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A New Solar Thermal Receiver Utilizing A Small Particle Heat Exchanger

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ABSTRACT

A dispersion of small absorbing particles forms an ideal system to collect radiant energy from concentrated sunlight to heat a pressurized gas that when expanded through a turbine will produce useful mechanical energy. A new type of solar thermal receiver based on this concept is being developed at LBL that is to be placed at the focus of a central tower or a parabolic dish concentrator system. An open cycle Brayton 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. The air particle mixture 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 vaporize. The optical efficiency of the receiver is 85-90% without a cavity and the thermodynamic efficiency of the Brayton cycle is greater than 40%. Calculations of the optical, thermal, and physical processes have been performed, candidate receiver designs and window materials have been determined, and the feasibility demonstrated in the laboratory.

BACKGROUND

The success of the solar thermal electric power program rests on the efficiency, reliability, and low cost of the three major subsystems: the heliostats, the central receiver, and the high temperature heat storage system. The concept of the Small Particle Heat Exchange Receiver (or SPHER), as proposed here, offers an attractive solution to the high temperature receiver design problem. In addition, because of the simplicity of the receiver design, it is easy to incorporate conventional fuel injectors into the system, thus enabling the plant to operate during periods of cloudiness or in the evening. The use of conventional fuel as a back-up eliminates the need for expensive, low efficiency heat storage systems. This type of hybrid solar-fossil operation should find favor with the utilities for its capacity credit and for network reliability considerations. The open cycle Brayton plant has the additional advantage of not requiring cooling water, an important feature since arid areas are the best solar collection sites because of solar availability and low land costs.

The system functions by compressing outside air and passing it through a recuperator for preheating. A very small mass of fine particles is injected into the gas stream before the mixture enters the transparent heating chamber where the solar flux is concentrated (referred to as the caldron). In the caldron the particles absorb the solar radiation and heat the gas. Since the particles are very effective heat exchangers their temperature does not rise substantially above the air temperature. The air-particle mixture continues to heat until the particles vaporize. The heated air then passes through the expansion turbine that provides power for the compressor and the generator. The exhaust gas flow is routed back to the recuperator to recover some of the heat. In this design the compressor, particle generator, turbine, and receiver are located in the central tower. There are many ways to arrange the system but the essential feature of this concept is the use of small particles as the solar-to-gas exchange medium.

The operating temperature of the receiver is determined by the oxidation rate of the particles. Carbon is an ideal material for this application because the gas reaction rates for various allotropes of carbon vary over many orders of magnitude. The use of carbon has the additional feature that the combustion product is carbon dioxide. The particles may be created by a quenched flame, a chemical reaction, or a high intensity arc. It should be emphasized at this point that the mass of particles used is extremely small compared to the amount of fuel burned by a conventional fossil fuel power plant. The amount of CO_2 generated is less than one-one hundredth of that produced by a fossil fuel plant of the same power.

A dispersion of particles distributed throughout a volume of gas is a very efficient absorber of sunlight if the particle size and optical constants are chosen properly. If the characteristic absorption length for light passing through the material comprising the particles 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. This results in a high absorption coefficient for the incoming sunlight, or equivalently a high optical efficiency for the receiver. Since the infrared re-radiation from the heated particle-gas mixture will be inhibited from leaving the chamber by the window, 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 illuminated from all sides. 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 much lower radiant temperatures in the chamber than of other solar receivers that produce gas of the same temperature.

There are several other advantages to the use of small particles as heat exchangers. Since the receiver basically consists of a hollow chamber with a window, there is no need for heavy and complex heat exchanger elements, resulting in a very light weight structure. 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. The heat exchanger is vaporized in the process of performing its function, so there are no problems associated with maintenance, failures, heat stress, or corrosion encountered 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 $2000^{\circ}C$ are achievable.

In the analysis that follows, the details of the important stages of the cycle are investigated. These include the examination of the small particle absorption process, the heat exchange to the gas, the choice of particles and their production, and the operating parameters of the receiver.

SMALL PARTICLES AS A SOLAR ABSORBING MEDIUM

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 the dominated by absorption. For small (Rayleigh) particles, the absorption is given by (1*),

$$Q_{abs} = 4 \cdot \frac{2\pi r}{\lambda} \quad \mathrm{Im} \left[\left\| \frac{m^2 - 1}{m^2 + 2} \right\| \right] \tag{1}$$

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 only one encounter of a photon on a particle.

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

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

where x is the distance traversed and β is the volume total scattering coefficient. As before, β 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,

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* Numbers in parentheses designate References at end of paper

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

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 1 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:

$$M = \frac{4r\rho}{3Q_{abs}1} \tag{3}$$

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. 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. This result is plotted in a qualitative way in Fig. 1. Consider the specific example of carbon particles. To calculate the mass loading for a chamber with a length of one meter combine equation 1 and 3 to obtain,

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

Using data for the optical constants of arc evaporated carbon (3) to determine the solar weighted 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 <u>absorbers</u> of sunlight. Now consider the collection efficiency of the receiver. Setting aside the question of the window reflection temporarily, consider the definition of the albedo for single scattering. The albedo, A, given by,

$$A = \frac{Q_{sca}}{Q_{sca} + Q_{abs}} \tag{4}$$

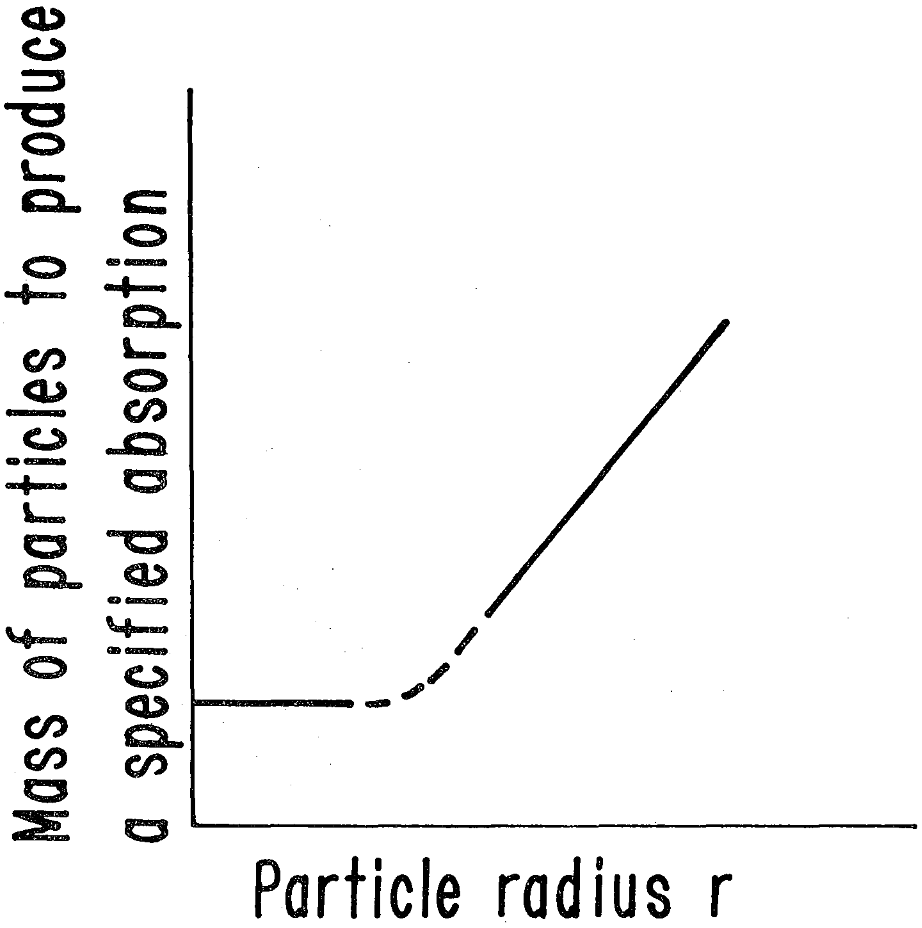

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Figure 1. Schematic illustration of the dependence of the mass of particles to produce a specified absorption as a function of particle radius.

is a measure of the relative probability of a particle scattering a photon, compared to the particle absorbing or scattering a photon.

The calculation of the albedo proceeds in a straightforward way from equations (1) and (4). The albedo is only 0.038 at a wavelength of 0.52 micrometers for scattering from particles of diameter of 0.05 micrometers and having the optical constants of arc evaporated carbon. It can be shown (4) that for the worst case, the loss from the receiver due to scattering will be less than two-thirds of the albedo if $Q_{abs} > Q_{sca}$. Thus, for particles with diameters less than 0.05 micrometers, the optical efficiency of the receiver will be in excess of 95%.

Some reflective losses will occur due to reflection from the window surfaces. Quartz, with an index of refraction of 1.5 will have a reflection of about 4% per surface for normal incidence. This reflectivity may be substantially reduced by the use of anti-reflection coatings or by controlling the surface morphology. If these coatings reduce the reflectivity of the window by half, the solar collection efficiency will still be in excess of 90% without the use of a cavity. This is an illustration of the characteristics of a diffuse suspension of small particles to act like a black body absorber.

THE PARTICLE TEMPERATURES

Once the particles have absorbed the incoming radiant energy they begin to heat up. The maximum rate of temperature rise in a vacuum neglecting radiation losses, for the conditions considered here, are of the order of several millions of degrees Kelvin per second. The high heating rates indicate that the thermal inertia of the particles is small. We may use this fact to simplify the treatment by restricting the analysis to the in- and out-going energy fluxes. The equilibrium temperatures calculated on this basis will be reached in an extremely short time compared to the residence time in the caldron.

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

$$P_A - P_E - P_C - P_S = 0 \qquad (4)$$

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. In the present treatment the heat removed from the particle by sublimation is neglected. The radiant power absorbed by the particles is given by,

$$P_A = 4\pi r^2 \int_0^\infty Q_{abs}(\lambda,r,m)\ F_{s\lambda} d\lambda \ + \ 4\pi r^2 \int_0^\infty Q_{abs}(\lambda,r,m) u\ F_I d\lambda \qquad (5)$$

where $F_{s\lambda}$ is the spectral flux density incident on the particle from the collector field and F_I is the spectra flux density from all non-solar sources. The first integral represents the solar input to the particles. The second integral represents the radiant heat returned to the particles from the gas-particle mixture and the chamber walls. This term only becomes significant for very high temperatures and is neglected in the present treatment. The quantity $\alpha\pi r^2$ is the effective cross sectional area of a spherical particle. For a plane parallel beam, the factor α would be unity. The power emitted by a particle is given by

$$P_E = 4\pi r^2 \int_o^\infty Q_{abs}(\lambda,r,m)F_{p\lambda}d\lambda \tag{6}$$

where $F_{p\lambda}$ is the Planck black body function at the temperature of the particle. The power lost by collisions is given by (5):

$$P_C = 2n_g r^2 \sqrt{2\pi k_B T_g/m_g}\; a(C_v m_g + 1/2\; k_B)\;(T_p - T_g), \tag{7}$$

where C_v is the specific heat of the gas at constant volume, a is an accommodation coefficient, taken to by unity, k_b is Boltzman's constant, T_p is the particle temperature, m_g is the mass, n_g the number density and T_g the temperature of the gas molecules.

To compute the equilibrium temperature an iterative technique is used to solve equation 4 by finding a particle temperature that balances the equation. The results are given in Table I. The calculations are for a particle radius of 0.025 micrometers and are based on a combination of graphite optical constants of Phillip (5) in the infrared and Arakawa et al (3) in the near infrared and visible. 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^oK the heat loss process is dominated by conduction. The last temperature entry indicates that for the assumed conditions the maximum attainable temperature is about 2250^oK. This value will depend on the particle size and will increase for smaller particles.

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 PRODUCTION AND REACTION OF THE PARTICLES

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. Redispersion must overcome the large surface forces that hold the particles together. 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 appear to be high intensity arcs (7), thermal decomposition of hydrocarbons (8) and high temperature pyrolysis of organic resins (9). The high intensity arc has been established as a method for industrial production of submicron particles. Carbon, metals, semi-conductors and many of their oxides have been produced at rates of kilograms to tens of kilograms per hour using a single arc (7). Carbon blacks have been produced commercially by thermal decomposition by the channel process since 1872. The properties of these blacks vary widely but they tend to be symmetrical in shape and to have particle diameters ranging from 0.01 to 0.5 micrometers. High temperature pyrolysis is used to produce vitreous carbon that has extremely high decomposition temperatures in air.

The choice of the operating parameters of the caldron and the gas turbine determine the desired characteristics of the particles. 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 forms of carbon. Calculations based on published bulk rates (10) 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 clearly necessary to determine the correct match of particles and applications.

PARTICLE CONFINEMENT DURING HEATING

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. There are several materials that meet the solar transparency requirement. The best candidates are pyrex and quartz. These materials pass nearly the entire solar spectrum and are also opaque to radiation with wavelengths greater than 4 micrometers. This opacity in the infrared will reduce the heat losses by radiation.

The pressure requirements on the window are modest, on the order of three to six atmospheres for the open cycle Brayton engine. Figure 2 illustrates the basic components of a receiver that would be used as a side facing cavity. The outer window is made of pyrex and forms the pressure vessel. It is a cylindrical section facing inward to insure the window remains in compression (the direction to provide the maximum strength for glass). The inner window is a thin sheet of quartz and acts as a heat shield. The compressed air enters the top of the chamber and passes on both sides of the heat shield. Particles are introduced only into the space behind the shield by placing the injectors below the top of the shield. Since no heating occurs in the cavity between the windows, the compressed air stream serves to cool the windows. This design has the advantage of not requiring a high temperature pressure seal to the quartz heat shield. Figure 3 illustrates the same basic concept but with a number of sections arranged to form a cylindrical, non-cavity type of receiver that may be illuminated from all sides.

SYSTEM CONSIDERATIONS

The SPHER may be used to heat a gas for use in either an open or or a closed Brayton cycle. The open cycle avoids the need for the large cooling towers and the attendant use of water that is usually associated with electric power plants. The closed cycle recirculates the working fluid, and therefore requires active cooling facilities to cool the gas before recompressing. Another drawback for closed cycle plants is the requirement of large heat exchangers to heat the gas if the hybrid mode of operation is desired. The following discussion deals primarily with the application of SPHER to the open cycle system.

To determine some of the operating characteristics of a plant incorporating SPHER, the module size will be 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 would be over 40%. The volume of gas passing through the plant would be about 300,000 cubic meters per hour. 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 electric arcs or the other 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.

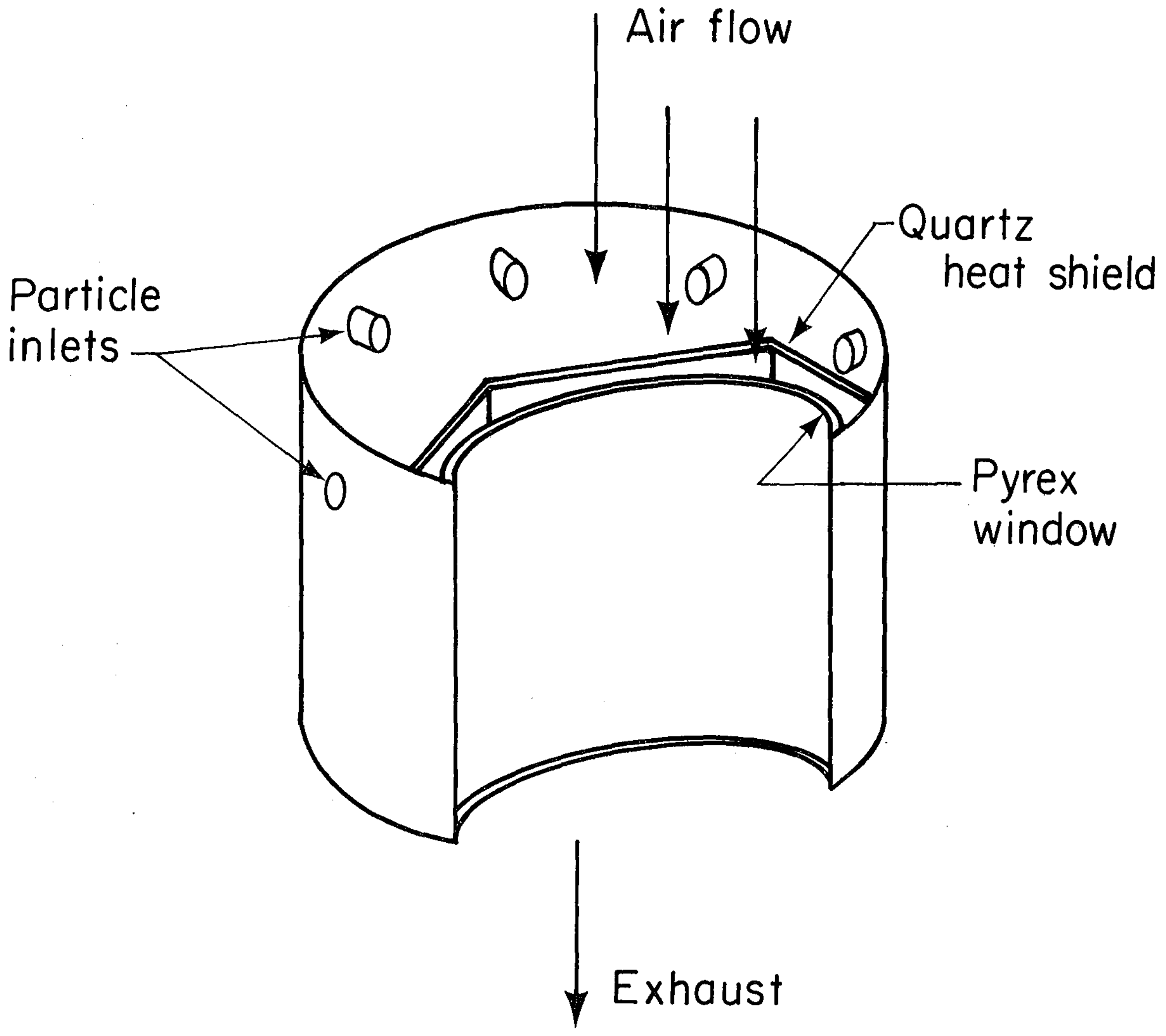

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Figure 2. Conceptual design of the heating chamber for a small particle heat exchanger.

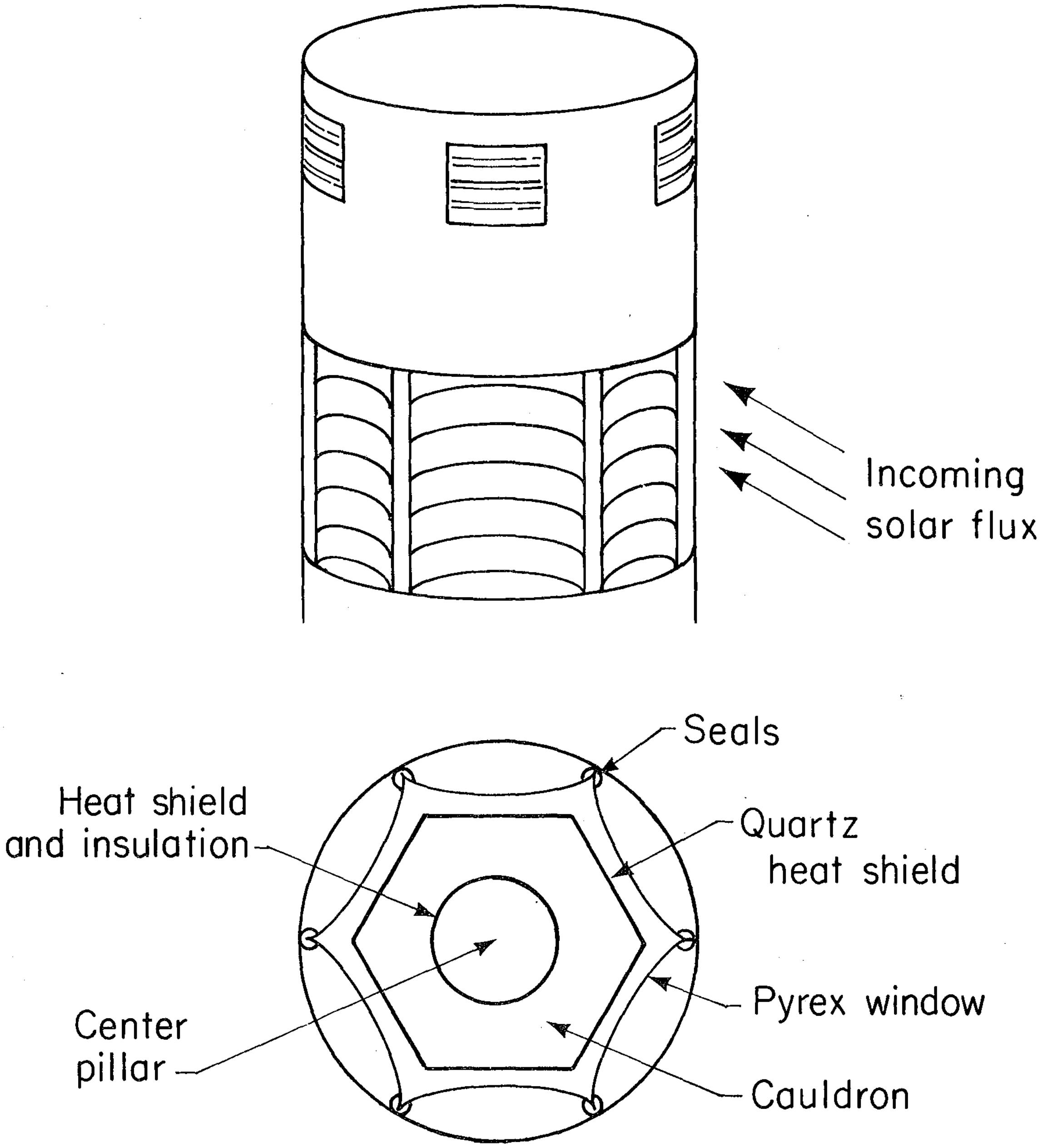

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Figure 3. Conceptual design of a heating chamber to be illuminated from all sides.

The SPHER concept may be used in a closed Brayton system. In this case however, a combination of particles and working gas must be found to prevent the agglomeration of the old particles. This problem could be avoided by a once-through use of the particles. This could be accomplished by vaporizing the particles and recondensing the material, or if air were the working gas carbon particles would form CO_2. In the latter case a small amount of additional air would be introduced to compensate for the loss of oxygen.

LABORATORY DEMONSTRATION

A simple laboratory apparatus was constructed to demonstrate the concept of a small particle heat exchanger and to gain practical experience in producing and handling gas-particle mixtures. The particles were generated by a diesel oil flame and conducted to a chamber to cool the gas and allow any clusters of particles to settle. The gas-particle mixture was then routed into the center of a radiant heating chamber. The temperature of the the gas stream leaving the chamber was monitored with a thermocouple.

Tests were run by turning the lamps on and establishing the gas flow rates by using a smokeless lamp. The system was operated until the temperature of the output gas stabilized. The oil lamp was then substituted for the smokeless flame and the temperature monitored until it stabilized. The flames were switched again and the measurement repeated. In spite of the fact the particle stream never reached an absorption of over a few percent, temperature changes of over $100^{\circ}C$ were recorded. This was encouraging considering the preliminary nature of the experiment, the inadequacy of the particle source and the very large thermal losses in the heating chamber. The experiment fulfilled its function in demonstrating the principle and indicated the areas for further work.

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 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 oxidation 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.

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