NOTES

Power Source for a 1-kw Arc Engine Test Capsule

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The potential application of arc jet engines for propulsion in space is linked closely with the type and characteristics of the power supply available. Discussed herein is a power supply designed to power a 1-kw arc engine for use with the Scout Electric Rocket Test (SERT) program. The most significant features of the power supply are the excellent control, stability, increased engine life, and efficiency. Data obtained from actual arc engine tests are included. The conclusions drawn are based on preliminary analysis of prototype engine and power supply test runs. Although the feasibility of the system has been demonstrated, the development is not considered complete.

Introduction

THE original power supply proposed for the 1-kw arc jet engine was a 112-v battery, current-limited by a ballast resistor. Despite the simplicity of the system, several disadvantages were encountered. The power losses in the ballast resistor limited the efficiency to 30 to 50%; the resistor required a large heat sink; arc stability was relatively poor; and the voltage requirement was not compatible with the power system of the SERT capsule.

Test data established a typical steady-state electrical characteristic for the prototype engines.[1] Figure 1 illustrates this characteristic as determined by varying the resistance in series with the engine and battery. Figure 1 also shows that engine characteristics can be described reasonably by the classical expression for an arc discharge which is

$$V = A + BI^{-n} \qquad (1)$$

where A is the electrode-potential drop in volts, B is a constant dependent upon the geometry of the engine and the arc length, I is the arc current in amperes, and n is a constant dependent on the type and condition of the gas. The values of the constants for the theoretical curve were $A = 30$ v, $B = 222$, and $n = 0.5$.

It is recognized that such a characteristic curve represents a specific set of engine parameters that are subject to such disturbances as variations in gas flow, electrode erosion, and temperature. It also is recognized that the dynamic electrical characteristics essential for design of a power supply

¹ Page, R. and Humpal, H., "The objectives and design of a 1 kw arc jet engine for space flight testing," ARS Preprint 2346-62 (March 1962).

which would best regulate the operation of an arc jet engine have not been defined yet.

Early tests with prototype engines using the battery-ballast system indicated that engine life and efficiency were inversely proportional to the arc current. It was found also that arc stability increased as the angle of intersection between the characteristics of the engine and the power supply approached 90°. Consideration of these factors indicated that a power supply with a constant current output would be better suited for operating the arc jet engine.

Design

An efficient means of obtaining a constant current from a battery as a primary source is a solid-state d.c. to d.c. converter using a saturable reactor operating in the suppressed
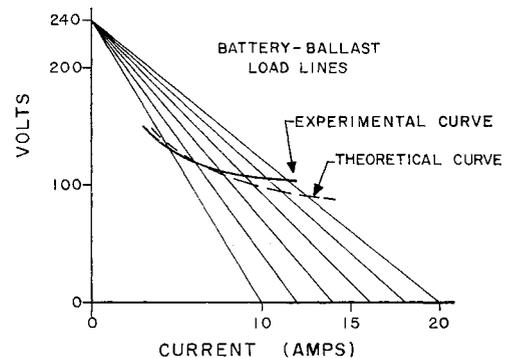

Fig. 1 Arc engine curve

even harmonic mode. The saturable reactor is composed of two toroidal cores, each containing a gate winding. The control winding may be common to both cores, or each may have an individual winding. The gates are connected series-opposing, between an a.c. source and the load. The controls are series-aiding and connected to a power source that is decoupled by a large iron core choke. The current through the control winding is set by a variable resistor that is also in series with the source. When the a.c. power is applied, the output of the network is a constant current that is dependent
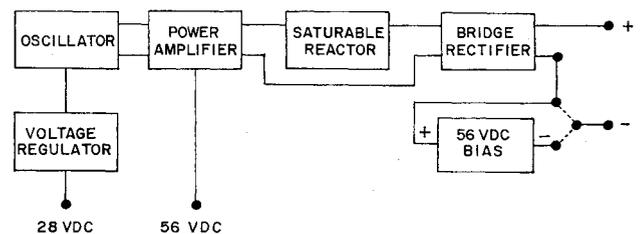

Fig. 2 Block diagram of constant current power supply

upon the turns ratio of the gate and control windings. This is consistent with the law of equal ampere-turns for any nonsaturated transformer.

A d.c. to d.c. converter using the saturable reactor was designed to meet the requirements of the arc jet engine (Fig. 2). The power requirements were to deliver 1 kw at a current level between 8 and 10 amp. With this converter, the efficiency of the power supply system was increased to approximately 85%. Subsequently, a weight and size reduction could be realized through the decreased power requirements of the battery and the elimination of the ballast resistor and associated heat sinks.

Tests

Two methods of operating the power supply were explored. The first method was with the power supply alone,
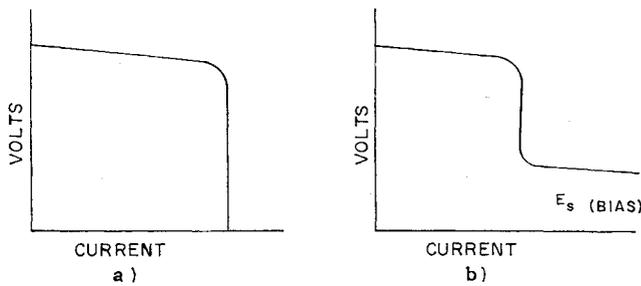
Fig. 3 Supply output waveforms

and the second was with the power supply operating in series with a battery bias. Figures 3a and 3b compare the power source output for these operational modes. Engine operation with the power supply and battery combination offers higher overall efficiency and reduces the heat dissipation requirements of the power supply.

Two basic engine designs, one with fixed electrodes and the other with pneumatically operated movable electrodes, have been started and operated with the power supply. The fixed-electrode engine required an externally applied high voltage to ionize the gaseous fuel and to reduce the arc resistance sufficiently to sustain conduction. One means of applying the starting voltage was to introduce a charged capacitor across the electrodes.

Starting tests began by determining the operating characteristics of the engine and power supply separately.

High voltage starting tests were performed with both hot and cold engines. Approximately 2000 v were required to start a cold engine. Typical steady-state engine operating voltages and currents using electric starting were 1) 110 v at 9.7 amp, 2) 103 v at 9.5 amp, and 3) 100 v at 10.0 amp.

Conclusions

Apparent advantages and disadvantages of the high voltage starting techniques still are being evaluated. Operational disadvantages encountered were 1) requirement of high voltage components and insulation, 2) detrimental influence of high voltage on engine life, and 3) need to adjust starting voltage (800 to 2000 v) to compensate for engine temperature.

Development of a mechanical start mechanism is a noteworthy advancement in the design of the arc engine. Starting of engines with movable electrodes could be accomplished at lower current levels and appeared to be more positive. This method was also more compatible with the power supply and eliminated the need for an additional high voltage source. The desirability of a constant current power supply in this case results in the fact that it also can limit the short circuit current at starting. Because of the initial short circuit with mechanical starting, a power supply and battery bias system requires additional current-limiting equipment. An external current-limiting resistor was provided for this type of start. In addition, a means also was provided for removing the limiter when the engine approached steady-state operation.

Summary

In summary, the advanced prototypes of the 1-kw arc engine and the power supply performed satisfactorily under laboratory test conditions. Although extensive testing still is to be performed, the power supply is considered to be practical for flight use. In addition to many operational advantages, the power supply offers significant savings in efficiency and payload weight. The degree of arc stabilization and control obtained with the saturable reactor is particularly attractive.

Since the saturable reactor can be operated directly from an a.c. source, it shows even more promise for future applications involving larger engines and a.c. power sources such as a SNAP VIII alternator.

Criterion for Slip near the Leading Edge of a Flat Plate in Hypersonic Flow

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On the basis of strong interaction theory estimates, a rarefaction parameter of the form $M_\infty{}^2 C_\infty / Re_{x_\infty}$ is proposed which appears to be useful in correlating experimental data in the slip-flow region near the leading edge of a flat plate. This parameter, which in fact is the square of the low-speed rarefaction parameter, can be interpreted as a measure of both the ratio of the mean free path behind the shock wave to the boundary layer displacement thickness and the ratio of the leading edge shock wave thickness to the distance downstream from the leading edge. To a first approximation, the parameter is independent of the temperature conditions at the wall.

1. Introduction

IN the past few years a number of experimental investigations[1-4] have been made of the pressure and heat transfer distributions near the leading edge of a sharp flat plate in hypersonic, low Reynolds number flow. These investigations have shown that, as the leading edge is approached, both the surface pressure and heat transfer depart from the predictions of viscous interaction theory and tend toward constant "plateau" values.† It can be argued with some force that this leveling-off of the pressure and heat transfer is a slip-flow or rarefaction effect. Presumably, then, the departure of the data from the predictions of no-slip viscous interaction theory should be capable of correlation with some appropriately defined Knudsen number. Because of the strong variations in local mean free path across the shock wave and boundary layer, several quite different Knudsen numbers can be defined. The purpose here is to discuss some of these Knudsen numbers and to show that a particular one can be chosen which appears to correlate quite well the initial departure of the data from the predictions of no-slip viscous interaction theory.

2. Knudsen Number

The Knudsen number Kn is defined as the ratio λ/d, where λ is a relevant mean free path and d some dimension characteristic of the flow field. One can express Kn in terms of the local Mach and Reynolds numbers by use of the approximate kinetic theory relation

$$\lambda = (\mu/\rho a)(\pi\gamma/2)^{1/2} \qquad (1)$$

in which μ and ρ are the viscosity and density, γ the specific heats ratio, and $a = (\gamma RT)^{1/2}$ the sound speed. One obtains the well-known formula

$$Kn = 1.25 \; \gamma^{1/2} \; M/Re_d \qquad (2)$$

where $M = U/a$, $Re_d = \rho U d/\mu$, and U is some characteristic velocity.

In low-speed boundary layer flows, the characteristic flow field dimension d usually is taken to be the boundary layer displacement thickness δ^*. Since the low-speed slip-flow

† The region very close to the leading edge (within a few mean free paths at the wall), where the heat transfer and surface pressure behavior is not yet well established, is not included here.