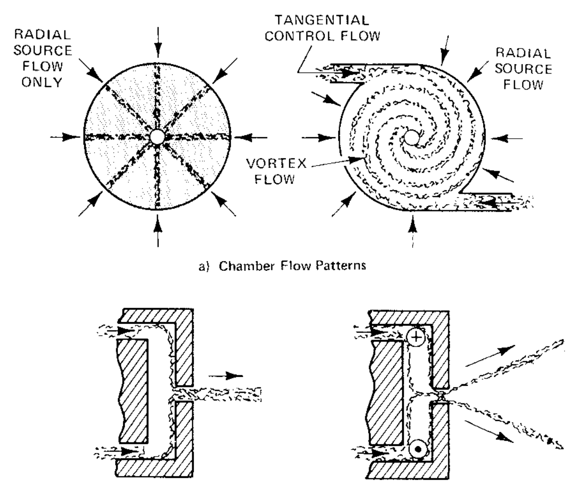

Fig. 1 Vortex valve configuration and operation.

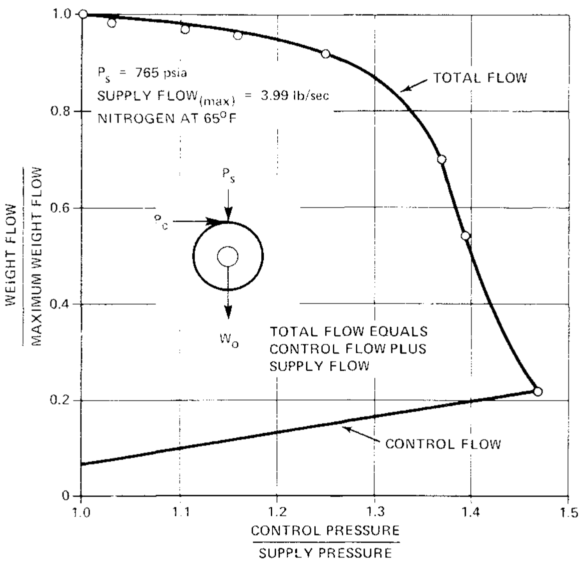

Fig. 2 Typical vortex valve flow turndown performance.

across the vortex flowfield in a radial direction. This pressure gradient opposes the incoming supply flow and modulates it. The strength of the vortex flowfield thereby produces a valving characteristic; i.e., an increase in control flow causes a reduction in total valve flow as shown in Fig. 2. The supply flow enters the vortex chamber through an annulus formed by a centerbody slightly smaller than the vortex chamber diameter (Fig. 3).

The vortex valve is insensitive to geometry variations such as small changes in chamber diameter, centerbody diameter, and location. It is sensitive to the tangency of the control holes and vortex chamber and to the control hole area and orifice coefficient. The performance of a vortex valve is as reproducible as the performance repeatability of a simple orifice.

The vortex valve is well suited for high-temperature work for two reasons: 1) it has no moving parts, no dynamic seals and no possibility of seizing, and 2) there is negligible unsymmetrical component distortion caused by thermal expansion to affect valve performance.

Control Technique

It is necessary to vary the control flow in order to change the vorticity in the vortex chamber. Control gas modulation, from about 20% of the maximum supply gas flow to zero may be accomplished by a mechanical valve or by another vortex valve. The control vortex valve would have approximately $\frac{1}{5}$ the flow capacity of the main vortex valve. However, the initial pilot stage control element will be a mechanical valve whose flow capacity is dependent upon the number of vortex valve stages employed.

The control gas should be at the same temperature as the supply stream. If a gas with other properties and/or at a different temperature is used, the turndown ratio of the vortex valve will be affected. A control gas temperature of 2000°F was selected to minimize the pilot stage mechanical problems as demonstrated in previous work.[1] The turndown ratio is the ratio of maximum supply stream flow divided by the control flow required to bring the supply flow to zero. Most important is the control momentum rate injected into the main stream. Conditions which affect the velocity or density of the injectant are critical to valve performance.[2]

The control gas must be at a higher pressure than the main stream gas for injection to occur. The static pressure at the injection point in the vortex chamber is less than that in the supply line because the center body increases the supply fluid velocity. This is the reason control flow exists at a P_c/P_s of 1.0 as in Fig. 2. The control pressure ratio, at which full turndown occurs, can be varied for particular applications. A practical range for control pressure ratio is between 1.1 and 1.8 to 1. A greater range is possible, but at lowered momentum exchange efficiency. Control momentum magnitude is the predominant factor affecting vorticity in the vortex chamber, and some tradeoff between control flow and control pressure can be made. At full turndown the only flow issuing from the valve is control flow. The turndown ratio is highest when control pressure at full turndown is high. Thus, by reducing the total area of the tangential control holes, an increase in turndown ratio

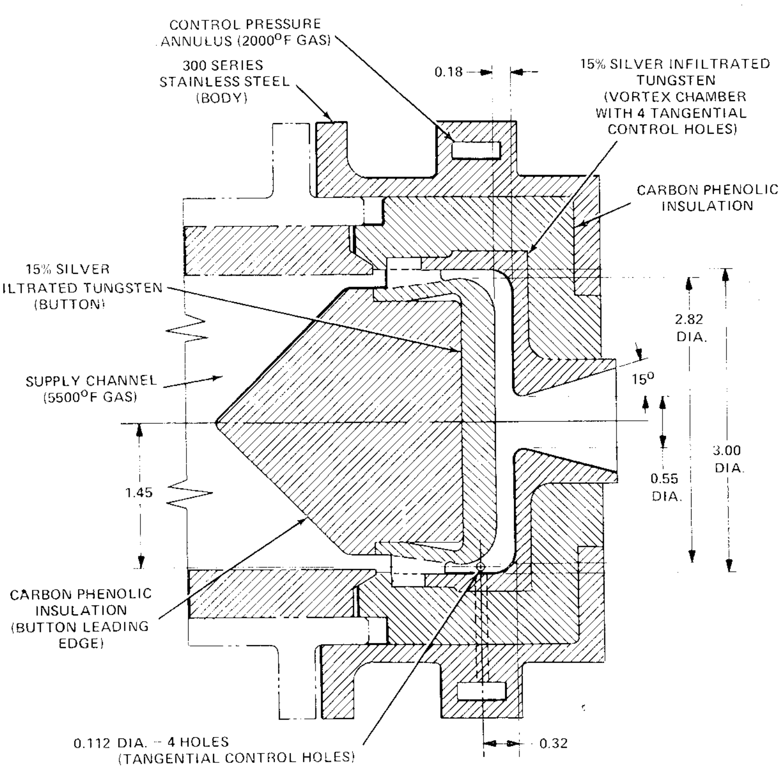

Fig. 3 5500°F vortex valve basic dimensions and materials.

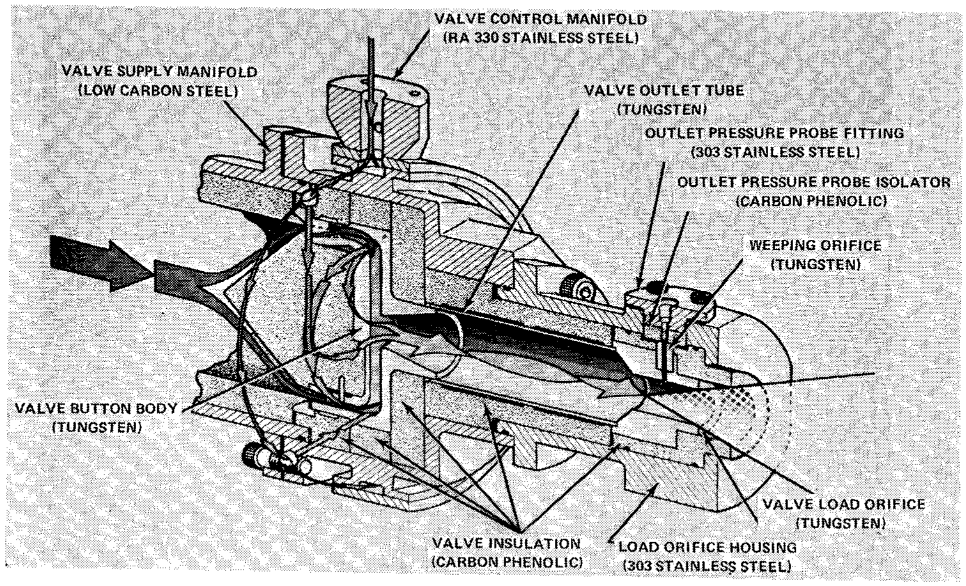

Fig. 4 5500°F vortex valve with load and flow measurement orifices.

can be obtained at the expense of using a higher control pressure. Other parameters of the tangential holes, (number, exact angle, discharge coefficient and axial location) have secondary effects on the turndown characteristics.

Vortex Valve Design

The configuration and critical dimensions of the final hot gas vortex valve are shown in Fig. 3. The 300 series stainless steel valve housing was lined with carbon phenolic thermal insulation, which mechanically retained the 15% silver-infiltrated tungsten vortex valve chamber. The silver-infiltrated tungsten and carbon phenolic vortex valve center-body assembly was supported by airfoil-shaped struts fitted into the chamber walls. The control gas was ducted to an annulus in the valve housing to four silver-infiltrated tungsten control injectors into the vortex valve chamber.

To simulate the vortex valve driving a secondary injection thrust vector control nozzle and to provide a means for measuring vortex valve flow, a load orifice was added to the basic vortex valve (Fig. 4).

The gas flow rate out of the vortex valve was measured with a "weeping" orifice system (Fig. 5), which was a port in the load orifice at subsonic conditions. The port was supplied with nitrogen from an upstream sonic orifice. A change in hot gas flow through the vortex valve load orifice changed the impedance of the weeping orifice. The resultant pressure variation was calibrated to provide the measurement of flow through the vortex valve.

Test Results

Prior to each hot gas test, the vortex valves were tested with unheated nitrogen to determine performance, and the flow measurement system was calibrated. Typical vortex valve turndown performance on nitrogen is shown in Fig. 2. The valves typically indicated a capability of providing 5-to-1 turndown at a pressure ratio of 1.45.

The hot-gas test circuit (Fig. 6) consisted of a main stage vortex valve system which modulated 5500°F gas and a 2000°F gas pilot stage which controlled the main stage valves. The main stage consisted of two push-pull operated vortex valves mounted on the 5500°F solid-propellant gas generator (SPGG). The push-pull mode of operation was utilized to impart a nearly constant impedance load to the SPGG, so that the gas generation rate would remain constant; operation was such that when one vortex valve supply flow decreased, the other vortex valve supply flow increased. As a result, the total flow consumption was approximately constant.

The pilot stage comprised two smaller push-pull operated vortex valves which were controlled by a torque-motor driven flapper-nozzle valve. The pilot-stage gas was supplied from a 2000°F SPGG, and vortex valves were constructed of molybdenum-0.5% titanium material. A signal to the torque motor displaces the flapper, which alters the pilot stage flow balance, causing the main-stage valves to change their flow output.

Hot gas flow measurement remained a chronic problem during the vortex valve development. Although performance data with hot gas are limited, a turndown curve is shown in Fig. 7. The maximum turndown performance recorded was 3.46 to 1, which is in reasonable agreement with the theoretical value of 3.56 to 1 with 2000°F control gas.[3]

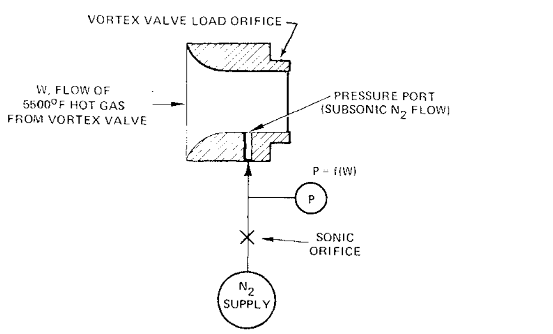

Fig. 5 "Weeping orifice" flow measurement system.

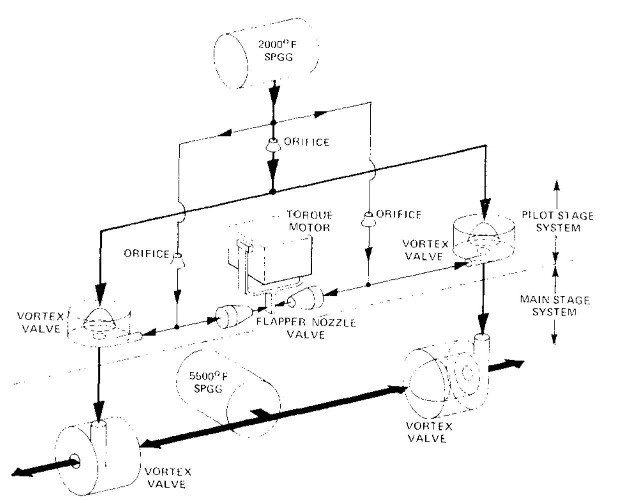

Fig. 6 Hot gas vortex valve test schematic.

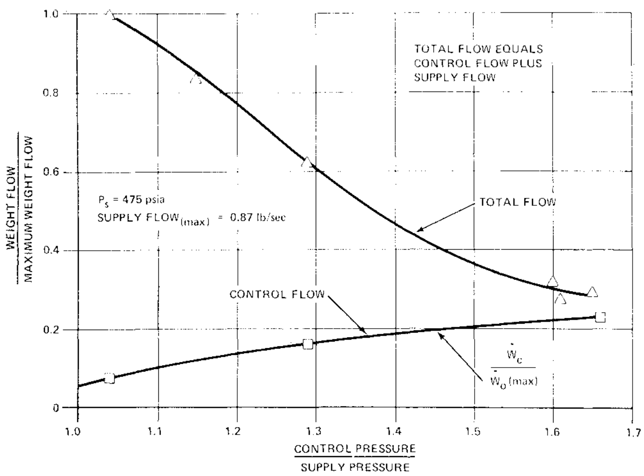

Fig. 7 Vortex valve hot gas turndown performance.

The ability of vortex valves to turn off the flow of hot 5500°F supply gas is graphically depicted in the section of two test movies shown in Fig. 8. These movie segments, which have a common time base, show two vortex valves in push-pull operation during a hot gas test. In the frames where no flow is visible, the supply (5500°F) flow is off but control (2000°F) is on. The control flow has much less luminosity than the aluminized supply gas. During this portion of the test, the hot gas flow was being modulated at approximately 5 Hz.

Dynamic response has been only partially evaluated due to difficulties in measuring hot gas flow. Test data obtained indicate phase shifts of approximately 5° and amplitude ratio attenuation of 0.6 at 15 Hz. Theoretically, the hot-gas vortex valve has a frequency response bandpass of 80 Hz. It has demonstrated a life capability for durations in excess of 50 sec. Figure 9 shows a postfired vortex valve which has retained its pretest features without serious distortion or errosion.

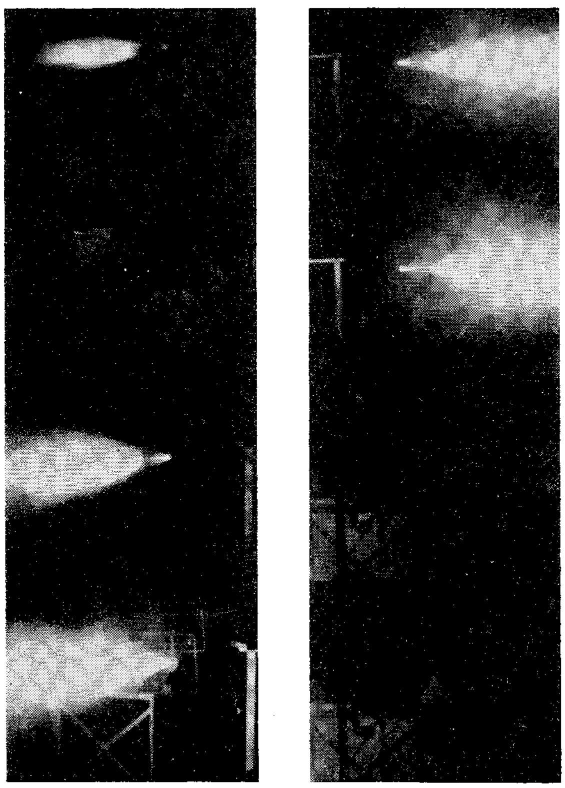

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Fig. 8 5500°F mainstage vortex valves during hot gas test.

Applications

Secondary Injection Thrust Vector Control (SITVC)

In a vortex valve controlled SITVC system, the main engine combustion chamber would also provide the secondary injectant gas. A reasonable pressure differential exists between the combustion chamber and the static pressure in the thrust nozzle at the point of injection. The vortex valve would modulate the flow of bleed gas in the injection port. Two vortex valves in each plane (yaw and pitch) are necessary to obtain thrust vector control. A method of implementation is shown in Fig. 10. The buried nozzle eliminates manifolding to the vortex valves. The pilot stage is mounted outside the engine pressure vessel and requires a high-pressure, auxiliary gas generator. The pilot-stage gas must be clean and free from materials that can plate out and plug orifices. It is believed that gas temperatures to 4000°F can be used for the pilot stage.

The secondary injection ports would always have flow issuing from them which will vary from full bleed flow to the minimum, which would be only control gas. At full demand for thrust vectoring, the injectant flow would be at high temperature with no swirl components. At zero thrust vector command, the injectant would be at lower temperature with a strong swirl component. Whether these injectant conditions would amplify or attenuate the effectiveness of the injectant is unknown.

The last test conducted with the hot-gas vortex valve was with a simulated SITVC system on a 30-lb/sec rocket engine.[3] Two vortex valves were mounted on the thrust nozzle at the 75% position, one in the yaw plane at 270°, and the other in the pitch plane at 0°. The injectant gas was supplied from an auxiliary 5500°F SPGG. This SITVC system produced side forces up to 4% of the engine thrust, equivalent to a thrust vector angle of 2.5°, which is within the range for hot-gas injection[4] (Fig. 11). Frequency response data indicated an amplitude ratio of −2.2 dB and a phase lag of 68° at 16 Hz. The use of integrated components, to reduce manifold volumes, would improve system dynamic performance.

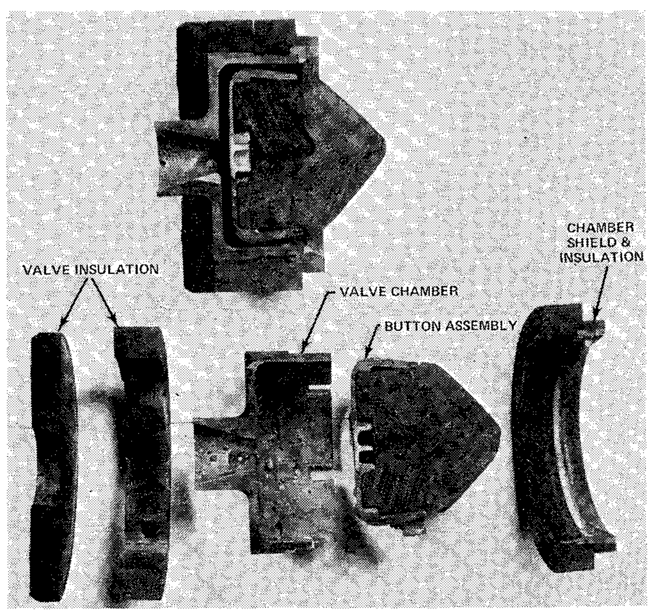

Fig. 9 Hot gas vortex valve post-test section.

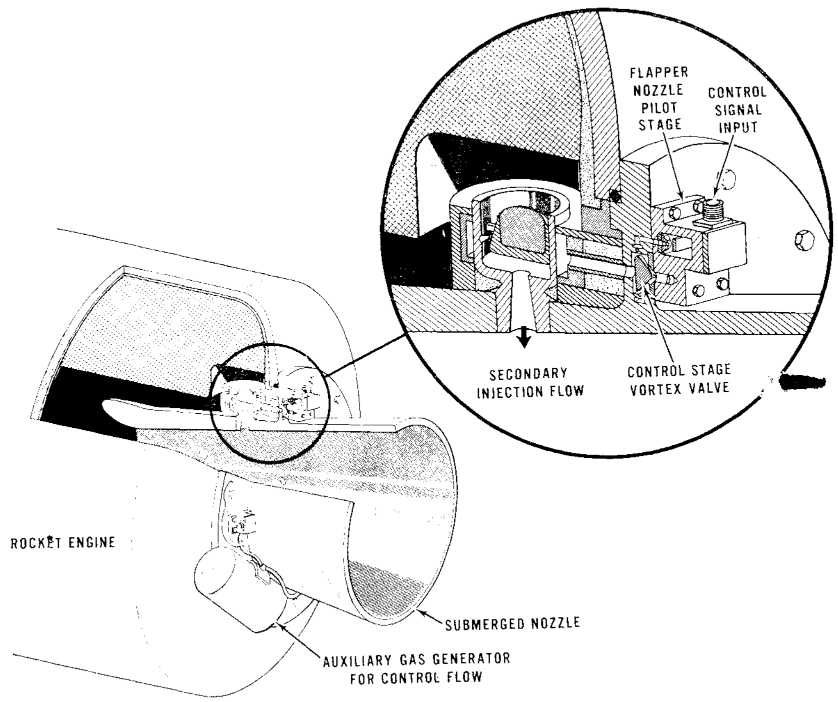

Fig. 10 Vortex valve secondary injection thrust vector control system—buried nozzle installation.

Throttling

The vortex valve flow control characteristics makes possible the throttling of a solid-propellant engine. The vortex valve has been used for liquid bipropellant reaction controllers where the outlet hole of the vortex valve was the throat of the thrust nozzle. Similarly, a vortex valve could be attached to a solid-propellant engine. Turning down the vortex valve would increase the nozzle impedance with a corresponding increase in engine thrust due to higher burn rate. An engine with a very sensitive propellant could be throttled in a more practical manner by two or more vortex valves symmetrically arranged around the thrust nozzle. When the vortex valves are turned down, the engine pressure and thrust would rise. It is believed that the fully turned down vortex valve-thrust nozzle concept generates less thrust for a given flow rate than if no swirl were present in the nozzle.

These systems require an auxiliary gas generator to provide the higher pressure control gas as previously discussed. Possible methods of implementing the concepts are shown in Fig. 12.

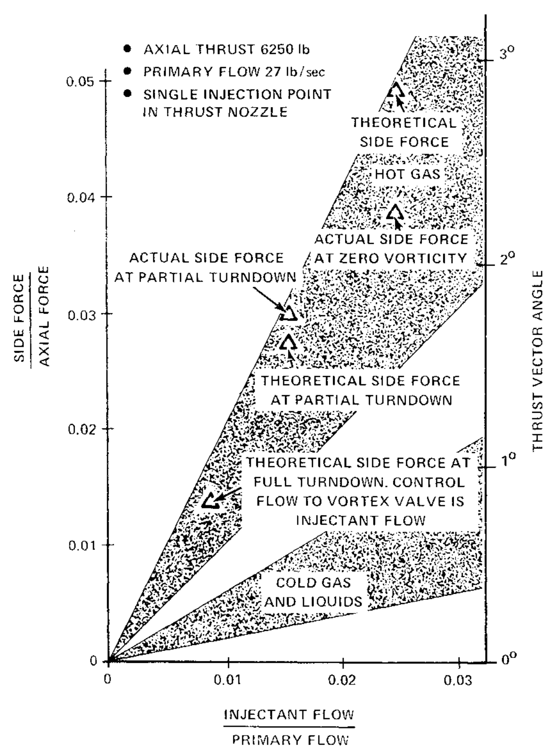

Fig. 11 Effectiveness of hot gas injection compared to cold gas and liquid injectants.

Thrust Termination

A solid-propellant engine may be shut down by rapidly reducing the combustion chamber pressure. Venting could be accomplished by use of one or more vortex valves commanded from the full turndown state to the full open state. The total increase in area has to be large compared to the original thrust nozzle throat area. The system would work best with a solid propellant having a rather high pressure exponent for burning rate (e.g., $r \propto P_c^{0.7}$) to minimize the number and/or size of the vortex valves required.

Tank Pressurization System

A simple tank pressurization system can be obtained with a vortex valve and an SPGG (Fig. 13). Some control systems

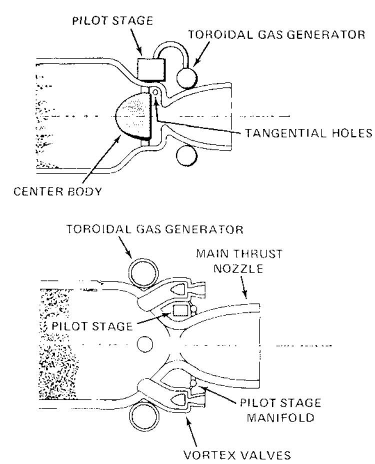

Fig. 12 Throttleable solid-propellant engine.

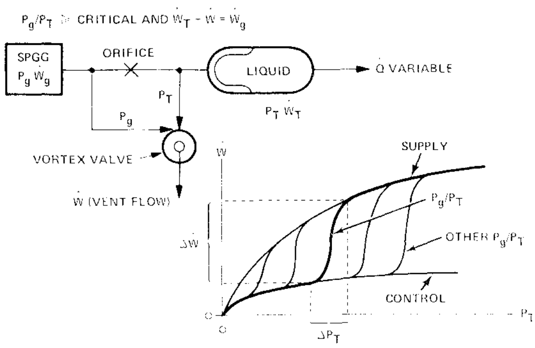

Fig. 13 Schematic of simple tank pressurization system.

use a liquid expulsion system in which the liquid flow rates are variable, but it is desirable to have the driving pressure remain reasonably constant.

Conclusions

The vortex valve has proven to be a suitable valving element for throttling the flow of hot gas from a typical high-performance solid propellant. The flow of 5500°F 16% aluminized from a gas has been throttled from 1 lb/sec to complete shutoff. The valve design has an operational life of 50 sec without serious material degradation. Possible applications of the vortex valve are: secondary injection thrust vector control, engine thrust control, thrust termination, and tank pressurization.

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Compatibility of Materials with Chlorine Pentafluoride

W. E. Hensley,* R. J. Walter,† W. T. Chandler,* and N. J. Hoffman*
Rocketdyne, A Division of North American Rockwell Corporation, Canoga Park, Calif.

Thirty-four materials (aluminum, copper, iron, and nickel alloys and plastics) were static tested for compatibility with ClF_5 and with moisture contaminated ClF_5 at ambient temperatures and at 160°F for 30 days; tests also were conducted for 580 days at ambient temperature. Results of visual and metallographic examinations and weight changes are reported. General corrosion in uncontaminated ClF_5 was small for all alloys tested. General corrosion was well within normally acceptable corrosion limits (2 mil/yr) for all alloys tested. Optical microscopy showed that severe localized attack of second phases or inclusions (stringers) occurred in the following monel alloys: 400, R-405, 500, 501, and 507. There was no noticeable surface attack of the nonmetallic materials, but these materials did gain considerable weight due to absorption to ClF_5. The alloys most resistant to attack by ClF_5 under all test conditions were Hastelloy C, Nickel 210, René 41, and Inconel X-750.

Introduction

CHLORINE pentafluoride (ClF_5) is a recently developed, dense, stable, storable oxidizer with a wide liquid temperature range. Its properties are remarkably similar to those of ClF_3, but it has superior rocket engine performance capabilities, and, in fact, is the most powerful, storable liquid oxidizer. A variety of physical and engineering properties of importance to rocket engine usage was determined under Air Force Contract AF04(611)-9563, including an evaluation of the compatibility of 34 engineering materials with ClF_5 under static conditions. The selection of the materials was based on utilization in the aerospace industry. The tests were conducted under conditions that simulated, as closely as possible, actual propellant storage conditions. Tests were conducted with high-purity (closed-system loaded) ClF_5 under ambient temperature (T_a) conditions (40°–100°F) and under controlled high-temperature conditions (160°F). In addition, selected materials were tested with moisture-contaminated ClF_5; i.e., the ClF_5 was loaded in the test chamber in the open air. The results of the compatibility investigation are presented herein.

Experimental Procedure

The test apparatus (Fig. 1) was made up of a 10-in.-long, 1-in.-diam, stainless-steel tube with a stainless-steel bellows valve at the top and a stainless-steel plug at the bottom. The tube was lined with Kel-F sheet to prevent galvanic corrosion between the samples and the stainless-steel wall of the bomb. A group of specimens was suspended on a Teflon-coated wire with alternate Teflon spacers. Each specimen was isolated from other specimens, below and above, by alternating Kel-F disks (Fig. 2) to avoid contamination from one specimen to another. This setup provided a means

Received May 5, 1969; revision received November 10, 1969. This program was sponsored by the Air Force Propulsion Laboratory Research and Technology Division, Air Force Systems Command, Edwards, Calif., with A. Beale acting as Contract Monitor.

* Member of the Technical Staff. Member AIAA.

† Member of the Technical Staff.