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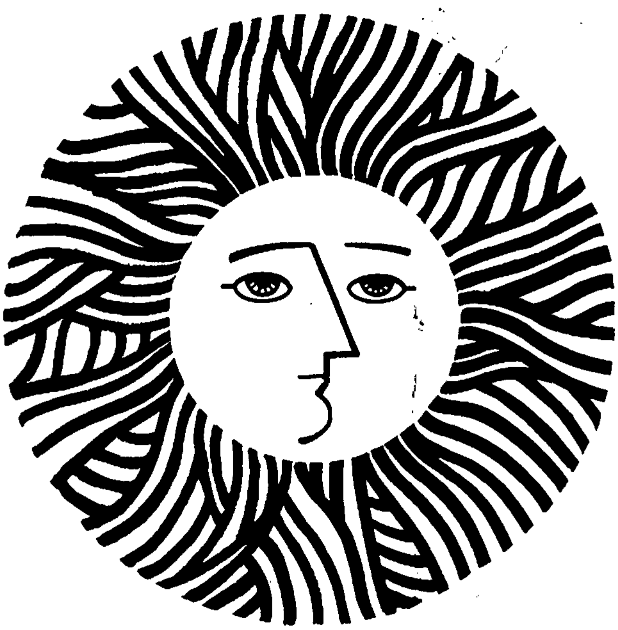

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Solar Radiant Heating of Small Particle Suspensions*

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ABSTRACT

This paper outlines the theory and development of a new class of solar thermal receivers based on the direct absorption of concentrated solar flux by small particles. The first Small Particle Heat Exchange Receiver (SPHER) was designed and built at LBL using this principle. The SPHER concept can be used to supply heated gas for power production, provide industrial process heat, or directly heat a reacting fluid. The paper reviews the results of theoretical and experimental studies of small particle systems, receiver design philosophy, and key issues in the direct radiant heating of two phase suspensions.

Concentrated sunlight is an intense source of radiant energy that offers an alternative to fossil fuels to provide high temperature industrial heat, operate heat engines, and process fuels and chemicals. Because sunlight originates from a radiating body with a considerably higher temperature than other common energy sources, solar radiation has quite different characteristics from those energy sources with which we are familiar. The work described here explores a novel approach to energy conversion that matches the characteristics of concentrated sunlight to the requirement of heating a gas.

The purpose of this work is to investigate and demonstrate a new type of high temperature receiver powered by a central tower or parabolic dish concentrator system. The solar-to-thermal conversion is accomplished by a dispersion of submicron particles suspended in a gas to absorb radiant energy directly from concentrated sunlight (1).

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 focused through a window. The particles absorb the sunlight and transfer the heat to the gas. The particles are very small and, therefore, not significantly affected by gravitational or inertial forces; they are effectively part of the gas. 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 fashion because of the very low requirement for carbon. The receiver can provide high temperature gas for process heat or operate a gas turbine. The SPHER concept is suitable for a wide range of powers and a variety of applications.

An extremely small mass of these particles provides very large 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. This results in a high absorption coefficient for the incoming radiation and a high optical efficiency for the receiver. Because the window reduces the amount of infrared re-radiation leaving the receiver, and because the window is at a lower temperature than the working fluid, the receiver has a high overall efficiency.

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The small size of the particles allows them to act as extremely efficient heat exchangers. The highest temperature present in the receiver is essentially that of the gas. This results in significantly lower radiant temperatures in the chamber compared to other solar receivers that produce gas of the same temperature. This lower temperature is an advantage because it lessens the requirements for high temperature materials used in the receiver. Other important advantages in using small particles as heat exchanger elements include low pressure loss in the gas circulated through the chamber, and low receiver weight.

The feasibility of the concept has been under study for several years at LBL; the operation of the various subsystems was investigated, the overall efficiencies and system parameters were determined, and calculations were performed to quantify the optical and physical processes. A variety of related topics were investigated, including particle production methods, window and chamber designs, and environmental and safety factors.

This paper outlines the principles of operation and the development of solar thermal receivers based on the direct radiant absorption of sunlight by small particles. The following sections describe the optical, physical, and chemical processes involved in using small particles as heat exchangers. A further section briefly discusses the design philosophy of a 30 kW solar receiver constructed in 1981 and to be tested in 1982 at the Advanced Components Test Facility (ACTF) at the Georgia Institute of Technology. The last section reviews some of the important factors in the more general problem of radiant transfer for solar thermal chemical processing.

OPTICAL PROPERTIES OF SMALL PARTICLE SUSPENSIONS

The attenuation of a parallel beam of monochromatic light passing through a suspension of small particles is given by,

$$I = I_o \exp -\sum_i N_i Q_{ext_i} A_i x \ .$$

The initial and final intensities are given by I_o and I respectively, the number density of particles N_i, with extinction efficiency Q_{ext_i}, and cross sectional area A_i, and the distance traveled is x. The extinction efficiency is defined as the ratio of extinction cross section to geometrical cross section of the particle.

In general, light passing through a medium containing small particles is both absorbed and scattered. The extinction efficiency, Q_{ext}, describes to the total attenuation of the light and may be divided into contributions from absorption and scattering as $Q_{ext} = Q_{abs} + Q_{sca}$. If the particles are very small and intrinsically absorbing, the extinction is dominated by absorption. This is true for particles of the size used in the SPHER. The absorption efficiency is determined by the dielectric function, size, size distribution, and shape of the particles.

The mass per volume of spherical particles, M_s, required to absorb a fraction of 1/e of light in a single pass through a suspension of thickness t is given by (2)

$$M_s = \frac{4\rho r}{3tQ_{abs}}$$

where r is the radius and ρ the density of the particle. The mass per unit volume of particles necessary to obtain a given absorption is dependent on particle size. For small particle radii the mass goes to limiting value; for large radii the mass increases linearly with size. In the size region between these extremes, M_s may have a minimum. For the carbon particles studied in this program, M_s is a minimum for particle sizes about 0.1 micrometer in diameter.

The mass of carbon particles to produce significant absorption in a one meter is extremely small. In typical applications, the carbon use rate is between one-tenth and one-half 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). In electric power applications, the cost of the carbon is less than one percent of the value of the electricity produced.

In addition to the excellent optical properties of small carbon particles for solar absorption, they also have very good infrared properties. At longer wavelengths the emissivity of carbon particle suspensions decreases significantly, resulting in low infrared emission. Therefore, a suspension of small carbon particles has inherent properties of high visible absorption and low infrared emissivity. In other words, it is a selective absorber.

THERMAL PROPERTIES OF SMALL PARTICLES

The combination of the large surface area and small size of the particles insures very efficient heat exchange between the gas and particles. This is illustrated by calculating the equilibrium temperature of a particle in a radiation field. The heat capacity of the particle is so small that we may assume thermodynamic equilibrium and need only treat the in- and out-going fluxes in order to calculate the particle temperature. This may be written:

$$P_A - P_E - P_C - P_R = 0$$

where P_A is the power absorbed by the particle, P_E is the power emitted by radiation, P_C is the power lost by collisions with gas molecules and P_R is the power lost by chemical reactions. The last term is neglected in this discussion because it is very small through most of the heating cycle. The equation is solved by substituting expressions for the radiant and conductive terms and using an iterative technique to balance the equation (2). The results of this calculation indicate that the particle temperature is within 0.1 ^oC of the gas temperature for particle temperatures from 600^oK to over 2000^oK. Thus the highest temperature present in the receiver is is essentially that of the working gas.

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 gaseous hydrocarbon. The experimental work on pyrolysis at LBL was successful in producing sufficient flows of well dispersed carbon particles to operate a 30 to 50 kW solar thermal receiver with a path length less than one meter. Laboratory measurements indicated that the particle diameters are between 0.05 and 0.1 microns and they have a specific extinction of 11 m^2/gm.

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 varies by five orders of magnitude depending on the allotrope of carbon used. These calculations indicate that vitreous carbon particles with a diameter of 0.1 micrometer will survive long enough at 1000^o C to act as effective heat exchangers. The output temperature of the receiver to be tested at the ACTF will depend on the oxidation rate of the particles from the pyrolysis generator. Initial laboratory measurements and the literature (3), indicate the particles we are using have low reaction rates in air. At present we estimate the particles will oxidize in the receiver at temperatures between 850^o and 900^o C.

SYSTEM STUDIES

SPHER designs have been explored for a wide range of power ratings. A detailed analysis at LBL 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 (4). The results indicated that a receiver using a single window with an etched antireflection coating has an efficiency of 93.6% at 1000^o C and that the efficiency increases significantly at lower temperatures.

RECEIVER DESIGN

To demonstrate the concept of a small particle heat exchanger, a 30 kW receiver, designated Mark I, was designed and built at LBL. Because of the fundamental difference between volume absorption receivers and traditional receivers, a new set of design criteria had to be developed. Because the energy absorbed in an incremental length within the suspension is proportional to the radiant intensity at that point, it is impossible to completely absorb the beam. The intensity decreases due to the absorption in the medium, and in concentrating systems, also from the divergence of the radiant flux density beyond the focus. The size of the receiver is therefore related to the properties of the particle suspension, and the characteristics of the collector.

The basic design philosophy was to maximize the absorption occurring within the volume consistent with the maximum allowable flux density on the walls. In addition, the entire volume of the receiver should be illuminated. This insures that no particles are wasted by passing through the receiver without being heated.

To determine the receiver size, first the maximum flux density striking the walls is determined. The ratio of the maximum allowable flux density on the wall to the flux density without the absorbing particles is given by

$$M_s g_{abs} x = -\ln \frac{I_w}{I_o}$$

where g_{abs} is the effective absorbing surface area per gram of particles. Since g_{abs} is determined by the particles, it is clear that the size of the receiver is inversely proportional to the mass of particles required to absorb the radiation. This is the basic engineering tradeoff between capitol equipment and operating costs. The reason that direct absorption receivers are practical is because g_{abs} is large, resulting in reasonable sized receivers for moderate power levels.

The shape of the receiver was determined by the combination of the flux distribution produced by the collector field and the absorption per unit length of the particle suspension. In designing Mark I, we took advantage of the opportunity to obtain data directly from the ACTF. To evaluate trial chamber shapes we developed a methodology using the ACTF data to predict the flux absorbed by the particle suspension and the flux density on the walls. The analysis was implemented with a computer program that provided graphical displays of the results (5).

Figure 1 is a drawing of the cross section of the Mark I SPHER. Concentrated sunlight enters the bottom of the receiver through the window. The extreme rays from the collector travel parallel to the walls (A). The gas particle mixture is routed into the nozzle ring B. A total of 18 nozzles (C) direct the gas flow from the nozzle ring into the chamber to cause a significant swirling motion. This circular motion organizes the flow in the chamber and reduces the possibility of hot spots originating from axially nonuniform flux distributions.

The gas-particle mixture circulates in a cyclone fashion to the axis near the window (D) where the exit tube (E) is located. A unique aspect of the design involves the transparent quartz tube that penetrates the high flux region. The tube acts as an exhaust port and insures that the gas-particle mixture passes through the maximum flux density region before leaving the receiver. The use of a quartz tube provides a refractory exhaust pipe that does not interfere with the flux distribution because it is transparent.

The nozzle ring and absorption chamber are supported by a set of flexible spring legs (F) mounted to a rigid toroidal tube that carries the weight of the receiver. A bellows assembly (G) near the top of the receiver reconciles the thermal expansion of the interior of the chamber with the cool outer skin (H). A Thermocouple equipped with multiple heat shields is located in the exhaust tube at location J. The region between the absorption chamber (A) and the outer skin is filled with compressible high temperature insulation to minimize the heat losses from the absorption chamber.

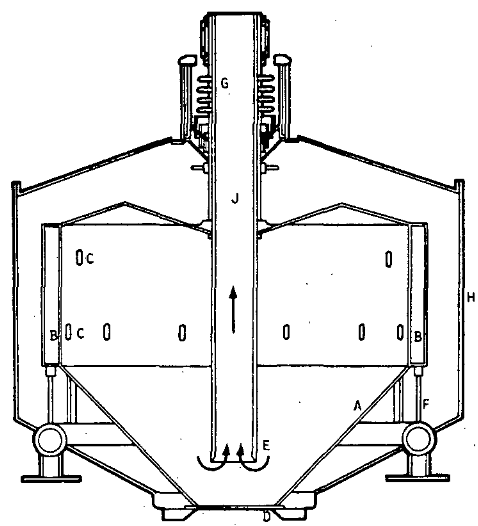

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Figure 1. View of the cross section of the Mark I SPHER.

To minimize costs, no "super" alloys were used in the construction of the receiver or generator. The lining of the receiver is stainless steel, fabricated mostly from sheet metal stock.

RADIATIVE HEATING FOR CHEMICAL PROCESSES

In addition to providing a basis for a new type of solar heat exchanger, direct radiant heating may be used to supply heat or light quanta to directly induce chemical reactions. Experiments have been performed to demonstrate the pyrolysis of biomass (6), gasify coal and oil shale (7), and carbonaceous materials (8). Others have demonstrated ore treatment and decomposition of metal oxides (9). These are only a few examples of experimental work on direct radiant processing, and is by no means an exhaustive list.

There are two general approaches to radiant processing; solar thermal processing, and photochemical processing. Here we limit the discussion to solar thermal processing. Solar thermal processes can generally be broken into the categories of pyrolysis, reaction of components, dissociation, and phase change. To effectively heat a solid feedstock material by solar radiation, it should be in a finely divided suspension. In this section the suspending fluid may be considered to be a gas or liquid.

When light enters a suspension of particles it may be scattered or absorbed. Both processes have the effect of reducing the intensity of the light for particles located further from the radiation source. To directly heat a substance by solar radiation it must be optically absorbing. This will occur if the material has intrinsic absorption or if an absorbing substance is added to the process stream.

Light will penetrate only a short distance through dense suspensions of particles of the size and concentration typical of process chemistry. This leaves the material behind shadowed from the incoming light. This is a fundamental problem that must be solved in any direct, radiantly-heated reactor design.

When the density of particles in the processing stream is low, or the particles are extremely transparent, incoming radiation may penetrate to a depth that is a significant fraction of the reactor size. In this case, the time available for the reaction approaches the residence time in the reactor. The SPHER is an example of volume heating of a particle suspension.

When radiant flux encounters a high density of particles with sizes a few microns or larger, the radiation will not penetrate the process material more than a few particle spacings. Once the flow rate (and hence the power) is chosen, and the radiant flux density decided, then the area available for the reaction is determined. The radiant flux can directly process a volume of material per unit time equal to the product of the illuminated area of the flow and the light penetration depth divided by the time required for a small parcel of material to move across the area. This basically sets a minimum facial velocity on the process stream. An additional requirement is that the reaction kinetics are sufficiently rapid to insure the desired process takes place in the receiver (or possibly downstream).

Only a few of the considerations important in direct radiant heating of fluid-particles suspension have been touched upon here. However it should be apparent that many new factors must be considered in addition to finding a suitable absorber or reactant.

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