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Sensible Heat Receiver for Solar Dynamic Space Power System

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ABSTRACT

The growth of electrical power requirements for space missions has stimulated the development of power system concepts that are more efficient and lighter than the state-of-the-art technology. Solar dynamic power systems are being studied for such high power space missions.

A sensible heat receiver considered in this study uses a vapor grown carbon fiber-carbon (VGCF/C) composite as the thermal storage media and was designed for a 7 kW Brayton engine. The proposed heat receiver stores the required energy to power the system during eclipse in the VGCF/C composite. The heat receiver thermal analysis was conducted through the Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA) software package.

The sensible heat receiver compares well with other latent and advanced sensible heat receivers analyzed in other studies while avoiding the problems associated with latent heat storage salts and liquid metal heat pipes. The concept also satisfies the design requirements for a 7 kW Brayton engine system. The weight and size of the system can be optimized by changes in geometry and technology advances for this new material.

INTRODUCTION

The growth of electrical power requirements for space missions has initiated considerations of solar dynamic power systems (SDPS). In low earth orbit (LEO) this system offers the potential of less drag than photovoltaic power systems which will result in lower orbital maintenance propellant requirements.

The solar dynamic power system consists of a concentrating mirror, a heat receiver, a thermal energy storage material, a thermodynamic heat engine, an alternator, and a heat-rejection system. Solar energy is directed through the heat receiver aperture by the concentrator. The heat receiver transfers heat to the working fluid, which is then used to drive a heat engine. Three heat engines are under consideration: an Organic Rankine cycle, a Brayton cycle engine, and a free piston/linear-alternator Stirling cycle engine. The mechanical output power of the heat engine operates the alternator, which then produces electrical power. The excess heat is rejected to space by the radiator.

In LEO the space power receivers must store enough energy during the sun period (57 minutes) to allow the production of power during the eclipse portion of the orbit (36 minutes) [1]. In solar dynamic systems, thermal energy storage is accomplished by the latent heat of fusion of alkali metals or by sensible heat. The inorganic salts and mixtures of salts are very attractive for latent heat storage because of their high heat of fusion. The problem with the salt systems is their low thermal conductivity, volumetric expansion and compatibility with containment vessels.

The heat receiver contributes 36 percent of the total solar dynamic power mass. Currently, goals are directed to decrease the size and weight of the receiver, increase efficiency and reliability, and reduce the fabrication cost and complexity.

In the past, sensible heat receiver concepts have been larger and more massive than latent heat systems (such as lithium fluoride salts); however, new material technology developments could improve those systems and make them competitive. The last few years have witnessed the maturing of technology to produce vapor grown carbon fibers which have higher specific thermal conductivities than any other material ($0.93\ W/m^2/kg\text{-}K$ or 40 % higher than diamond) [2]. When these fibers are incorporated into carbon-carbon composites, they form a high thermal conductivity, low density material which is excellent for a solid heat pipe. Given that the specific heat of the fibers is also about 700 J/kg, this material may be very effective for sensible as opposed to latent heat storage in solar dynamic heat receivers.

The sensible heat receiver concept generated in this study uses vapor grown carbon fiber-carbon (VGCF/C) composite as the thermal energy storage media and was designed for a 7 kW Brayton engine. The objective of this study was to evaluate the thermal response of the VGCF/C as a sensible storage media. It is not our purpose either to provide a detailed design nor to optimize the heat receiver in this paper. A thermal analysis of this sensible heat receiver was conducted for 48 kW incident in the tubes that forms the heat receiver cavity. The proposed design was compared with other latent and advanced sensible heat receivers concepts.

HEAT RECEIVER ANALYSIS

The design requirements are similar to those specified for latent receiver studies [3], Table 1. The proposed heat receiver concept stores the required energy to power the system during the eclipse in the vapor grown carbon fibers-carbon (VGCF/C) composite. During the eclipse, the VGCF/C gives up heat to the working fluid which is a helium/xenon mixture.

TABLE 1. - BRAYTON RECEIVER CONDITIONS

Parameter	Condition
Power conversion system efficiency	29 percent
Working fluid heat load	24.1 kW
Working fluid	Helium/Xenon mixture molecular weight = 40
Inlet fluid temperature	892 K
Outlet fluid temperature	1089 K
Flow rate	0.2536 kg/s

Although carbon-carbon composites have been in use for many years, VGCF/C is a qualitatively different material. The thermal conductivity of VGCF is about 2000 W/m-K, as compared with a thermal conductivity of less than 10 W/m-K for polyacrylonitrile (PAN), based carbon fibers which are used in conventional aircraft. This is due to the highly crystalline nature of the fibers. There is a strength penalty, with respect to PAN based fibers, to be paid for this increased thermal conductivity, but they still retain an ultimate tensile strength greater than 1 GPa, more than adequate for a heat receiver. VGCF/C is still an experimental material, yet test coupons with relatively low density (0.86) still had thermal conductivity as high as copper with one-tenth the mass. Thermal conductivity of VGCF/C can be expected to increase as fabrication techniques become more refined. Bulk densities of 1.80 to 1.85 g/cm^3 are anticipated as a result of the development efforts.

The heat receiver thermal analysis was conducted through the Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA) software package [4]. This software system possesses capabilities that make it suited for solving lumped parameter representations of physical problems governed by diffusion-type equations. The system was originally designed as a general thermal analyzer that utilizes resistor-capacitor network representations of thermal systems.

The receiver, figure 1, consists of twenty thermal energy storage tubes of 182.88 cm length with a 10.16 cm outside diameter and the working fluid (helium/xenon gas mixture) flowing inside of the tube (2.54 cm inside diameter).

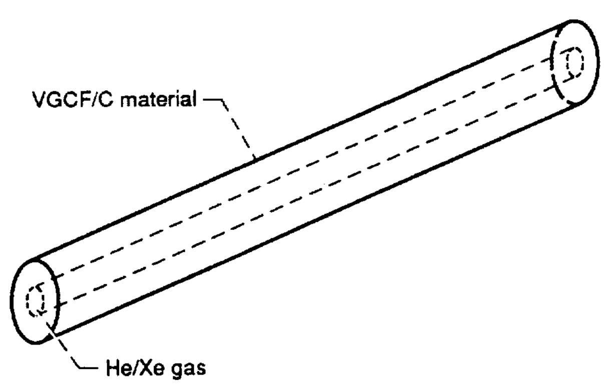

Figure 1.—Schematic of the VGCF/C composite tube.

Thermophysical properties of the VGCF/C composite are presented in Table 2 [5]. The VGCF/C has high thermal conductivity and might be used up to an operating temperature of 3500 K or higher. Properties of this material are expected to improve since it is in the developmental stage.

TABLE 2. - THERMOPHYSICAL PROPERTIES OF VGCF/C COMPOSITE

Properties	Fibers	Composite
Thermal diffusivity, cm^2/s	4.45	5.01
Density, g/cc	2.09	0.86 (41 % void)
Thermal conductivity, W/cm-°C	6.55	3.01

A heat load of 48 kW, uniformly distributed along the tubes, was selected for this analysis. The thermal analysis of the tubes was performed under the following assumptions:

(a) inlet working fluid temperature of 892 K
(b) tubular heat transfer surfaces
(c) initial tube temperature of 1000 K
(d) radiation through the aperture was not considered
(e) surface losses were not considered

The size of the tubes were based on earlier receiver designs [3, 6]. The amount of VGCF/C required for the specified tubes length and diameter is 239 kg.

In figure 2, the lumped parameter/resistor-capacitor network which represents the thermal energy storage tube is presented. The mass of the tube has been divided into regions which are called nodes, and each node has been assigned an arbitrary identification number. The heat conduction paths are shown schematically as resistors, which are called conductors, also have an arbitrary identification number assigned. A heat source Q is shown entering each external node.

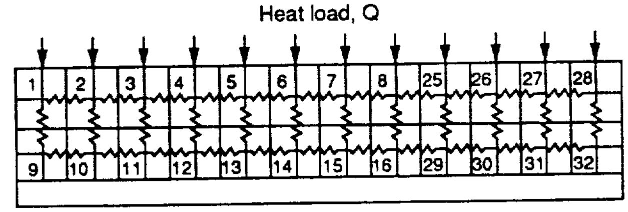

Figure 2.—Schematic of the resistor/capacitor network.

Two basic conductors were used: linear (conduction, convection) and a radiation type conductor. The conductance of a linear conductor is input in units of energy per unit time per unit degree and the heat flow rate through such a conductor is calculated in the network solution routines as:

$$Q = G\ (T_i - T_j)$$

where Q is the heat rate, G is the conductance, and T is the temperature. The conductance for heat transfer by conduction, convection, and mass flow are defined, respectivly, as:

$$G = k\ A_c/L$$

$$G = h\ A_s$$

$$G = m\ C_p$$

where k is the thermal conductivity, A_c is the cross sectional area, L is the length of the conduction path, h is the convection heat transfer coefficient, A_s is the surface area, m is the mass flow rate, and C_p is the specific heat of the working fluid. All of these conductors were used for the thermal analysis.

The conductance of a radiation conductor is input in units of energy per unit time per degree to the fourth, and is defined as:

$$G = \sigma F A_s$$

where σ is the Stefan-Boltzmann constant, and F is the gray-body emittance (0.85 for VGCF/C).

The convection heat transfer coefficient, h, was calculated using the relation by Dittus and Boelter [7]:

$$Nu = h\, d/k_f = 0.023\, Re^{0.8}\, Pr^{0.4}$$

or

$$h = 0.023\, Re^{0.8}\, Pr^{0.4}\, (k_f/d)$$

where Nu is the Nusselt number, d is the inside diameter (2.54 cm), k_f is the thermal conductivity of the working fluid. The Reynolds (Re) and Prandlt (Pr) number are defined as:

$$Re = v\, d\ /\mu$$
$$Pr = C_p\, \mu/\, k_f$$

where v is the fluid velocity, μ is the fluid viscosity, and is the fluid density. Using this correlation, the heat transfer coefficient obtained is:

$$h = 124\ W/m^2\text{-}K$$

The inlet temperature of the working fluid specified, 892 K, is based on the advanced solar dynamic system for the Brayton engine cycle.

Since a transient analysis was desired, a routine from the SINDA's 85 library which performs transient analysis by the Forward-Backward (FWDBCK) finite differencing technique was used [4].

RESULTS

The thermal response of the working fluid inside the VGGF/C composite is presented in figure 3. The results shows that the exit temperature of the fluid met the design goals of 1089 K at the end of the eclipse. This concept requires a temperature gradient of 300 K in the VGCF/C to meet the design goals. One of the main advantages of this material is the high thermal conductivity, which provides an excellent heat path from the outside walls to the fluid.

The use of this material with a He/Xe gas mixture requires protection of the tubes's inside diameter against possible diffusion of the gas mixture through the composite. Studies conducted at the NASA Lewis Research Center [8] found good adhesion between graphite and tungsten at high temperatures, which makes tungsten a very attractive candidate for this purpose.

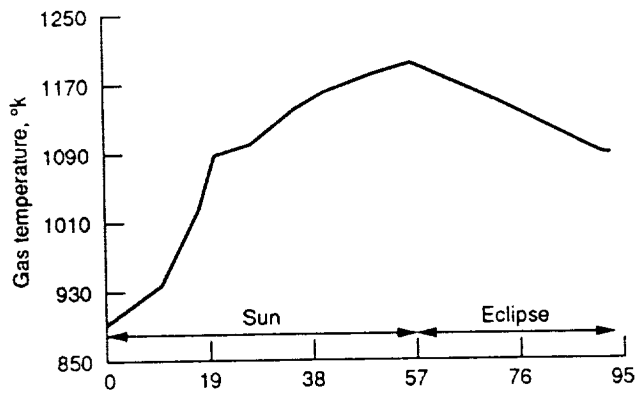

Figure 3.—Helium/Xenon gas temperature as function of time.

Table 3 presents a comparison between the VGCF/C sensible heat design and other latent and sensible heat advanced heat receivers. The VGCF/C composite heat receiver compares well with other designs. The weight and size of this concept can be further reduced by optimization of the tube size and cavity dimensions. Also, the expected advances in this technology would provide additional means to improve the system performance such as, higher composite densities, use of the material anisotropy thermal conductivity, and others.

TABLE 3. - HEAT RECEIVER WEIGHTS COMPARISON

Receiver	Weight, kg
1. Baseline [3]	461
2. Packed bed [3]	334
3. Plate-fin [3]	382
4. Heat pipe [3]	353
5. Lithium sensible heat [9]	406
6. VGCF/C sensible heat	358

Figure 4 illustrates the cost of a space mission as function of weight for the heat receivers in Table 3. One of the critical issues for space flight is weight and volume of the systems, due to transportation cost and cargo space on the space vehicle. In addition to reduction in weight when compared to the baseline, the VGCF/C heat receiver eliminates all the issues related to phase change materials, such as void formation, and thermal racheting.

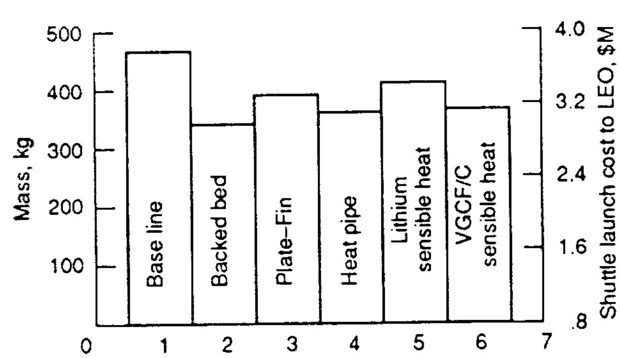

Figure 4.—Launch costs as a function of heat receiver type.

CONCLUSIONS

The sensible heat receiver evaluated in this study uses vapor grown carbon fiber-carbon (VGCF/C) composite as the thermal energy storage media and was designed for a 7 kW system (Brayton engine). The thermal analysis of this concept was analyzed through the SINDA software package.

This concept compares well with other latent and advanced sensible heat receivers, while avoiding the problems asociated with latent heat storage salts and liquid metal heat pipes.

At this time VGCF/C is making the transition from a laboratory curiosity to an engineering material. The process has matured to the point that it is feasible to fabricate products which require tens to hundreds of grams of material. Fabrication techniques, however, are still being developed, and great advances are expected to materialize over the next few years which will enable adequate scale-up to fabricate devices such as the heat receiver described in this study.

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The growth of electrical power requirements for space missions has stimulated the development of power system concepts that are more efficient and lighter than the state-of-the-art technology. Solar dynamic power systems are being studied for such high power space missions. A sensible heat receiver considered in this study uses a vapor grown carbon fiber-carbon (VGCF/C) composite as the thermal storage media and was designed for a 7 kW Brayton engine. The proposed heat receiver stores the required energy to power the system during eclipse in the VGCF/C composite. The heat receiver thermal analysis was conducted through the Systems Improved Numerical Differencing Analyzer and Fluid Integrator (SINDA) software package. The sensible heat receiver compares well with other latent and advanced sensible heat receivers analyzed in other studies while avoiding the problems associated with latent heat storage salts and liquid metal heat pipes. The concept also satisfies the design requirements for a 7 kW Brayton engine system. The weight and size of the system can be optimized by changes in geometry and technology advances for this new material.

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