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A New Solar Thermal Receiver Utilizing Small Particles

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A NEW SOLAR THERMAL RECEIVER UTILIZING SMALL PARTICLES

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ABSTRACT

A new type of solar thermal receiver is being developed that utilizes a dispersion of very small particles suspended is a gas to absorb concentrated sunlight. An open Brayton cycle heat engine utilizing a Small Particle Heat Exchange Receiver (SPHER) operates by injecting a very small mass of submicron carbon particles into the compressed gas stream before it enters the receiver. The particles absorb the radiation, release the heat to the surrounding gas, and are vaporized. The phase change (vaporization) stabilizes the output temperature and eliminates the particles from the gas stream before it passes into the exhaust turbine. Two receiver designs have been investigated and both have theoretical efficiencies greater than 90% at output gas temperatures of 1000^{o} C. This design gives thermal cycle efficiencies in excess of 40%. Calculations of the optical and thermal processes have been performed and the concept has been demonstrated in the laboratory.

1. INTRODUCTION

Solar energy is being considered as a practical source of high temperatures to operate very efficient heat engines. The success or failure of the solar thermal power program may be determined by how well we match the technology to harness the resource with the characteristics of that resource in the most efficient and practical way. Many current concepts for conversion of sunlight to heat are based on traditional, non-solar technologies. The work that is discussed here involves a novel approach that matches the characteristics of concentrated sunlight to the requirement of heating a gas.

The purpose of the work is to develop a new type of solar thermal receiver that utilizes a dispersion of very small particles suspended in a gas to absorb the radiant energy from concentrated sunlight. An open Brayton cycle heat engine utilizing a Small Particle Heat Exchange Receiver (SPHER) operates by compressing ambient air and injecting a very small mass of fine particles into the gas stream (fig. 1). The air-particle mixture enters a transparent heating chamber into which the concentrated solar flux is directed. The particles absorb the radiation and because of their very large surface area, quickly transfer the heat to the surrounding gas. The air-particle mixture continues to heat until the particles vaporize. The heated air passes through an expansion turbine to provide power for the compressor and load. The exhaust gas is then routed to a recuperator before being exhausted.

The starting point for the concept of the small particle heat exchanger is the desire to maximize the transfer of solar radiant energy to sensible heat in the gas. The fundamental difference in the approach results in significant advantages over other types of solar receiver designs.

The outstanding characteristic of these small particles is the extremely large surface area per unit mass of absorber material. (One gram of particles for this application has a surface area of approximately 70 square meters.) Thus, as light traverses the chamber, it encounters an absorbing surface that has an area many times larger than the chamber opening. This results in a high absorption coefficient for the incoming sunlight and a high optical efficiency for the receiver. Since the infrared reradiation from the heated particle-gas mixture will be inhibited from leaving the chamber by the window, and the window is at a lower temperature than the gas, the receiver will have a high overall efficiency. One consequence of this is that the receiver is not restricted to a cavity type, but may be built to be illuminated from all sides.

Another advantage of the very large surface area of the particles occurs because the effectiveness of a heat exchanger is proportional to its surface area. The combination of the large surface area and the small size of the particles insures that the particle temperature stays to within a fraction of a degree of the gas temperature. Thus, the highest temperature present in the receiver is essentially that of the gas. This results in considerably lower radiant temperatures in the chamber compared to other solar receivers that produce gas of the same temperature.

There are several other important advantages to the use of small particles as heat exchanger elements. There is no need for heavy and complex heat exchanger elements, since the receiver basically consists of a hollow chamber with a window, resulting in a very light weight structure.

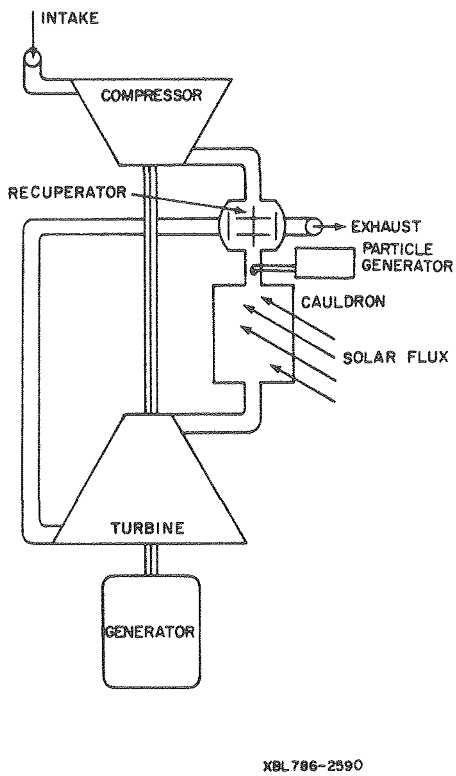

Fig. 1 Open cycle Brayton system utilizing a small particle heat exchanger

Because the heat exchanger is uniformly distributed throughout the chamber, it is not necessary to pump the gas through pipes or small orifices. This has the effect of considerably reducing the amount of energy required to overcome pressure losses.

Since the heat exchanger is vaporized in the process of performing its function, there are no problems associated with maintenance, failures, heat stress, or corrosion that occur with conventional heat exchanger elements.

Applications of the small particle heat exchanger are not necessarily limited to Brayton cycle heat engines. Since there are no temperature limitations on the heat exchanger in the usual sense, there may be applications to the field of high temperature solar process heat. The ultimate temperatures achievable are limited only by the chamber walls, the window (if pressurized operation is desired) and the second law of thermodynamics. It appears that temperatures in excess of 2000°C are achievable.

The operation of the various subsystems has been investigated and the overall efficiencies and system parameters were determined. Calculations were performed to quantify the optical and physical processes of absorption and heating of the particles. A variety of related considerations were investigated, including particle production methods, window and chamber designs, hybrid fossil-solar compatibility, as well as environmental and safety factors. A modest laboratory apparatus was built that successfully demonstrated the concept.

In the analysis that follows, the important stages of the system are discussed. These include the small particle absorption process, the heat transfer to the gas, the particle choices and the operating parameters of the receiver.

2. SMALL PARTICLE OPTICS

Light passing through a medium containing small particles may be scattered or absorbed. If the particles are sufficiently small and are composed of material that is intrinsically absorbing, the extinction (name given to the combined effect of scattering and absorption) of a beam of light passing through the medium will be dominated by absorption (1). This a is desirable condition for solar applications because less light will be scattered out of the receiver and the collection efficiency will be higher.

The attenuation of a beam of light propagating through a scattering medium is given by Beer's law;

$$\frac{I}{I_0} = e^{-\beta x} \qquad (1)$$

where x is the distance traversed and β is the volume total scattering coefficient. The coefficient β can be divided into an absorption and a scattering contribution, $\beta = \beta_{abs} + \beta_{sca}$. These quantities may be expressed in terms of the number of particles per unit volume N_i, with absorption efficiency (ratio of absorption cross section to geometrical cross section) Q_{abs_i} and cross sectional area A_i as,

$$\beta_{abs} = \sum_i N_i Q_{abs_i} A_i . \qquad (2)$$

To determine the mass per unit volume M of particles necessary to produce a given absorption as a function of particle size, note that,

$$M = \sum_i N_i V_i \rho \qquad (3)$$

where ρ and V_i give the volume and density of the i^{th} particle. If L is the absorption length available in the receiver and we desire an 1/e absorption for a one way trip ($1/e^2$ for a round trip) and assume all the particles are uniform sized spheres of radius r we obtain from eqns. 1, 2, and 3

$$M = \frac{4r\rho}{3Q_{abs}L}. \qquad (4)$$

This equation is applicable to any particle size. For absorbing particles with sizes greater than $2r/\lambda \sim 1$, Q_{abs} is roughly constant with increasing particle size (2) and the mass of particles necessary to produce a given absorption is proportional to r. The absorption efficiency (ratio of the absorption cross section to geometrical cross section) for small (Rayleigh) particles is given by

$$Q_{abs} = 4 \cdot \frac{2\pi r}{\lambda} \; \mathrm{Im}\left[\frac{m^2 - 1}{m^2 + 2}\right], \qquad (5)$$

where λ is the wavelength of light and m the complex index of refraction. Thus for the case of Rayleigh scattering Eq. (5) indicates that Q_{abs} is proportional to r. Thus, the mass of particles required for a given absorption becomes a constant for small particle sizes. This result is plotted in a qualitative way in Fig. 2 and indicates that to minimize the material usage the particles should be small enough to be Rayleigh scatterers. For carbon this size is less than 0.1 micrometer in diameter. To calculate the minimum mass loading required for a chamber with a depth L, combine equation 4 and 5 to obtain,

$$M = \frac{\rho\lambda}{6\pi\, L\, \mathrm{Im}\left[\frac{m^2 - 1}{m^2 + 2}\right]}. \qquad (6)$$

Using data for the optical constants of arc evaporated carbon (3) to determine the solar weighted average for Q_{abs} yields a value for M of 0.37 gms/m^3. This is a very low mass loading.

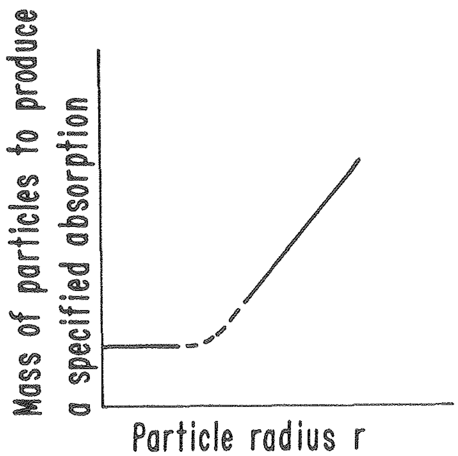

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Fig. 2. Schematic illustration of the dependence of the mass of particles to produce a specified absorption as a function of particle radius.

In the analysis above, it has been demonstrated that small amounts of fine particles can act as effective absorbers of sunlight. However the optical efficiency of the receiver is related to the amount of light scattered back out of receiver. To investigate this consider the definition of the albedo for single scattering, A. It is given by

$$A = \frac{Q_{sca}}{Q_{sca} + Q_{abs}} \qquad (7)$$

and is a measure of the relative probability of a particle scattering a photon, compared to the particle absorbing or scattering a photon. The albedo calculated from equation 7 for particles .05 micrometers in diameter at a wavelength of 0.52 micometers is 0.038. The loss from the receiver will be considerably less than this because of solid angle and multiple scattering effects (4). Thus the optical efficiency (neglecting the window) for small particles is greater than 96%.

A laboratory program has been started to measure the particle absorption efficiencies utilizing direct heating and photoacoustic techniques. A simple apparatus was constructed that successfully demonstrated the concept of a small particle heat exchanger.

3. PARTICLE TEMPERATURES

It is of interest to determine the temperature difference between the particles and the gas for various operating conditions to ascertain how effectively the particles act as heat exchangers. If the temperature differences are small the particles will be good heat exchangers. The heat capacity of the particles is so small that it is possible to treat the particles as if they are in thermodynamic equilibrium and consider only the in and out going fluxes in order to calculate their temperature.

The condition for energetic equilibrium of a particle in a gas is given by

$$P_A - P_E - P_C - P_S = 0 \qquad (3)$$

where P_A is the power absorbed by the particle, P_E is the power emitted by radiation, P_C is the power lost due to collisions with the gas molecules and P_S is the power lost by sublimation. The particle cooling due to sublimation is neglected in this treatment. This equation may be solved by substituting the proper expressions for the radiant and conductive terms and using an iterative technique to balance the equation (4,5).

The results of the calculation are given in Table I for particles of 0.05 micrometers diameter and optical constants given in refs. 3 and 6. The incoming solar flux was assumed to be 1 Kw/m^2 and a concentration of 2000 was picked as typical of advanced concept solar power plants. For conditions of interest, the particle temperature never rises over a fraction of one degree Kelvin above the gas temperature. The table also indicates that below 1500°K the heat loss process is dominated by conduction.

Table I

Temperature differences between particles and gas and the ratio of power loss by emission and conduction for various temperatures at a pressure of 6 atmospheres

T_p (°K)	$T_p - T_g$ (°K)	P_E/P_c
600	0.090	0.0004
1000	0.080	0.008
1500	0.050	0.11
2000	0.023	1.1
2250	~0	(all emission)

The last temperature entry indicates that for the assumed conditions the maximum attainable temperature is about 2250°K. This value will depend on the particle size and will increase for smaller particles.

4. PARTICLE PRODUCTION AND REACTION

Small particles for heat exchanger applications may be produced in several ways. Dispersion of premanufactured powders is extremely difficult due to the tendency of small particles to agglomerate. The best approach is to produce the particles, entrain them in a gas system, and conduct them to an injection port, thus minimizing the chances for agglomeration. The best methods for producing particles for this application are high intensity arcs, thermal decomposition of hydrocarbons and high temperature pyrolysis of organic resins (4). There is a considerable variation in the properties of carbon particles that depends on their method of production. The most important physical characteristic of the carbon particles for the present application is the oxidation rate at a given temperature in air. While little experimental data are available for small particles, there are wide variations in bulk reaction rates for different form of carbon. Calculations based on published bulk rates (7) indicate that at 1000°C the times for complete combustion of particles with a diameter of 0.1 micrometer vary from approximately 20 microseconds for baked carbon to about 0.5 second for vitreous carbon. Thus, it appears that good candidates exist for a wide variety of operating conditions. An experimental program is under way to determine the correct match of particles and applications.

RECEIVER DESIGN

The function of the window of the heat exchanger is to allow the solar flux to enter the chamber, to confine the pressurized gas-particle mixture and to prevent substantial losses of heat by infrared radiation. The best candidates are pyrex and quartz. These materials meet the necessary temperature requirements, pass nearly the entire solar spectrum and are opaque to radiation with wavelengths greater than 4 micrometers. This opacity in the infrared and the lower window temperatures will reduce the heat losses by radiation. Receiver designs utilizing both single and double windows have been investigated. The double window design shows lower thermal losses while the single window has higher optical efficiency. Figure 3 illustrates the basic components of a receiver that would be used as a side facing cavity. The window is a cylindrical section facing inward to insure the window remains in compression.

Some losses will occur due to reflection from the window surfaces. This is about 4% per surface for untreated glass. This reflectivity may be substantially reduced by the use of anti-reflection coatings or by controlling the surface morphology. Borosilicate glasses have been prepared that have only about 1/2 percent solar reflectivity for two surfaces (3). Using this technology the optical efficiency of the receiver will be more than 95% without the use of a cavity.

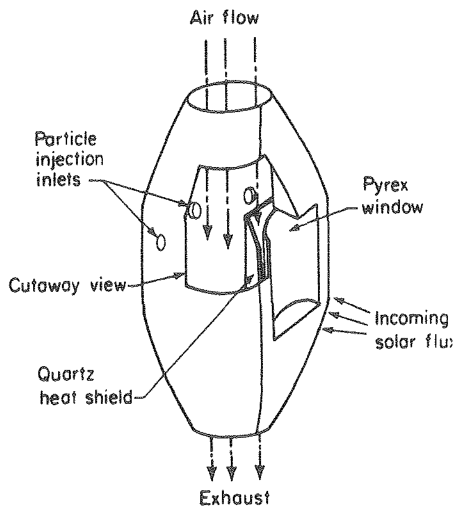

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Fig. 3. Conceptual design of the heating chamber for a small particle heat exchanger.

6. OPERATING CONDITIONS

To determine some of the operating characteristics of a plant incorporating SPHER, the module size is assumed to be 10 Mwe. The results are based on an assumed pressure ratio of four and 80% recuperation of the exhaust heat. For a gas temperature of 980°C the plant efficiency is over 40%. The mass of gas passing through the plant would be about 45 Kg/sec. At these flow rates the amount of carbon needed is only about 15 Kg/hr. This modest requirement for carbon can easily be met by the particle production methods discussed previously. The amount of CO_2 produced from this carbon is about equivalent to that generated by a single automobile. Thus, the environmental impact of this aspect of the plant is minimal.

7. CONCLUSIONS

A new type of solar thermal receiver utilizing small particles as the heat exchanger is proposed. The analysis of the scattering properties of small particles indicates the diameter of the particles should be 0.1 micrometers or less to maximize the absorption per unit mass. Carbon is suggested as the ideal particle composition because of its optical, chemical and physical properties. An analysis of the particle heating indicates that the particle temperature stays very near to that of the gas. The operating temperature of the particle-gas mixture is determined by the vaporization rate of the carbon allotrope used to make the particles. Several methods of producing the particles appear feasible. The amount of material needed for the operation of a solar power plant is very small. Plant efficiencies in excess of 40% appear feasible without the use of cooling towers or bottoming cycles. The use of small particles as heat exchanger elements was demonstrated on a small scale in the laboratory.

8. ACKNOWLEDGEMENTS

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