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ABSTRACT

The development of a new type of high temperature gas receiver that utilizes the direct absorption of concentrated solar flux by small particles suspended in the working fluid is described. 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 concentrated sunlight that is passed through a window. The receiver can provide power to a Brayton cycle engine or supply industrial process heat. The advantages of this receiver are its simplicity, low pressure loss, light weight, and high efficiency. The paper outlines the analytical and experimental results to date including the optics of the small particle absorbers, the analysis of receiver efficiency and recent experimental results.

1. INTRODUCTION

Solar energy is being considered as a serious alternative to fossil fuels as an energy source to operate heat engines and provide industrial process heat. A significant international program is underway to develop large scale solar thermal power plants capable of providing electricity to large segments of the population. A parallel effort is underway to utilize point focusing systems including parabolic dishes to operate small power systems. These systems can be deployed in any desired number to satisfy a wide range of power requirements.

The technology that underlies the current state of solar thermal conversion is mostly borrowed from more than one hundred years of experience with the use of fossil fuels. This has the advantage of being able to use the products of a mature technology. However, it has the disadvantage of biasing our thinking in terms of convection and conduction as dominate heat transfer mechanisms.

Concentrated sunlight represents a source of energy with quite different characteristics from those with which we gained our power conversion experience. The source derives from a radiating object with a black body temperature considerably higher than any other practical energy supply. The work described here involves a novel approach that matches the the characteristics of concentrated sunlight to the requirement of heating a gas.

The purpose of this work is to develop a new type of solar thermal receiver that is placed at the focus of a central tower or a parabolic dish concentrator system. The principle of operation differs from other advanced receiver designs under development in that the solar to thermal conversion is accomplished by a dispersion of ultra-fine particles suspended in a gas to absorb radiant energy from concentrated sunlight. The very large ratio of surface area to volume exhibited by small particles makes them ideally suited for this application.

The Small Particle Heat Exchange Receiver (SPHER) can be used to power a Brayton cycle engine, supply industrial process heat, or directly heat a gas to provide energy for a chemical reaction. The advantages of this type of gas receiver are its simplicity, low pressure loss, light weight, high optical efficiency, lower chamber temperatures for a given gas temperature and lack of problems associated with heat exchanger life time. The SPHER concept is suitable for a wide range of sizes and a variety of applications.

The approach is to investigate the particle production methods, study the optical and physical processes of absorption and heating of the particles, design and build a receiver chamber and conduct laboratory and field tests of the complete system. 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.

This paper describes the important features of the concept, the optical analysis of small particles as a heat exchanger, and recent experimental and analytical results. The methods of producing the particles and their physical characteristics are discussed. Experimental data is presented that indicates that the particle suspensions are even more effective absorbers that early theory predicted. The results of an analytical study of the efficiency of single- and double-window high temperature gas receivers utilizing small particles are discussed.

2. SMALL PARTICLE HEAT EXCHANGERS

A dispersion of small particles is an ideal medium to absorb radiant energy, transform it to sensible heat, and effectively transfer the heat to a surrounding fluid. Because the absorption occurs within the fluid, the temperature drops that occur across the walls of conventional solar receivers are eliminated, resulting in higher efficiencies and lower operating temperatures. The optical properties of a small particle suspension may be taylored to the spectrum of the incoming light to maximize the absorption and minimize the reradiation of the thermal energy. Thus a small particle suspension offers the features of a selective surface absorber, but with the advantages of direct absorption within the fluid.

The direct absorption technique has wide spread applicability, being suitable for gas or liquid media. Flat plate liquid collectors have been proposed to meet space heating requirements (1) and provide a combined collector and heat storage medium for passive solar applications (2). A liquid salt-particle suspension has been investigated for use with central receivers systems (3). Use of a small particle suspension in a gaseous medium has been proposed for point focus applications including heating a gas to operate a turbine (4), providing industrial process heat (5,6), and using the sun to provide energy to operate a deep space rocket engine (7).

This paper treats the case of heating a gas with a dispersion of ultrafine particles. An open cycle heat engine utilizing SPHER operates by compressing ambient air and injecting a very small mass of carbon particles in to gas stream. The air-particle mixture then enters a transparent heating chamber where the solar flux is concentrated. The particles absorb the radiation and, because of their very large surface area quickly release the heat to the surrounding gas. The air-particle mixture continues to heat until the particles oxidize. The heated gas then passes through the expansion turbine to provide power for the compressor and load before passing through a regenerator and being exhausted.

A dispersion of very small particles distributed throughout a volume is a very efficient absorber of sunlight if the particle size and optical constants are chosen properly. If the characteristic absorption length for the light passing through the material comprising the particle is greater than the particle diameter, the entire volume of the particle is active as the absorber. For this and other reasons sub-micron particles are used.

The choice of composition of the particles is determined by the desired optical and physical properties. Various forms of graphite and carbon are ideal choices because of their optical characteristics and the fact that the method of production affects their combustion rate. They have the additional advantage that the combustion product is carbon dioxide. The use of material is very small (see the discussion below), so that the amount of CO_2 generated is less than one percent of that produced by a conventional fossil plant of the same power.

3. DIRECT ABSORPTION BY SMALL PARTICLES

Electromagnetic radiation passing through a medium containing particles may be scattered or absorbed. If the particles are small and 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 the dominated by absorption. For small (Rayleigh) particles, the absorption is given by (8),

$$Q_{abs} = 4 \cdot \frac{2\pi r}{\lambda} \; \text{Im} \left\| \frac{m^2 - 1}{m^2 + 2} \right\| \qquad (1)$$

where r is the particle radius, λ the wavelength of light and m the complex index of refraction. For simplicity the following treatment will be restricted to interactions with a single encounter of a photon on a particle.

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

$$\frac{I}{I_0} = e^{-\beta x}$$

where x is the distance traversed and β is the extinction coefficient. It is divided into two contributions, $\beta = \beta_{abs} + \beta_{sca}$. The absorption coefficient may be expressed in terms of the number of particles per unit volume N_i, with the absorption efficiency Q_{abs_i} and cross sectional area A_i as,

$$\beta_{abs} = \sum_i N_i Q_{abs_i} A_i$$

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

$$M = \sum_i N_i V_i \rho$$

where V_i and ρ give the volume and density of the i^{th} particle. If d is the absorption length available in the caldron 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, we obtain:

$$M = \frac{4r\rho}{3Q_{abs}d} \tag{3}$$

For absorbing particles with sizes greater than $2r/\lambda \sim 1$, Q_{abs} is roughly constant with increasing particle size (9) and the mass of particles necessary to produce a given absorption is proportional to r. For the case of Rayleigh scattering however, Eq.(1) shows that Q_{abs} is proportional to r. Thus, the absorption becomes a constant for small particle sizes. For carbon particles the mass loading for a chamber with a length of one meter can be calculated by combining equation 1 and 3 to obtain,

$$M = \frac{\rho\lambda}{6\pi\ d\ \mathrm{Im}\left\|\left[\frac{m^2 - 1}{m^2 + 2}\right]\right\|}$$

Using data for the optical constants of arc evaporated carbon (10) to determine the solar weight average for Q_{abs} gives a value for M of 0.37 gms/m^3. This is a very low mass loading.

In the analysis above, it has been demonstrated that small amounts of fine particles can act as efficient absorbers of sunlight. It can also be demonstrated that fine particles have very small scattering cross sections, in fact Rayleigh theory predicts that the amount of scattered light decreased with the fourth power of the ratio of particle size to wavelength. This means that the light scattered out from a receiver will be small and the receiver efficiency will be high.

4. EXPERIMENTAL PROGRAM

A laboratory has been obtained, equipped, and is in full operation. Work has begun on three alternative methods of producing carbon particles suitable for high temperature receiver work. The first generation method utilizes an enclosed diffusion flame and has successfully produced very dense particle streams. Most of the experimental data has been obtained using this technique. The second method relies on a high intensity arc. This technique is currently being explored in order to produce highly refractive particles that will operate at high temperatures. The third method utilizes pyrolysis of hydrocarbon gases and looks encouraging for a high yield particle source that can be incorporated into the receiver design. Work is just begining on this technique which is essentially the same as the one used in the industrial production of carbon blacks.

A schematic diagram of the experimental apparatus for particle production and collection and for opacity and mass measurements is shown in Figure 1. The diagram shows the experimental set up used for producing particles from a fuel rich flame. An extinction tube used with a He-Ne laser is used to determine the opacity of the gas-particle suspension. Nuclepore filters are used to collect the particles for weighing and transmission and scanning electron microscopy.

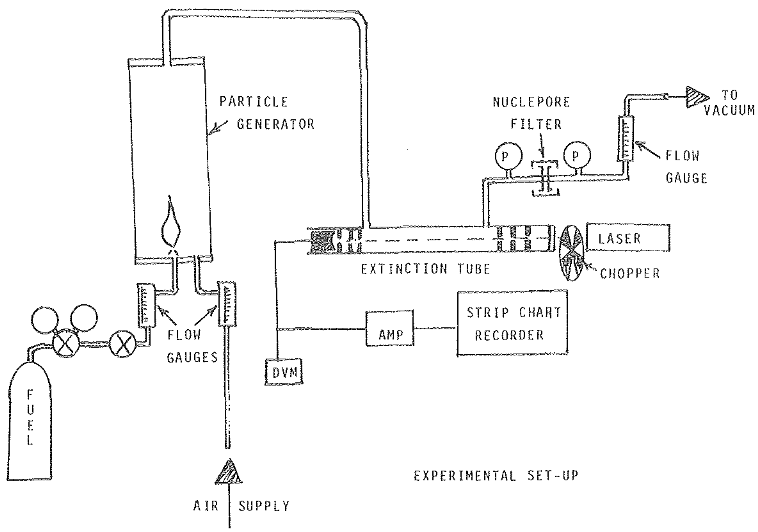

Figure 1. Schematic Diagram of the apparatus for the production and measurement of small particle suspensions.

Opacity measurements performed on particles produced by the flame method yield extinctions in excess of 95% for one way light paths of 30 cm. Simultaneous mass loading measurements have been performed specific extinction coefficients of 15-20 M^2/gm have been measured. This result is extremely encouraging, since it establishes that the particles have four times greater absorption than the Rayleigh theory predicts. This higher extinction has the effect of reducing the already extremely low requirement for particles.

The experimental absorption being higher than that predicted by elementary Rayleigh scattering theory is probably due two causes. An electron micrograph of a collected sample of carbon particles is shown in Figure 2. The median size of the smallest components is about .04 microns in diameter. Mie calculations for particles this size give extinction coefficients about two times that predicted by Raleigh theory. The second reason for the higher absorption coefficients is probably due to the chain like character of the agglomerates. Under some circumstances the cylinder like geometry can sometimes produce greater extinction than that from a sphere. It is likely that these two effects in combination are responsible for the enhanced absorption. This data is approximate agreement with other recent measurements of the characteristics of particles produced under similar circumstances (12).

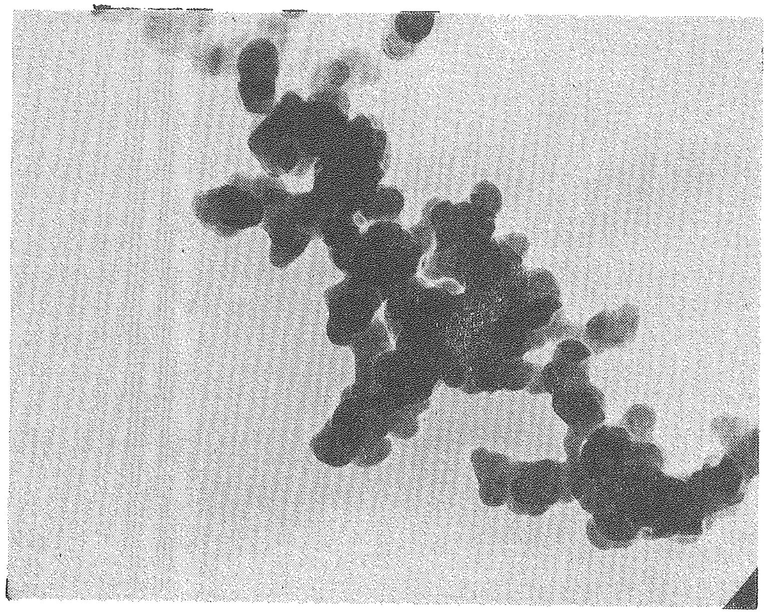

Figure 2. Transmission electron micrograph of particles generated from the apparatus diagramed in Figure 1. The smallest particle diameter is approximately .05 microns. (XBB-806-7255)

5. WINDOW EFFICIENCY

The (SPHER) concept utilizes a windowed receiver to confine a suspension of ultrafine carbon particles that act as the solar absorber and heat exchanger. This and other receivers have been proposed to heat a gas to a high temperature for powering a gas turbine or to supply industrial process heat. Other applications of windowed receivers include their use to confine suspensions of feedstock materials during solar heating.

In view of these applications of high temperature windowed receivers, an analysis was performed to determine the overall efficiency of two specific receiver designs. The designs were intended for use with the SPHER concept, but the methodology developed (13) is applicable with only slight modification to a wide variety of windowed receiver designs and sizes.

Two basic designs were analyzed. One used a single window with a hot working gas flowing behind it. The second design used two windows with a cooling gas flowing between them. Both designs were assumed to be used in conjunction with a regenerated gas turbine system providing several megawatts of mechanical power. An efficiency analysis was first performed for a baseline design. Then a sensitivity analysis was performed by changing the value of each parameter to determine its effect on the receiver efficiency. A detailed window energy balance was used to predict the window temperature. The receiver energy losses, receiver efficiency, and associated thermodynamic cycle efficiency were calculated. The efficiencies for the base line design for single and double-windowed receivers are 93.8% and 95.4% respectively.

6. SUMMARY AND 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 in the Rayleigh size region to maximize the absorption per unit mass. Carbon is suggested as the ideal particle composition because of its optical, chemical and physical properties. Several alternative methods of producing the particles appear feasible and one technique has produced particles with four times the mass extinction that was predicted on the basis of simple theory. An analysis of the efficiency of a windowed receiver using the sphere concept indicates that very high efficiencies are achievable.

7. ACKNOWLEDGEMENTS

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