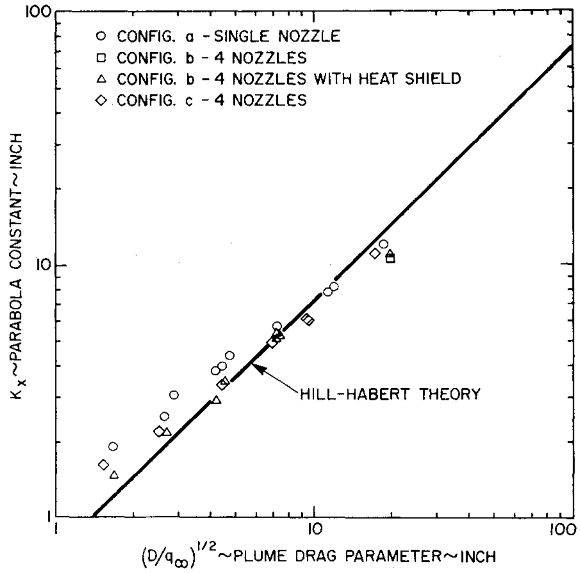

Fig. 3 Plume bow shock wave parabola constant.

heat shield which is located at the nozzle exit plane and fills the area between the four nozzles. The variation of the rocket exhaust plume parabola constant with plume drag parameter, $(D/q_\infty)^{1/2}$, is similar for all vehicle configurations that were analyzed. A usual approximation in theoretical calculations of the exhaust flow from multinozzle configurations is to replace the multinozzle configuration with a single "equivalent" nozzle. This assumption is supported by the limited data at $(D/q_\infty)^{1/2} = 20$, which shows nearly equal parabola constants for plumes from the four nozzle configuration (b) without heat shield and its single equivalent nozzle configuration (a).

The plume parabola constant predicted by the theory of Hill and Habert is shown in Fig. 3 for comparison. They predicted that

$$K_x = 0.57(\gamma_\infty/J_0)^{1/2}(D/q_\infty)^{1/2}$$

where γ_∞ is the ratio of specific heats in the ambient and J_0 is a function of γ_∞ tabulated in Ref. 6. For the experiments, J_0 is equal to 0.85. The plume shock position predicted by the Hill-Habert theory is noted in Fig. 2.

The excellent agreement between the Hill-Habert theory and the present experimental results for $(D/q_\infty)^{1/2}$ as low as 5.0 may be fortuitous, however, since their theory was originally developed for high-altitude plumes with $(D/q_\infty)^{1/2} > 5 \times 10^3$. With due consideration for this possibility, the excellent agreement with experiment indicates that the theory may be used to provide rapid and accurate estimates of dimensions of rocket exhaust plumes at significantly lower altitudes.

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Gas Effects in Attitude Control Systems

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DIFFUSION through a tank bladder is a slow way of saturating a body of propellant with gas if the propellant is quiescent. However, any motion due to sloshing or thermal convection increases the solution rate. When bladders are made of materials (such as Teflon) with different permeabilities for pressurant gas and propellant vapor, free gas bubbles can grow in the propellant by osmosis. When the propellant is saturated with pressurant gas, the partial pressure of the pressurant gas may be lower on the liquid side of the bladder than on the gas side. This partial pressure difference arises because the bladder tends to prevent the propellant vapor from making as big a contribution to the total pressure on the gas side of the system as it does on the liquid side of the system (where its vapor pressure is exerted). (The amount of gas in the propellants can be minimized by techniques such as using aluminum bladders. This was done on the Lunar Orbiter vehicles.[1] The Surveyor vehicles did not use this type of gas barrier but a program of ground tests was conducted to insure that gas effects would not interfere with obtaining mission objectives.[2])

During a mission, propellant pressures and temperatures can change because of blowdown operation, temperature changes in the environment, thermal soakback from the rocket engine, or because propellants flowing through a rocket engine meet lower pressures and higher temperatures between the engine inlet and the rocket injector orifices. When the propellant temperature and pressure conditions change so that the amount of gas in the propellant exceeds the equilibrium amount, some dissolved gas may come out of solution.

When propellants contain dissolved gas, free gas bubbles can form in the propellant feed lines and propellant valve bodies during priming. Exposure of the gas-containing propellants to the low pressure and turbulent flow during priming generates free gas, which may not redissolve when priming is complete. If the feed lines are not evacuated before priming, the trapped gas contributes to the free gas in the system after priming.

Free gas can affect attitude control system (ACS) operation in a number of ways: combustion pressure oscillations, transient changes in chamber pressure and thrust, long ignition delays, and shifts in pulsing and steady-state performance parameters.

Analytical and Experimental Results

Figure 1 shows two types of special test equipment used to evaluate gas effects on ACS operation. Special tanks with

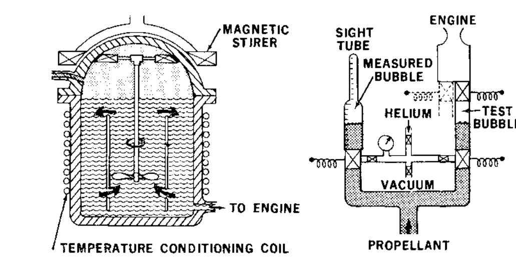

Fig. 1 Test apparatus.

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gas pressurization lines, temperature conditioning coils and magnetically driven stirrers were used to condition propellant to the desired pressure, temperature and dissolved gas content.[3] The other piece of apparatus was used to evaluate ACS engine ignition with large free gas bubbles adjacent to the engine propellant valves. Similar apparatus relocated nearer the propellant tanks could be used to determine the effects of free gas bubbles on steady-state performance parameters. In the use of the bubble insertion apparatus, the space between the engine valve and the line valve is evacuated and then this space is pressurized to a value such that the desired bubble volume is obtained when the line valve is opened and the pressure in the space reaches tank pressure.

Stability Effects

The relationship between propellant temperature, engine design parameters, and low-frequency stability has been analyzed.[4] The equations relating the pressures and flows in an engine were linearized, and a transfer function was derived for the dynamic interaction between propellant flow rate and combustion chamber pressure. The frequency response characteristics of this transfer function were plotted over a range of propellant temperatures. Figure 2 compares analytical results with test data from two engines, which were similar except for the length of the injector holes. The design with the greater stability margin had longer final injection passages. This moved the injector resonant frequency away from the frequency range where the coupling with the combustion dynamics was strongest. Both engine designs showed smaller stability margins (evidenced by a larger oscillatory component in chamber pressure) at low propellant temperatures, because smaller amounts of gas were released at lower temperatures. The lower compressibility of the gas-propellant mixture in the injector resulted in less favorable injector dynamics.

Smooth combustion requires that adequate gain margin be designed into the interaction loop transfer function. Dissolved gas release can make the propellant compressibility vary as a function of propellant temperature and this must be considered in evaluating the interaction loop transfer function. Engine tests to evaluate stability should use the same pressurizing gas, degree of saturation, and propellant temperature range expected in the engine's intended application.

Bubble Effects during Startup

Gas bubbles in the propellant lines near the valve seat area may delay ignition or cause mismatch between the injection of fuel and oxidizer. Bubbles must be expelled from the system before normal propellant flow from the injector can occur.

Two computer programs were developed to predict the bubble expulsion times for both continuous firing and pulsing engine operation. For small bubble volumes, waterhammer wave propagation is considered; with larger bubbles, waterhammer effects on expulsion times become negligible. Both programs assumed a defined propellant-gas bubble interface which moved towards the engine valve as a function of the propellant mass and momentum, and gas pressure and volume. The tank pressure was a constant value, and gas expulsion through the valve was assumed to be choked and thus to vary linearly with the gas bubble pressure. The programs keep track of the propellant-bubble interface and bubble pressure during the pulsing off and on times so that the start conditions for the next pulse are known. Pulsing and steady-state engine tests were conducted to determine experimentally the effects of gas bubble ingestion. Figure 3 compares the analytical results with test results from steady-state runs. Equally good agreement was found for actual and predicted pulsing mode operation.

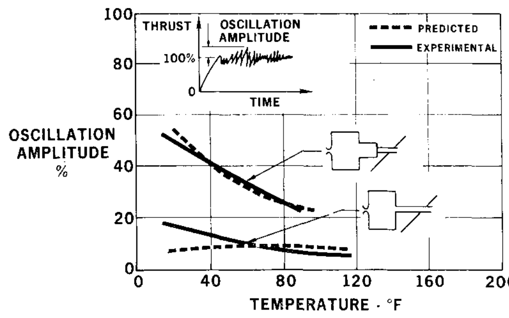

Fig. 2 Temperature effect on stability.

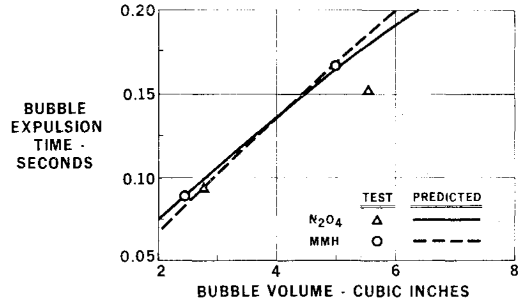

Fig. 3 Nitrogen gas bubble expulsion time.

Bubble Effects During Steady Firing

If a pressurant gas bubble flows into an engine inlet while the engine is firing, a momentary rise in engine thrust may occur because the gas bubble produces less pressure drop for a given flow velocity than the liquid propellant. This causes the flow to accelerate while the gas bubble is passing through the engine. Subsequently, the thrust will drop when the gas bubble passes through the injector, momentarily starving the combustion process.

Performance shifts can occur even when the propellants flowing into the engine inlet contain only dissolved gas and no free gas. The shifts may only be significant in certain propellant temperature ranges; they result from gas-caused changes in the flow resistances of various parts of the rocket hydraulic system, and sometimes, by interference with normal mixing and combustion. The most common effect is similar to cavitation. The drop in pressure as the propellant flows through flow restrictions in the engine causes the release of gas by the propellant. This reduces the net propellant flow rate and causes a shift in the engine mixture ratio and, usually, an accompanying shift in specific impulse.

Conclusions

Gas in a propellant can cause thrust oscillations, sluggish starts, thrust excursions and performance changes. The combination of mathematical modeling and controlled engine tests over the range of pressure, temperature, gas content and engine operating conditions required during the application can be very helpful in identifying and solving any problems that arise.

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