Flexibility of the Closed Brayton Cycle for Space Power

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ABSTRACT

New commercial and military applications for space power are developing over a wide range of nominal and peaking power requirements. Power levels far exceed the capabilities of photovoltaic array and battery systems. Factors such as manned and unmanned missions, long mission durations, zero-maintenance requirements, hardening from attack, and mission orbit or mission payload impact space power system specifications and dictate the type of energy source. This has led to emphasis on the closed Brayton cycle (CBC) with its inherent flexibility as a dynamic power source.

Unique features of the CBC contribute to its application to the multiplicity of space power requirements. These include flexibility of design, operation, energy source selection, and future growth.

A primary contributor to the high degree of flexibility of the CBC is its use of a single-phase gaseous working fluid. This provides:

- A working fluid which is not affected by zero gravity, freezing, vehicle accelerations during launch, or flight maneuver loads;
- Space environment testing which can be accomplished entirely on Earth;
- Complete freedom in the selection of pressure and temperature values throughout the cycle;
- Full compatibility with the alternative heat sources and their characteristics;
- Similar adaptability to various thermal management radiator types and sizes;
- The capability of CBC operation at different power levels by varying the working-fluid inventory and system pressure level;
- The ability to optimize the total CBC system design for specific application criteria;
- Scalability of the CBC to various power classes; and
- Development economy by virtue of the above flexibility, scalability, and low test costs.

INTRODUCTION

New commercial and military applications for space power are developing over a wide range of nominal and peaking power requirements. Power levels far exceed the capabilities of photovoltaic array and battery systems. Factors such as manned and unmanned missions, long mission durations, zero-maintenance requirements, hardening from attack, and mission orbit or mission payload impact space power system specifications and dictate the type of energy source. This has led to emphasis on the closed Brayton cycle (CBC) with its inherent flexibility as a dynamic power source.

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DISCUSSION

Cycle Description

Figure 1 presents a basic flow diagram of a recuperated CBC for space power. Figure 2 illustrates the thermodynamic cycle. The recuperator is the key cycle modifier for achieving high cycle efficiency as well as a major contributor to the flexibility of design. As shown in the referenced figures, energy from an external heat source is used to heat the high-pressure gaseous working fluid to the maximum cycle temperature. The high-pressure gas is expanded through a turbine to produce useful electrical output power and drive the compressor. The turbine discharge gas is cooled, first in the recuperator heat exchanger and then the radiator, before being introduced into the compressor. The low-pressure gas is compressed to the highest cycle pressure and then heated at essentially constant pressure in the recuperator before being directed to the heater, thus completing the closed loop.

Flexibility of Design

Design flexibility of the CBC is evidenced by the fact that the design driver may be maximum cycle efficiency, minimum system weight and/or volume, minimum heat-rejection system size, cost, reliability, or a desirable combination of these. The major independent cycle parameters selected during the optimization process are:

- Compressor and turbine inlet temperature,
- Recuperator effectiveness (Er),
- Compressor pressure ratio (CPR),
- Pressure loss parameter (b),
- Engine shaft speed (N),
- Compressor-specific speed (N_s),
- Choice of working fluids, and
- Molecular weight of working fluid.

Compressor inlet temperature (CIT), the lowest temperature level in the CBC circuit, is significant in terms of radiator sizing. While it is desirable to utilize a low CIT to improve cycle efficiency, a relatively large radiator size will result.

Turbine inlet temperature (TIT) is the maximum cycle temperature and contributes directly to cycle efficiency and specific power output. A maximum value may be limited either by the heat-source characteristics or the design materials and life criteria of the turbine.

Recuperator effectiveness (Er) is the ratio of heating provided to the compressed gas [heat source inlet temperature (HIT)-compressor discharge temperature (CDT)] to the maximum temperature differential available [turbine discharge temperature (TDT)-CDT]. A high effectiveness decreases the amount of thermal input required from the heat source with consequent increase of thermal efficiency.

Compressor pressure ratio (CPR) optimization is related to the maximum/minimum (TIT/CIT) cycle temperature levels and the recuperator effectiveness.

Typically a system will optimize with a CPR on the order of 2:1, which is readily achievable at high efficiency with a single centrifugal compressor stage. Similarly, this magnitude of pressure ratio for turbine expansion may be efficiently handled by a single-stage radial inflow or two-stage axial turbine.

CBC pressure level is usually defined at the highest level of compressor discharge pressure (CDP). For a given power requirement and other cycle parameters, increased pressure level will decrease the size of many components: primarily, the compressor, the turbine, and heat exchanger frontal area. In addition, increasing the operating speed of the turboalternator assembly will reduce the size of the compressor, alternator, and turbine. An optimum range of pressure level is determined by the specific speed and efficiency characteristics of the turbomachinery. Selected operational pressure levels follow a general trend of higher values for increased power rating.
The system utilizes a noble inert gas working fluid. This single-phase working fluid provides excellent heat-transport characteristics, ensures good compressor/turbine efficiencies, simplifies the heat source interface, and provides unparalleled compatibility with materials over a wide range of operating temperatures. Working fluid choices include, but are not limited to, neon, krypton, helium xenon (He-Xe), nitrogen, or argon. The choice of gas and its molecular weight are important design variables in the CBC design trade studies.

Garrett-developed design state-point and off-design computer programs utilize this flexibility for trade studies to optimize the CBC design for key application drivers. A program for optimizing design provides a direct graphic assessment of the impact of each variable over the maximum/minimum limits specified.

Flexibility of Operation

Flexibility of operation is afforded by:

- Excellent off-design performance;
- The use of a working fluid which is not limited by extreme temperatures or affected by zero gravity; and
- The ability to change the power level for a given design by changing working-fluid inventory, turbine operating speed, or turbine inlet temperature independently of each other.

The resultant flexibility of operation allows power turn-up or turn-down to meet nominal-to-peaking power requirements. The single-phase working fluid is stable over a wide temperature and pressure range consistent with broad power band operation. The aerodynamic components provide a relatively flat or constant stage efficiency over a wide range of working fluid inventory for constant-speed operation. Some space power applications require short durations of higher power, which could be supplied by temporarily increasing the operating pressure, temperature, and speed, then returning to normal operating parameters.

CBC operation in space power systems is also enhanced by its ease of starting restarting in space. With an alternator programmed as a starter, this feature provides additional reliability and options for power level changes in space. The start-up may also be accomplished by pressure injection of the working fluid into the heat source and expansion through the turbine wheel.

Another facet of operational flexibility involves the use of redundant CBC systems. Reliability becomes a key driver in the selection of space power systems as space missions become increasingly ambitious in terms of power levels and longer mission durations. Requirements for uninterrupted power for the duration of the mission add to the desirability of redundant units, either one of which could supply full power in event of failure of a single unit.

Redundancy may be accomplished in one of three ways: (1) two complete units capable of independent operation; (2) one system comprising two units sharing a common heat source and common radiator, but with other major components duplicated; each unit retains independent start and restart capability; and (3) one system having redundant alternators operating with a single compressor-turbine.

In a fully redundant system, one unit may be operated at the required power level with the other unit shut down on standby. An alternate approach for fixed energy sources would have both units operating in parallel at reduced power such as 50 percent of the required power level. Both units operate at reduced pressure, but at rated speed and TIT. Should one power-conversion loop shut down, a signal would cause the release of additional gas into the surviving loop. The working pressure in the surviving loop would increase so that the single unit would meet the full mission power requirement without interruption.

Flexibility of Energy Source Selection

The CBC with its single-phase, gas working fluid provides a simple interface compatible with any of the potential heat sources for space applications.

The single-phase gaseous working fluid is not pressure- or temperature-limited and therefore will not impact the cycle state-point, as found with two-phase fluid cycles. The CBC system is compatible with any heat source that provides thermal input to the working fluid, either directly or through an appropriate heat exchanger. Some of the heat source alternatives are discussed below.

Isotope Energy Source. Isotope-powered CBC systems for space, as shown in Figure 3, have been considered for several applications involving surveillance or communications applications, vehicles for deep space or solar system exploration, and space-based telescopes. This energy source supplies a fixed level of energy with a highly predictable, slow rate of energy decay. The isotope-powered system provides high-quality, uninterrupted power but is limited to approximately 10 kW, due to isotope-imposed packaging requirement.

Solar Energy Source. Solar dynamic CBC systems are under development for a variety of space applications, including the electrical power system for the NASA Space Station, shown in Figure 4. The heat source for this type of system includes three basic components: the collector/concentrator, the receiver, and thermal energy storage. Cycle heat rejection is provided by a pumped-loop radiator. This energy source is quite variable due to orbit altitude, sunlight, and dark or occult portions of a given orbit, as well as the seasonal variation in the solar insolation constant.

A critical issue for all solar space power systems is the requirement for continued power delivery during occultation periods. For solar dynamic power systems, this task is most effectively accomplished by the use of thermal energy storage. The latent heat of fusion of individual salts or eutectics is utilized to provide a nearly constant temperature source with reasonable containment volumes and weight. Because of its excellent performance over a wide range of temperatures, the CBC can meet high performance goals with a variety of thermal storage materials. The solar receiver and thermal energy storage are integrated with the heat-source heat exchanger to obtain optimum performance, minimum weight and minimum material temperatures.
Nuclear Energy Source. Nuclear-powered CBC systems have been suggested for variable energy source, higher-power, continuous-duty requirements. Two types of nuclear thermal reactors have been considered: (1) the fast-spectrum, liquid-metal-cooled design and (2) the compact high-temperature, gas-cooled reactor (HTGR), shown in Figure 5.

The liquid-metal-cooled fast reactor system includes cooling fluid inventory, redundant pumps and shielding. The reactor system and heat exchanger are placed behind the shield to assure shielding of the radiator from the liquid-metal coolant.

The HTGR coolant and the CBC power conversion working fluid can be the same fluid. The need for an intermediate heat exchanger is eliminated. The inert gas essentially eliminates working fluid radiation. The particle bed reactor configuration of the HTGR offers the lightest weight for a CBC system.

Chemical Energy Source. The chemical-thermal energy source in a closed-cycle system can be utilized for peaking power in conjunction with a fixed energy primary source, as shown in Figure 6. This secondary heat source can be added in series downstream of the primary source. An open-cycle H₂/O₂ combustion system can be utilized with overboard dumping. The system can be repeatedly used but results in effluent around the spacecraft and requires relatively large fuel storage volume and weight. For a limited number of peaking requirements, a series of small, stored-chemical-energy, closed-loop systems can be considered.

Flexibility for Future Growth

Excellent performance, efficiency, and specific weight (kg/kWe) currently are assured for smaller CBC systems up to one megawatt with a TIT of 1033K (1400F). Material selections are all production-characterized materials with the ability to assure 10- to 30-year mission duration requirements. In the future, significant weight and volume reductions and performance improvements of space power systems will be required to meet the requirements of smaller payloads, longer mission durations, and increased power levels. Operation at higher temperatures will be mandated. Materials, such as superalloys, composites, and ceramics which are in production (but not yet characterized for space environments) or those under development, can offer improvements of 20 to 30 percent in cycle performance. Generally, a bonus of weight reduction will also result. The inert working fluid of the CBC makes it compatible with an array of materials over a wide range of operating temperatures.

CONCLUSIONS

The CBC is ideally suited for space power applications with any of the proposed energy sources due to high cycle efficiency and the flexibilities of design and operation. System design simplicity, attendant reliability, and growth potential (as high-temperature materials are qualified for space) ensure CBC suitability for space power.

Long life, high reliability, and safety of the system result from the use of an inert, noble gas as the working fluid since it is extremely stable, single-phase, and non-toxic.

The operational capabilities of the system are outstanding. Start-up is achieved by operating the CBC alternator as a motor until the self-sustaining
The straightforward operation of a single-phase working-fluid system, such as the CBC, lends itself ideally to health monitoring where pressure, speed, and temperature-sensing accurately depicts the operational status of the power system.

Since the working fluids are single phase, zero-g testing can be completely simulated on the ground.

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