Title
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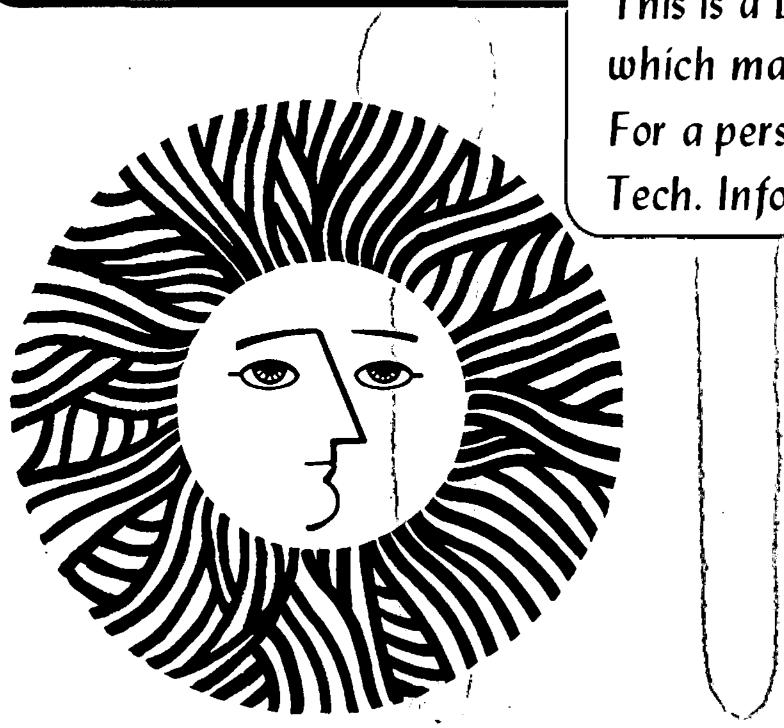

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ABSTRACT

This paper describes the development of a high temperature solar thermal gas receiver using direct absorption of concentrated sunlight by a suspension of small carbon particles. The Small Particle Heat Exchange Receiver (SPHER) can be used to power a Brayton cycle engine, supply industrial process heat or heat a gas to provide energy for a chemical reaction. The advantages are simplicity, low pressure loss, light weight, and high optical efficiency. The experimental and theoretical progress in the design of a 30 kW thermal test receiver is discussed.

KEYWORDS

Solar thermal; gas receiver; high temperature; direct absorption; small particles; heat exchanger; solar power; industrial process heat.

INTRODUCTION

The solar resource has quite different characteristics from traditional power sources that present day energy conversion technology is based upon. Sunlight arrives on earth in the form of pure electromagnetic radiation and is characteristic of a source with much higher temperature than any other present day energy supply. These two features distinguish solar from traditional energy sources. When seeking more effective ways to utilize this resource it is important to reevaluate energy conversion techniques in light of these differences. A simple adaptation of conventional heat exchange equipment often is not the best approach. The work described here utilizes a novel approach to match the unique characteristics of concentrated sunlight to the requirement of heating a gas.

The Small Particle Heat Exchange Receiver (SPHER) operates by injecting a very small mass of ultrafine carbon particles into a gas stream and exposing the suspension to sunlight that is focused through a window (Hunt, 1979). The particles absorb the sunlight and act as very efficient heat exchangers to transfer the heat to the gas. The particles

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are very small and therefore not significantly affected by gravitational or inertial forces; they are effectively part of the gas. An extremely small mass of these particles provides an enormous surface area for both solar collection and heat exchange. The use of small particles to absorb radiation is very effective because the interaction of sunlight with matter is dominated by absorption on surfaces.

After the particles have absorbed the sunlight, they transfer the heat to the surrounding gas with a very small temperature difference. The particles continue to heat until they react chemically with the gas or vaporize. For gases containing oxygen, the maximum output temperature is determined by the oxidation rate of the carbon particles. The particles may be used in a once through mode because of the very low requirement for carbon. The receiver can provide high temperature gas to operate a gas turbine or for use in industrial process heat applications. The advantages of this type of receiver are its simplicity, light weight, low pressure loss, and high efficiency. Other advantages to this approach are that it allows the chamber to operate at a lower temperature for a given gas temperature and there are no problems associated with the heat exchanger life time. The SPHER concept is suitable for a wide range of sizes and a variety of applications.

In the next section the major considerations in the use of small particles as heat exchangers are summarized. The following section contains a discussion of the development of the concept. The design and operating characteristics of a 30 kw thermal system to be tested at the Advanced Components Test Facility at Georgia Institute of Technology in Atlanta, Georgia are discussed.

CONSIDERATIONS IN DIRECT ABSORPTION RECEIVERS

Optical Properties of Small Particle Suspensions

The optical properties of a small particle suspension can be tailored to a given application by choosing the material, size, and shape of the particles. Carbon is ideal for a solar absorber because of its intense blackness when finely divided. The blackness results from a combination of high absorption and low scattering. In the infrared, the emissivity of carbon particle suspensions becomes significantly smaller for two reasons. First, the intrinsic absorption of carbon decreases significantly. Second, particle size effects cause the emissivity to decrease with the cube of the ratio of particle size to wavelength (van de Hulst, 1957). Therefore a suspension of small carbon particles has inherent properties of high visible absorption and low infrared emissivity, in other words, a selective absorber.

Light passing through a suspension of small particles is absorbed and scattered. The attenuation of a plane parallel beam of light is given by Beer's law;

$$I = I_o \exp(-Mgx). \quad (1)$$

The initial and final intensities are given by I_o and I respectively, the mass per unit volume of particles is M, the extinction cross section per unit mass is g and the distance traveled is x. The mass of particles, M_r, required to absorb a fraction of 1/e in a single pass through a suspension of thickness t is given by;

$$M_r = 1/gt = (4\rho r/3t)\int_0^\infty F_s(\lambda)\, Q_{abs}(\lambda)\, d\lambda / \int_0^\infty F_s(\lambda)\, d\lambda \qquad (2)$$

where r is the radius and ρ is the density of the particle, Q_{abs} is the absorption efficiency, and F_s is the spectral flux density incident on the particle from the collector, and λ is the wavelength of light (Hunt 1980). The mass of absorbing particles to obtain a given extinction is dependent on particle size, as illustrated in Fig. 1. Note that at small radii the mass goes to a limiting value; for large sizes the mass increases linearly with size. The region between is indicated with a dotted line and depends on the details of the size distribution, particle shape and dielectric function. Measurements on the particles produced in the laboratory indicate that they are in the intermediate size range and that the required mass is about one quarter of that for small sizes, as indicated in the figure. The maximum absorption per unit mass occurs for particle sizes about 0.1 micrometer. The absolute amount of mass required to produce significant absorption in a one meter depth is extremely small. In typical applications the carbon use rate is between one tenth and one percent of the mass of fossil fuel required to operate a plant of similar power (e.g. 5 Kg/hr to heat gas for a 10 Mw_e turbine.) From the economic point of view, the cost of the carbon is about one percent of the value of the electricity produced.

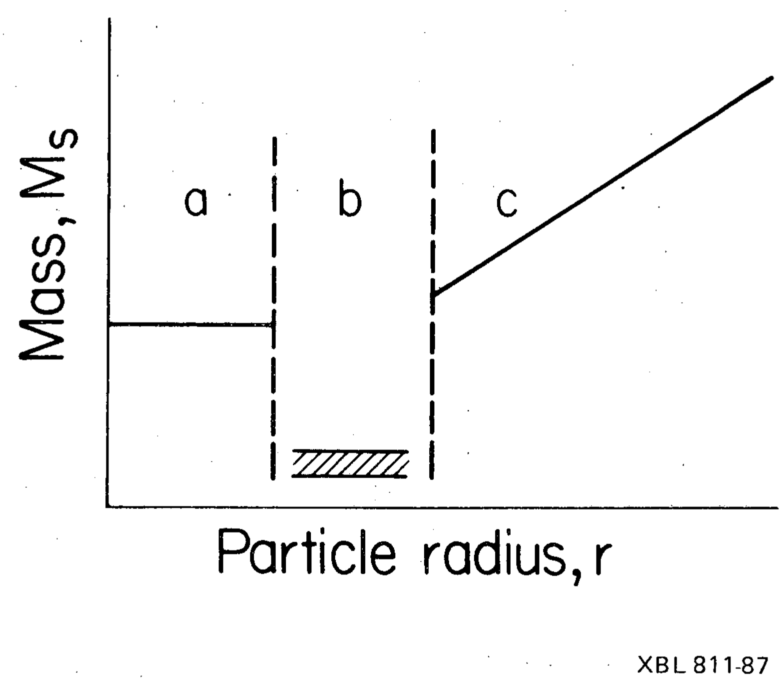

Fig. 1. Mass of particles required to produce a specified absorption vs. particle radius.

Thermal Properties of Small Particles

The combination of large surface area and small size of the particles insures very efficient heat exchange between the gas and particles. Calculations based on a mass transfer model indicate that the particle temperature stays to within a fraction of a degree of the gas temperature (Hunt, 1979). Thus the highest temperature present in the receiver is is essentially that of the working gas. This results in significantly lower radiant temperatures in the chamber compared to other solar receivers that produce gas of the same temperature.

Particle Production and Oxidation

Several methods for producing the particles have been explored at LBL. The most successful method relies on the pyrolysis of a hydrocarbon gas to produce the particles. The results of the experimental work on pyrolysis will be discussed in more detail in the next section.

The oxidation rate of carbon in air determines the highest temperature that can be reached for a given residence time in the receiver. Calculations based on bulk reaction rates indicate that the time for a particle to oxidize at a given temperature depends on the allotrope of carbon and varies over five orders of magnitude. These calculations indicate that particles of 0.1 micrometer radius will survive long enough at 1000^{o} C to act as effective heat exchangers.

System Studies

Base line designs have been explored for SPHER for power ratings from 10 Kw to 10 Mw. A detailed analysis of the efficiency of a 5 MW thermal receiver with a 1.7 meter diameter window established the feasibility of the system and determined the efficiency (Fisk, Wroblewski, and Hunt, 1980). A receiver using a single window with an etched antireflection coating was shown to have an efficiency of 93.6% at 1000^{o} C.

DEVELOPMENT OF A 30 KW SOLAR RECEIVER

An experimental receiver is being designed and fabricated at LBL to be tested at the Advanced Components Test Facility at the Georgia Institute of Technology. A hollow, windowed test chamber is being designed to match the flux characteristics of the facility. A particle generator is being developed for field use to supply carbon particles of the proper size and at the correct rate.

Chamber Design

The goal for the design of a direct absorption receiver is to maximize the solar flux that is absorbed by the gas particle mixture, while providing an efficient and economical structure. Because the absorption of solar flux takes place within a volume, the shape of the receiver chamber is determined by the flux density contours from the collector, modified by the absorption of the particle suspension. The gas-particle suspension is injected along the sides of the receiver to help in cooling the walls of the receiver. The gas exit from the chamber should be near the region of highest flux to maximize the output gas temperature. The size of the receiver is determined by a trade-off between operating costs of providing the carbon flow and the capitol costs associated with the dimensions of the chamber.

To determine the optimum chamber shape, the flux profiles from the collector must be determined. Measurements of the flux density in the volume behind the focus are very helpful in this regard, although analytic models or simple geometrical arguments will give enough information for preliminary designs. The rate of flux fall off is determined by the convolution of the unperturbed flux profiles and the absorption, integrated over the paths to a given point from the receiver opening. If the particle density within the chamber is uniform, or if an average density is determined, an approximate value for the flux at the rear wall of the chamber can be obtained from Equation 1.

The method outlined above can be used to determine the flux on the rear walls of receiver. The receiver dimensions and particle densities should be chosen so as to reduce the flux at the rear to a level compatible with the material capabilities and cooling environment. If the cooler incoming gas is injected at the back the chamber size can be reduced.

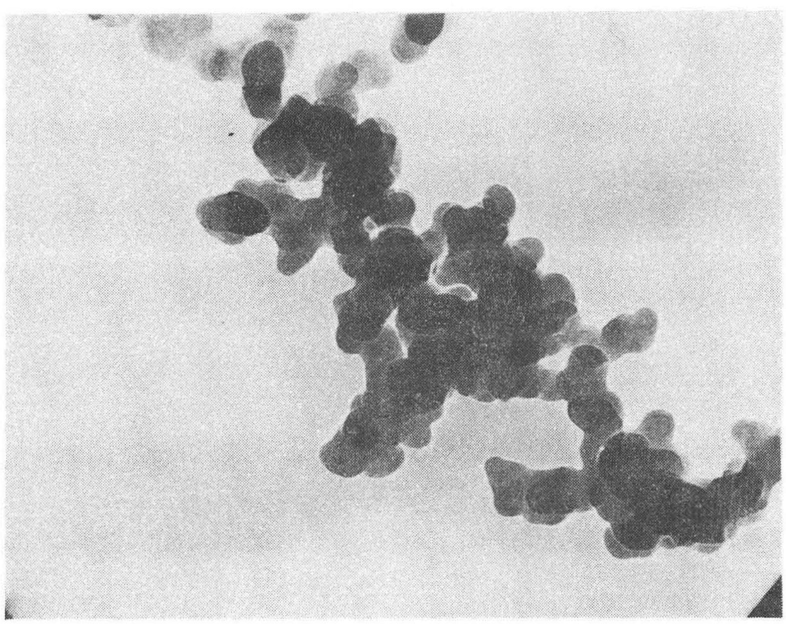

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Fig. 2. Transmission electron micrograph of carbon particles from the pyrolysis generator.

Particle Generator

An experimental program has been underway at LBL to develop techniques of particle generation and to characterize the optical, physical and chemical properties of the particle suspensions. It was determined early in the program that it is very difficult to obtain finely divided particle suspensions by redispersing commercially available carbon into a gas. A pyrolysis technique has been found to be the most suitable method for the generation of carbon suspensions for use with a 30 KW receiver. A hydrocarbon gas is injected into a heated region to decompose the gas into carbon and hydrogen. The technique was easily scaled to the flow rates necessary to absorb 30 Kw of thermal power in an absorption distance of 70 centimeters. A transmission electron micrograph of collected carbon particles is shown in Fig. 2. The individual particles are less than 0.1 micron in diameter. The collected particles show a chain-like structure that is likely an artifact of the collection technique. These samples were photographed at the edges of the openings of an electron microscope grid, and therefore had to be connected together to be collected.

During the development of the particle generator, part of the output was routed to a chamber where the transmission of the suspension was monitored continuously. Membrane filters were used to collect samples for weighing. The volume of gas corresponding to the sample was measured to determine the mass loading per unit volume. Samples were also regularly taken for viewing with scanning and transmission electron microscopes.

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