ROCKET ENGINES FOR OUTER SPACE

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Most rocket power plants in use today are designed to operate in the earth's atmosphere; to date, few engines have been developed for operation exclusively beyond this atmosphere. Furthermore, the development-testing of these engines and systems has been done at sea-level conditions. Our thinking on rocket power plant design is being influenced to a large extent by the information obtained during this ground testing.

To achieve an optimum engine system design for operation in outer space, two basic environmental changes must be considered: (1) in effect, the ambient pressure in space will be zero and (2) gravitational acceleration will differ in magnitude and relational direction from that on earth.

THE IMPORTANT FACTORS

There are three primary variables affecting the specific impulse that a given thrust chamber will produce. These are the combustion temperature, the mean molecular weight of the exhaust products, and the pressure ratio through which the expansion of the exhaust gases takes place. A rocket engine designed to operate at sea level, against an appreciable external pressure, must maintain a high chamber pressure if a reasonable pressure ratio is expected. On the other hand, it is seen that as ambient pressure approaches zero, the pressure ratio becomes a function of the nozzle area ratio while chamber pressure, *per se*, becomes less important. Indeed, there are many desirable advantages to be gained by reducing chamber pressure, not the least of which is the over-all weight reduction of the propellant supply system and of the chamber itself. Another interesting advantage in reducing chamber pressure is the possibility of alleviating, to some degree, the problem of heat transfer from the chamber. Lowering the density of the combustion gases would reduce the magnitude of the heat flux density to the chamber walls, thereby permitting the use of higher combustion temperatures. For example, there would be no compulsion to use less energetic propellants or non-optimum mixture ratios because of heat flux density limitations.

However, there may be some disadvantages and limitations to using low chamber pressures. Coolant boiling within the chamber walls might become a serious problem, in a regeneratively cooled thrust chamber. Although little experimental evidence is available on this point, there are indications that while the propellant flow rate through the cooling jacket decreases proportionately to the chamber pressure, the heat transfer would not decrease quite so rapidly. Consequently, the temperature rise across the cooling jacket constantly increases as chamber pressure is reduced.

Another disadvantage to chamber-pressure reduction must be considered. At a fixed level of thrust, the physical dimensions of the rocket engine must increase as chamber pressure is reduced. The weight reduction realized because of minimal structural requirements with low chamber pressures might well be offset by this increase in size.

A further disadvantage to reducing the combustion chamber pressure might be the limitation imposed by an increase in dissociation. Most chemical-propellant reactions cannot be as complete at low pressures as at high pressures; a reduction of heat yield with a consequent decrease of specific impulse may be expected at low pressures. Theoretically, the magnitude of dissociation can be calculated, but in practice it is masked by variations of combustion performance as pressures are changed.

BULK-BOILING PHENOMENA

Limitations to weight saving by reducing chamber pressure also occur in designs which must be launched from the ground, as opposed to those systems to be constructed in space. A tanked propulsion system would have to withstand a 1 *g* load without rupture, while on the ground, and between 5 and 15 *g* during the boost phase. The minimum thicknesses of tanks that can be fabricated are another limitation factor in weight reduction.

The above are primarily limitations resulting from extrapolation of conventional design techniques. On first appraisal, it appears that the most severe limitation to chamber pressure reduction will be bulk-boiling of the coolant. With some of the more favorable designs, this occurs at about 100 p.s.i.

Little information is available on what happens as the phenomenon of bulk-boiling is approached by reduction of chamber pressure. It appears certain that burnout results when large amounts of vapor form in the coolant at high heat flux densities. However, in all conventional boilers, bulk-boiling proceeds without damage to equipment, even where flame temperatures are higher than the melting point of the heat-transfer surface. The problem concerns finding the precise range of pressure and temperatures within which bulk-boiling is harmless. Difficulty in attaining adequate mixture-ratio control may be expected when bulk-boiling occurs. Currently, mixture ratio is controlled primarily by injector hole size. When boiling takes place, the flow through an injector hole probably would be critically affected by the amount of boiling. Since heat transfer rate usually is not reproduceable, it is likely that poor mixture-ratio control will result. However, this sensitivity is determined by the way the total tank-to-combustion-chamber pressure drop is proportioned between the injector and other places. If the pressure drop in the passages downstream from the boiling is lowered and the drop upstream is increased, the sensitivity of mixture ratio to amount of boiling is reduced. Although in most conventional designs a reduction in injector drop is accompanied by lowered combustion efficiency, an appreciable amount of boiling might tend to increase combustion efficiency by increasing the degree of atomization. Work with starting processes at high altitude, conducted at the Jet Propulsion Laboratory at the California Institute of Technology has shown the atomizing action which results as a fraction of superheated liquid flashes into vapor upon passing through the injection passage.

Possibly this atomizing action may permit a very low injection drop, thus allowing an adequate degree of mixture-ratio control even when boiling takes place in both cooling and injection passages.

OTHER FACTORS

The loss of specific impulse which is occasioned by dissociation may be compensated for by increasing the nozzle area ratio as necessary. The increase in engine weight which accompanies such a greater area ratio would be added to other possible weight increases resulting from the larger dimension of the engine. To determine whether increased engine size and weight will have a serious effect on over-all vehicle performance, it is necessary to see the effect on the absolute thrust requirement. One may view this problem by considering gravitational forces during the trajectory. Most practical trajectories involve some approximation of the minimum energy, or 'zero-lift type' ascent; that is, the trajectory is allowed to bend under the action of gravity. The flight path angle continually decreases so that the gravity loss becomes less and less at later stages of the trajectory. If a staged rocket is used, the penalty of using a small thrust engine with a long burning time is small in the later stages. The acceptable minimum thrust is that required to accelerate the vehicle. When the missile is on the ground, a thrust-to-weight ratio greater than unity is required to lift it. However, once a stable orbit is reached, the minimum thrust approaches zero. This fact permits the use of smaller engines; the degree of smallness depends on the portion of the trajectory and the type of trajectory being considered. For many applications, even ion or photon rockets may be a practicable means of propulsion. In any case, as the thrust weight ratio is reduced, the power-plant weight and size become less critical because the engine becomes a smaller and smaller fraction of the vehicle weight. This tends to minimize the penalty incurred if chamber weight increases with lower chamber pressure, and also tends to raise the optimum area ratio.

OPTIMUM SPACE ENGINE

What is the optimum engine design for operation solely under conditions of zero back pressure and comparatively small flight-path angles? Chamber pressures could be extremely low, perhaps as low as 2 atm. This low pressure will permit a pressure ratio that will result in critical flow through the nozzles and permit engines to be tested on the ground without special exhaust ducting to simulate altitude performance. A lower pressure would allow back pressure to influence combustion chamber performance and cause development difficulties.

Chamber cooling is visualized as conventionally regenerative. Construction of the chamber will utilize techniques not permissible in an engine of high heat-flux density. One technique may be the fabrication of the chamber from very thin sheet metal by nesting two concentric assemblies together and bonding them by seam welding or soldering. The necessary coolant passage can be created by hydraulically inflating the assembly after bonding. Materials of thinner gage than those required by current fabrication methods could be utilized, and the inherent extra mass of bonding material (weld metal or other excess material) would be eliminated. The low heat transfer expected at low pressures may prevent burnout at the bonding points or seams.

Injector concepts will differ from conventional designs in that the pressure drop may be as low as 1 p.s.i. The nozzle area ratio will be great; certainly 20:1, at least, and perhaps as much as 100:1. A simple pressure feed system will be needed, and the most energetic propellants available will probably be utilized. Mixture ratio will be tailored for maximum thrust without regard for chamber temperature. Engines of this general type will be the best choice. Much research and development is needed in the very low chamber-pressure field, and engines specifically designed for this purpose should be under study.

THE SOLID ASPECTS

There are similar advantages gained when reducing the chamber pressure in solid-propellant rockets. The main advantage would be a reduction in the case weight which can be accomplished by lowering the chamber pressures. The chamber pressure can be reduced by lowering the ratio of the burning surface to nozzle throat area or by changing the propellant composition. For any given throat area and total impulse, pressure can be reduced by altering the charge geometry; the ultimate product being an internal burning grain, spherically shaped. End-burning cylindrical grains could be designed to give any burning area desired, but such designs forego the case-insulating effect of the internal-burning configuration. Advanced studies are required to further the needs of high specific impulse propellants that burn stably at low pressures as well to conduct explorations into the low-pressure long-burning configurations vs. total rocket weight. Nozzle weight constitutes the major fraction of total weight and is more nearly proportional to total impulse, hence the possibility of a large over-all weight reduction does not appear as promising as with the liquid systems.

THE STARTING PROBLEM

The two environmental conditions previously examined may give rise to two new problems. Both are concerned with engine-starting and are applicable to the liquid-propellant engines. To date, starting liquid-propellant rocket engines has been confined to environments containing a back pressure of one atmosphere. It appears that starting kinetics could be different at zero back pressure, particularly if the propellants are hypergolic (spontaneously ignitable). This is a problem necessitating intensive investigation prior to vacuum operation. A second consideration arises from a zero-gravity condition and involves the need for some form of initial positive propellant supply. If the initial condition prior to starting is one of free fall, the location of any bubbles is impossible to predict. If such bubbles were in the line or at the bottom of the tank, it might be impossible to satisfactorily start the engine.

There are a number of ways of avoiding this condition; one technique is to use a small solid-propellant rocket to create a definite acceleration, thereby ensuring that the bubbles will remain at the top of the tank. Another is to eliminate bubbles by providing a positive separation between gas and liquid in the form of diaphragms, balloons, etc. A third technique is to reduce the 'zero-*g*' period to a minimum, thereby reducing bubble dispersion.

Systems designs used in the past may be adequate to handle these problems. When sufficient money and manpower are allotted to this effort, we will have our first space engine.