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Small Particle Heat Exchangers

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Introduction

A dispersion of small absorbing particles forms an ideal system to collect radiant energy, transform it to heat, and efficiently transfer the heat to a surrounding fluid. If the heated fluid is a pressurized gas, it can be passed through an expansion turbine to create useful mechanical energy. The most obvious application of this technique is its use in a solar collection system. In this case, the incoming sunlight is used to heat a compressed gas in an engine utilizing a Brayton cycle. The solar collection system may utilize high concentration as provided by a central receiver or parabolic dish, medium concentration from a linear collector, or possibly no concentration using a flat plate collector, if precautions were taken to reduce the heat losses.

The same concept may be applied generally to non-solar heat exchangers. These may be of the type used to heat a gas from a combustion source, or in general as a gas to gas heat exchanger. The latter application may be limited to rather high temperature.

In the following discussion, each of the above applications is treated. First, a description of the concept is applied to a solar central-tower system. In this section the general principles are described, including the optical and physical characteristics of the particles, the confinement of the gas-particle mixture, and the system considerations; the latter include the amount and type of particles, the receiver efficiency and the generation of the particles.

In the succeeding sections, the same considerations are reviewed for applications to linear trough and flat plate receivers. Finally, the use of small particles in non-solar heat exchangers is considered.

The Small Particle Heat Exchange Receiver (SPHER) for Solar Thermal Central Electric Applications

General

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 effective solution for two of the three subsystems. First, it can heat a working gas in a solar receiver to a high temperature for powering a Brayton cycle gas turbine. The major advantages of SPHER over other gas receiver designs such as the honeycomb heat exchanger, or a cavity lined with refractory pipes, are its simplicity, efficiency, light weight, and reliability. Second, because of the simplicity, 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.

Principles of Operation

The very large ratio of surface area to volume exhibited by small particles makes them ideally suited for use in a solar receiver. A dispersion of particles distributed throughout a volume of gas is a very efficient absorber of sunlight if their 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. When the particles have absorbed the sunlight and their temperature begins to rise they quickly give up this heat to the surrounding gas because of the large surface area per mass of material. (To illustrate, one gram of spherical particles 600Å in diameter with a density of water have a surface area of 100 square meters.)

Thus, small particles can simultaneously absorb sunlight throughout a volume of gas to be heated and exchange the resultant heat to the gas functioning as a heat exchanger with a very large surface area.

A schematic diagram of the design is shown in Figure 1. Air enters at the top and is compressed by the turbine. At this point, a very small mass of fine particles is injected into the gas stream. The air-particle mixture then enters the transparent heating chamber where the solar flux is concentrated (referred to as the cauldron). In the cauldron the particles absorb the solar radiation and heat the gas. Since the particles are such effective heat exchangers their temperature does not rise substantially above the air temperature. The gas-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 may be routed back to a recuperator to recover some of heat and thereby improve the overall conversion efficiency. 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 proposal is the use of small particles as the solar-to-gas exchange medium.

The particles may be created either by a high intensity arc or a chemical reaction. The use of several parallel particle generators provides reliability and control of the number of particles entering the cauldron. Control of the particle density provides a means of throttling the output power since when there are fewer particles not all the solar flux will be absorbed.

The choice of the composition of the particles is determined by the desired operating temperature. Graphite or vitreous carbon particles are ideal because their method of production determines the combustion temperature and the combustion product is carbon dioxide. 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 hundreth of that produced by a fossil fuel plant of the same power. Other materials can be used for the particles, of which the best candidates are probably metals. In this case, the particles do not vaporize but form oxides. This is not a serious problem since the particles are so small they pass harmlessly through the turbine. The amounts are so small they can be discharged directly into the air and not violate particulate air pollution standards. Iron and silicon are alternative candidates because of their good optical characteristics and the fact that they are environmentally benign.

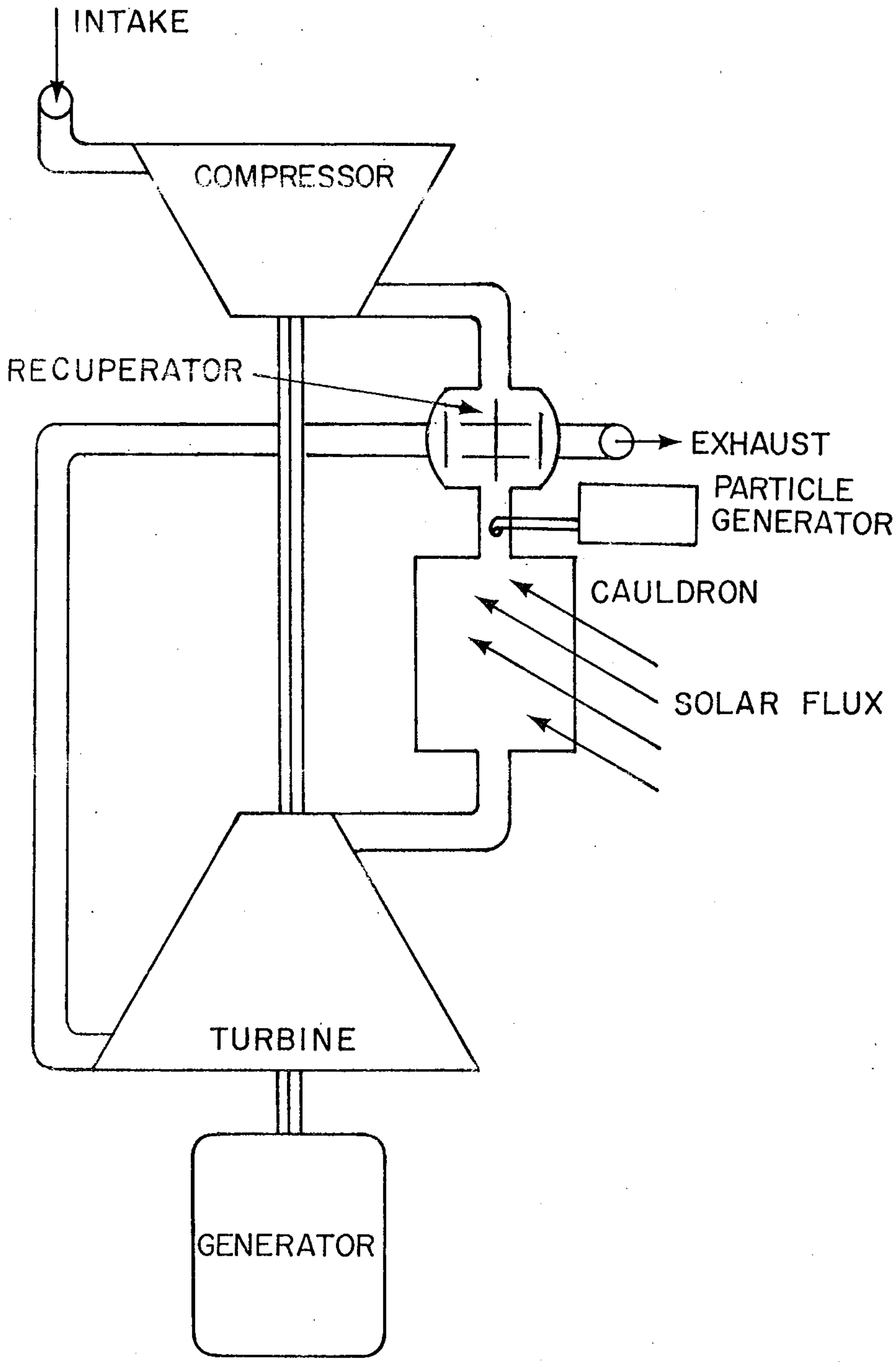

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Figure 1. Open cycle Brayton system utilizing a small particle heat exchanger.

In the analysis that follows, the details of the important stages of the cycle are examined in more detail. These include the analysis 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 dominated by absorption. This can be seen by examining the contributions to the extinction efficiency,*(1)

$$Q_{ext} = Q_{sca} + Q_{abs}$$

For small (Rayleigh) particles,

$$Q_{abs} = 4.\ \frac{2\pi r}{\lambda}\ \text{im}\left[\frac{m^2 - 1}{m^2 + 2}\right] \qquad (1)$$

and

$$Q_{sca} = \frac{8}{3}\left(\frac{2\pi r}{\lambda}\right)^4 \left|\frac{m^2 - 1}{m^2 + 2}\right| \qquad (2)$$

were r is the particle radius, λ the wavelength of light and m the complex index of refraction. For decreasing r at constant wavelength it is apparent that $Q_{abs}/Q_{sca} \to \infty$ for any particle that has non-vanishing absorption (given by $\text{im}[\frac{m^2 - 1}{m^2 + 2}]$). Thus, for small absorbing particles, it is more probable for absorption to take place than scattering. This is not a necessary condition for small particles to be effective absorbers but it does simplify the analysis. With this assumption we will restrict the following treatment to interactions dominated by only one encounter of a photon on a particle.

*The extinction efficiency is given by the ratio of the absorption plus scattering cross section to the geometric cross section of the particle. It may exceed unity since the particle will both block and diffract a beam of light.

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

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

where x is the distance traversed and β is the volume total scattering coefficient. As before, β is divided into two contributions, $\beta = \beta_{abs} + \beta_{sca}$. These quantities may be expressed in terms of the number of particles per unit volume N_i, with absorption and scattering efficiencies Q_{abs_i} and Q_{sca_i} and cross sectional area A_i as,

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

$$\beta_{sca} = \sum_i N_i Q_{sca_i} A_i$$

To determine the mass per unit volume M of particles necessary to produce a given amount of 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 ith particle. If x is the absorption length available in the cauldron 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:

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

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 Raleigh scattering however, Eq. (1) shows that Q_{abs} is proportional to r. Thus, the absorption becomes a constant for small particles sizes. This result is plotted in a qualitative way in Fig. 2.

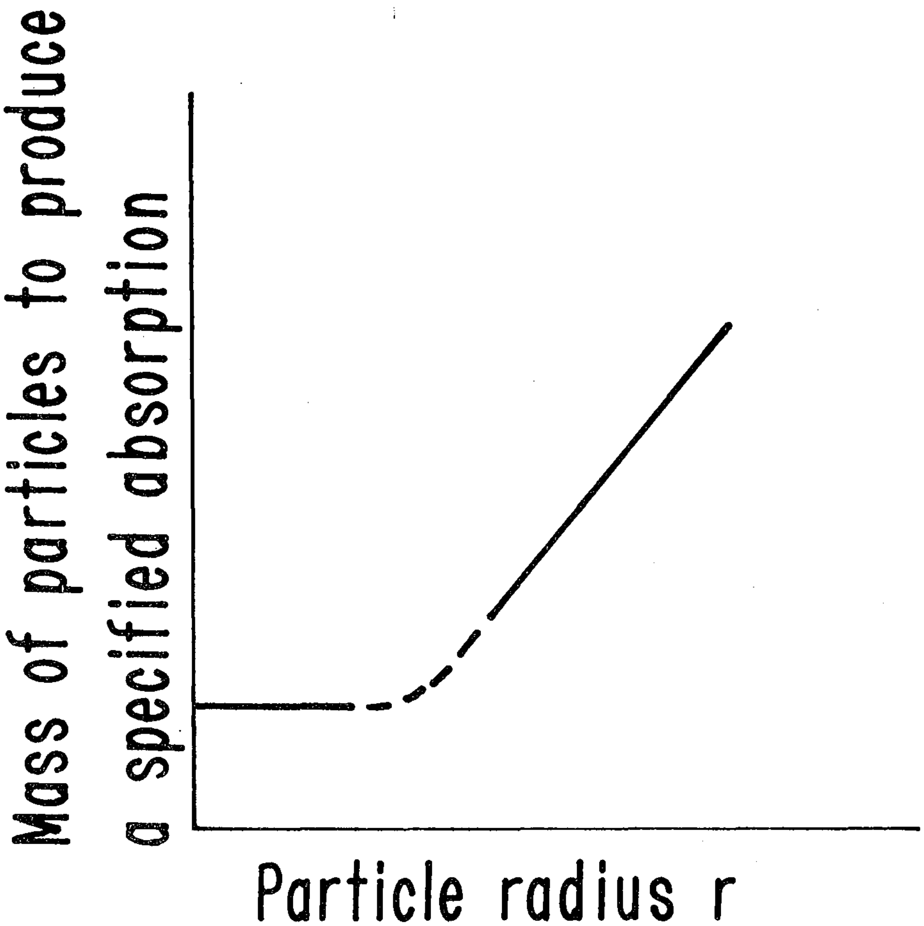

Figure 2. Schematic illustration of the dependence of the mass of particles to produce a specified absorption as a function of particle radius.

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,

$$M = \frac{\rho\lambda}{6\pi \times im[\frac{m^2 - 1}{m^2 + 2}]}$$

Using values of optical constants for arc evaporated carbon[3] at a wavelength of 0.52 micrometer ($m = 2.30 + .87i$) we obtain $M = 0.27$ gms/m^3. This is a very low mass loading.

In the analysis above, we have demonstrated that small amounts of fine particles can act as efficient absorbers of sunlight. We must now ask the converse question of what fraction of the sunlight is scattered out of the cauldron. Another way of phrasing this question is, "what is the collection efficiency of the receiver?" Setting aside the question of the window reflection temporarily, consider the definition of the albedo for single scattering, A, given by,

$$A = \frac{Q_{sca}}{Q_{sca} + Q_{abs}} \qquad (4)$$

The albedo is a measure of the relative probablity of a particle scattering a photon, compared to the particle absorbing or scattering a photon. Again, restricting the discussion to small particles, the photon will be scattered with roughly equal probability in all directions. If it is scattered forward it will have further chances to be absorbed. If scattered backward it may leave the receiver, or encounter another particle on its way out. For multiple encounters in the forward direction and no encounters in back scattering the loss due to scattering will be less than two-thirds the albedo if $Q_{abs} > Q_{sca}$. If larger particles are considered, more light is scattered in the forward direction, decreasing the chances for the photon leaving the cauldron without absorption.

The calculation of the albedo preceeds in a straightforward way from equations (1), (2) and (4). Table I gives the albedo for scattering from particles of a diameter of .05, .08, and .1 micrometers and having the optical constants of arc evaporated carbon.

TABLE I

Optical Characteristics of Small Carbon Particles

$\lambda(\mu)$	ε_1^a	ε_2^a	A $r = .025\mu$	A $r = .04\mu$	A $r = .05\mu$
2.1	11.5	11.5	.002	.008	.015
1.8	11.9	11.7	.003	.012	.023
1.5	8.5	10.9	.004	.016	.031
1.2	4.8	7.7	.004	.018	.034
1.0	3.9	4.9	.005	.02	.039
.88	4.4	3.6	.008	.031	.059
.77	4.9	3.3	.014	.054	.10
.69	5.4	3.4	.022	.085	.15
.62	5.3	3.6	.029	.11	.19
.56	5.0	3.9	.035	.13	.23
.52	4.5	4.0	.038	.14	.24
.48	4.3	3.9	.045	.16	.27
.44	3.4	3.9	.051	.18	.30
.41	3.6	3.8	.057	.20	.33
.39	3.4	3.8	.062	.21	.34
.36	3.2	3.7	.07	.24	.38
.34	2.9	3.6	.07	.25	.39
.33	2.8	3.5	.08	.26	.40

[a]Derived from the Optical Constants given by Arakawa et al for Arc-evaporated carbon films in Ref. 3.

As can be seen by examining the table, the albedo for small particles is low throughout the solar spectrum. Since the losses encountered will be less than two-thirds of the albedo it is clear that for particles with diameters ≤ .05 microns, the receiver efficiency 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 topic of reradiation from the particles at infrared wavelengths will be treated later in this description, but at present note that glass and quartz are very poor transmitters of light at the wavelengths where the reradiation is important. This means that the particles will not transmit substantial amounts of heat by reradiation through the window.

The Physical Characteristics of Small Particles in a Gas

Probably the single most important characteristic of small particles is the very large surface area for a given volume. In the case of spheres, the surface area for a given mass,M,of particles is given by $A = 3M/\rho r$, for cubes it is $A = 6M/\rho \ell$ where ℓ is the dimension of a cube side. Two things should be noted, first the inverse relationship between particle size and area, second the surface area per mass for non-spherical shapes is greater than for spheres. In the following discussion, we shall continue to assume that the particles are spherical but it should be kept in mind that real particles rarely have that shape. Thus, any results based on spheres represent a conservative estimate for processes that are proportional to the surface area.

Once the particles have absorbed the incoming radiant energy they begin to heat up. The maximum rate of temperature rise (neglecting all losses) is given by,

$$\frac{dT}{dt} = \frac{\pi r^2 Q_{abs} F}{Mh} = \frac{3 Q_{abs} F}{4\rho r h}$$

where F is the power density of the incident radiant flux and h is the specific heat of the particles. Typical values of dT/dt for the conditions considered here are of the order of several millions of degrees Kelvin per second. From this it may be concluded that the heating rate will not be a limiting factor even if the particles are exposed to the radiant energy for a short time.

The high heating rates indicate that the thermal inertia of the particles is small. We may use this fact to simplify the treatment by restricing the analysis to the in-and out-going heat fluxes. The equilibrium temperatures calculated on this basis will be reached in an extremely short time compared to the residence time in the cauldron.

The condition for temperature equilibrium of a particle in a gas is given by:[4]

$$P_A - P_E - P_C = 0 \qquad (5)$$

where P_A is the power absorbed by the particle, P_E is the power emitted by radiation and P_C is the power lost due to collisions with the gas molecules. The radiant power absorbed by the particle is given by,

$$P_A = \varepsilon \pi r^2 \int_0^\infty Q_{abs}(\lambda, r, m)\, F_{s\lambda} d\lambda \qquad (6)$$

where $F_{s\lambda}$ is the spectral flux density incident on the particle from the collector field. The quantity $\varepsilon \pi r^2$ is the effective cross sectional area of a spherical particle. For a plane parallel beam, the factor ε would be unity. The power emitted by a particle is given by

$$P_E = 4\pi r^2 \int_0^\infty Q_{abs}(\lambda, r, m)\, F_{p\lambda} d\lambda \qquad (7)$$

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

$$P_C = 2n_g r^2 \sqrt{2\pi k_B T_g/m_g}\ a(C_v m_g + 1/2\ k_B)\ (T_p - T_g), \qquad (8)$$

where C_v is the specific heat of the gas at constant volume, a is an accommodation coefficient, taken to be unity, k_B is Boltzman's constant, T_p is the particle temperature, m_g 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 5. The gas temperature is set, and a particle temperature is chosen. The left hand of equation 5 is examined, if it is positive a higher particle temperature is picked; if it is negative a lower temperature is tried. The procedure is continued until the particle temperature is found to balance the equation. The results of the calculation are given in Table II. They are dependent on the particle radius only through the dependence of Q_{abs} on size. The calculations are based on a combination of graphite optical constants of Phillip[5] in the infrared and Arakawa et al[3] in the near infrared. 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 0.1°K above the gas temperature. The table also indicates that below 1500°K the heat loss process is dominated by conduction. This is due in part to the low infrared emissivity of carbon and the several atmospheres of pressure in the cauldron. In addition, the particles do not reach high enough temperatures to be effective radiators. The low ratio of emission to conduction also means that infrared reradiation from the particles will be suppressed.

The last temperature entry indicates that for the assumed conditions the maximum attainable temperature is 2375°K. This value will depend on the particle size and will increase for smaller particles and decrease for larger particles. The temperature difference $T_p - T_g$ is roughly inversely proportional to the gas pressure and the ratio of P_E/P_C is independent of pressure.

Table II

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	0.09	0.0004
1000	0.069	0.007
1500	0.052	0.079
2000	0.029	2.1
2375	~ 0	(all emission)

*The results of this table are based on values of Q_{abs} for particles of 0.025μ radius and optical constants from references 3 and 5.

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 are high intensity arcs,[6] thermal decomposition of hydrocarbons or carbon monoxide[7] and high temperature pyrolysis of organic resins.[8] 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[6]. The size distribution and crystaline structure may be varied by changing the quenching time and electrode material. Carbon blacks have been produced by thermal decomposition by the channel process since 1872. An entire industry has been built on the production and use of fine carbon particles. The properties of these blacks vary widely but they tend to be symmetrical in shape and to have particle diameters ranging from 0.01 micrometers to 0.5 micrometers. Carbon produced from carbon monoxide forms filaments of thickness of the order of 0.1 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 cauldron and the gas turbine determine the desired characteristics of the particles. As was indicated in the previous discussion, there is a considerable variation in the physical 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 oxidization rate at a given temperature in air. While no experimental data are available for small particles, there are wide variations in bulk reaction rates for various forms of carbon. Calculations based on published rates indicate that at 1000°C the times for complete combustion of particles with a diameter of 0.1μ vary from approximately 20 microseconds for baked carbon to about 0.5 sec. 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.

Another question to be considered is what happens if some of the particles do not vaporize, and enter the exhaust turbine. This can cause a serious erosion problem to the turbine blades if the particles have diameters of several micrometers or larger. Fortunately, this should not be a problem for particles in the submicron size range and most certainly not for particles with diameters less than 0.1μ. The particles are simply so small they follow the motion of the gas stream and avoid hitting the turbine blades.

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 four to six atmospheres for the open cycle Brayton engine. The optimum window-cavity design to confine these pressures depends on a number of factors, including the window temperature, temperature cycling, and aperature size. Pyrex has superior strength qualities and is cheaper than quartz but does not have the high temperature capabilities of quartz. Figure 3a 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 chamber. It is a cylindrical section facing inward to ensure 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 putting 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. The gas streams would be mixed again below the chamber. Figure 3b gives a more complete view of the receiver. This design has the advantage of not requiring a high temperature pressure seal to the quartz heat shield. Figure 4 illustrates the same basic concept but with a number of sections arranged to form a cylindrical, non-cavity type of receiver that is illuminated from all sides.

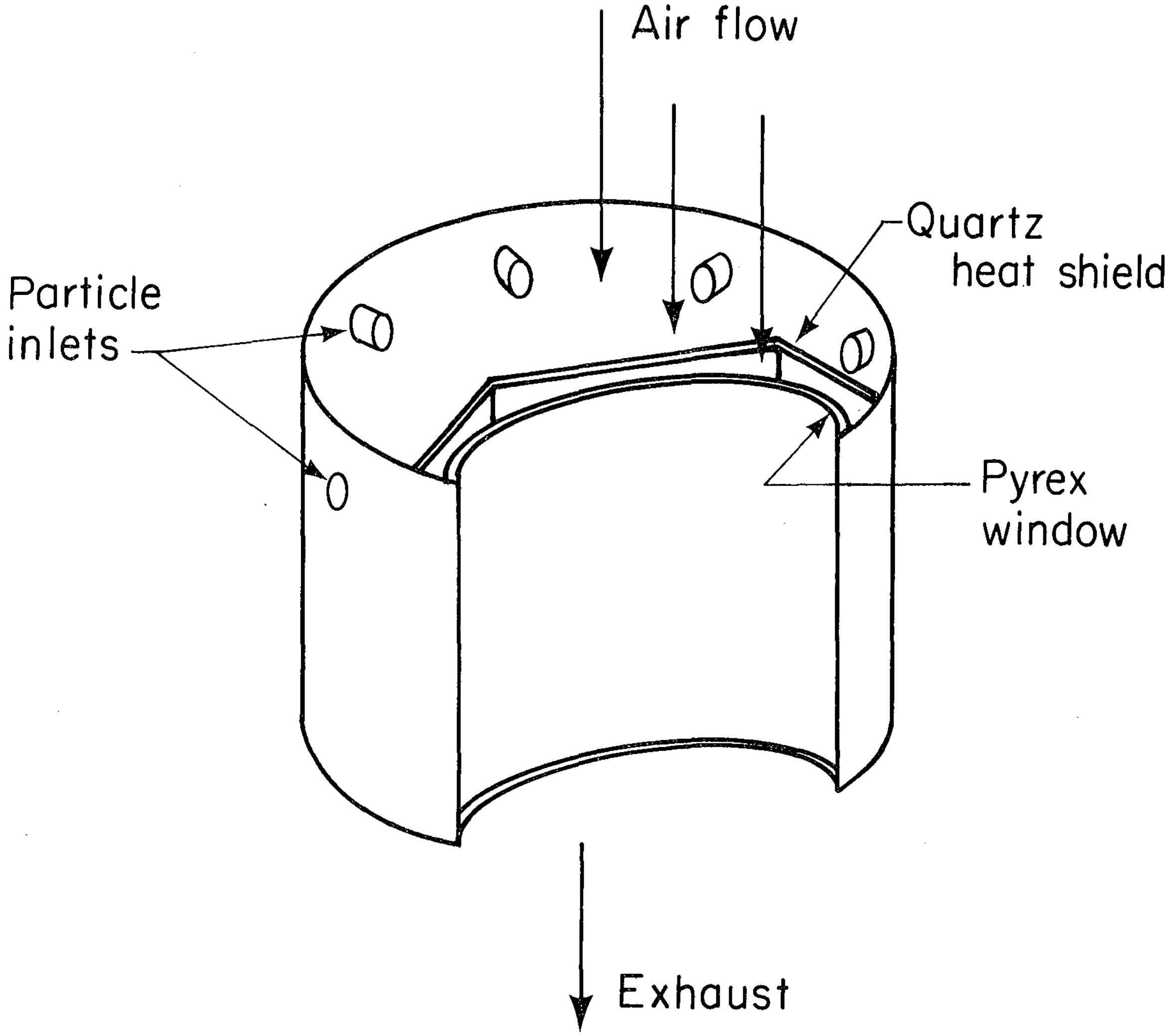

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Figure 3a. Conceptual design of the central portion of the heating chamber for a small particle heat exchanger.

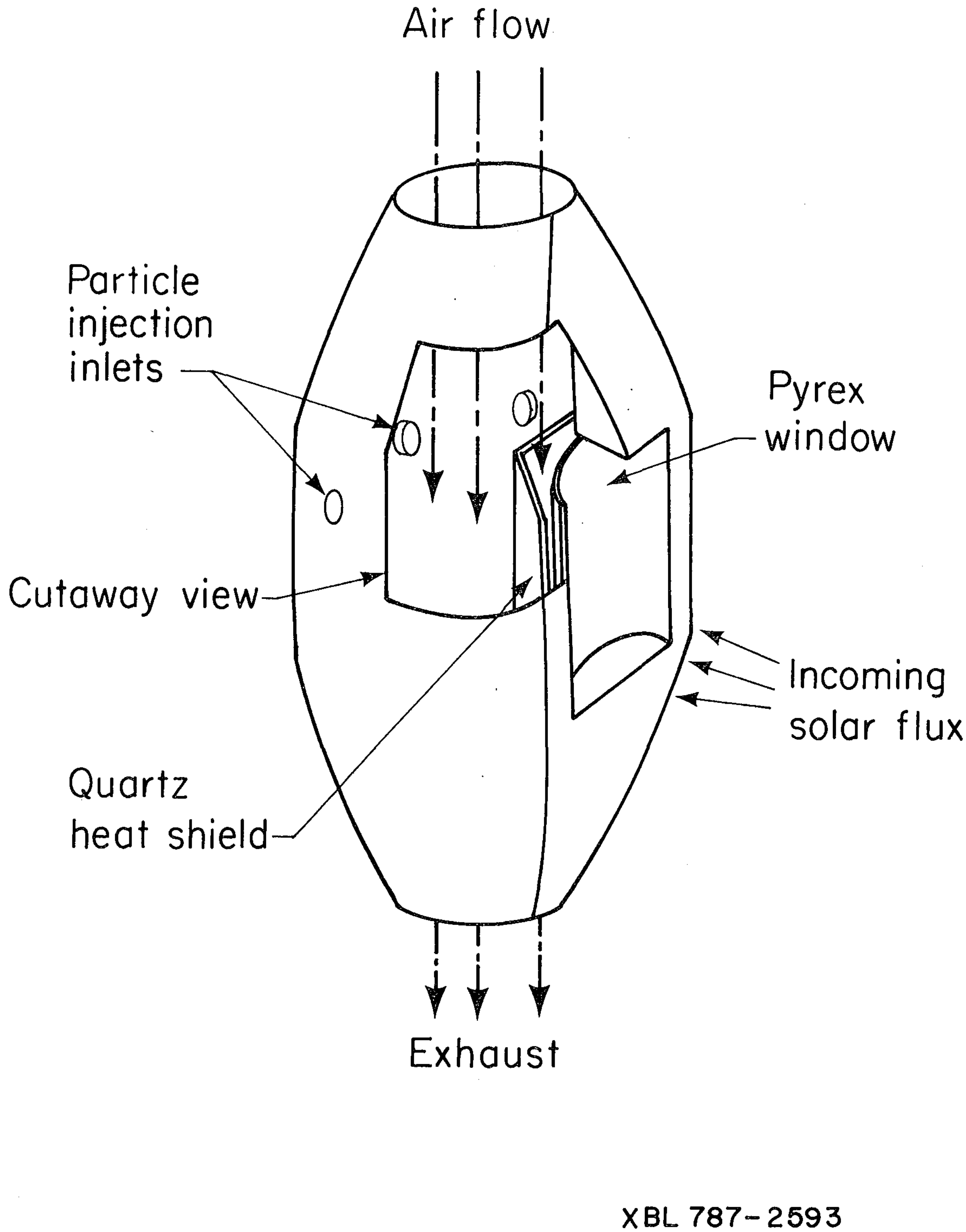

Figure 3b. Conceptual design of the heating chamber for a small particle heat exchanger.

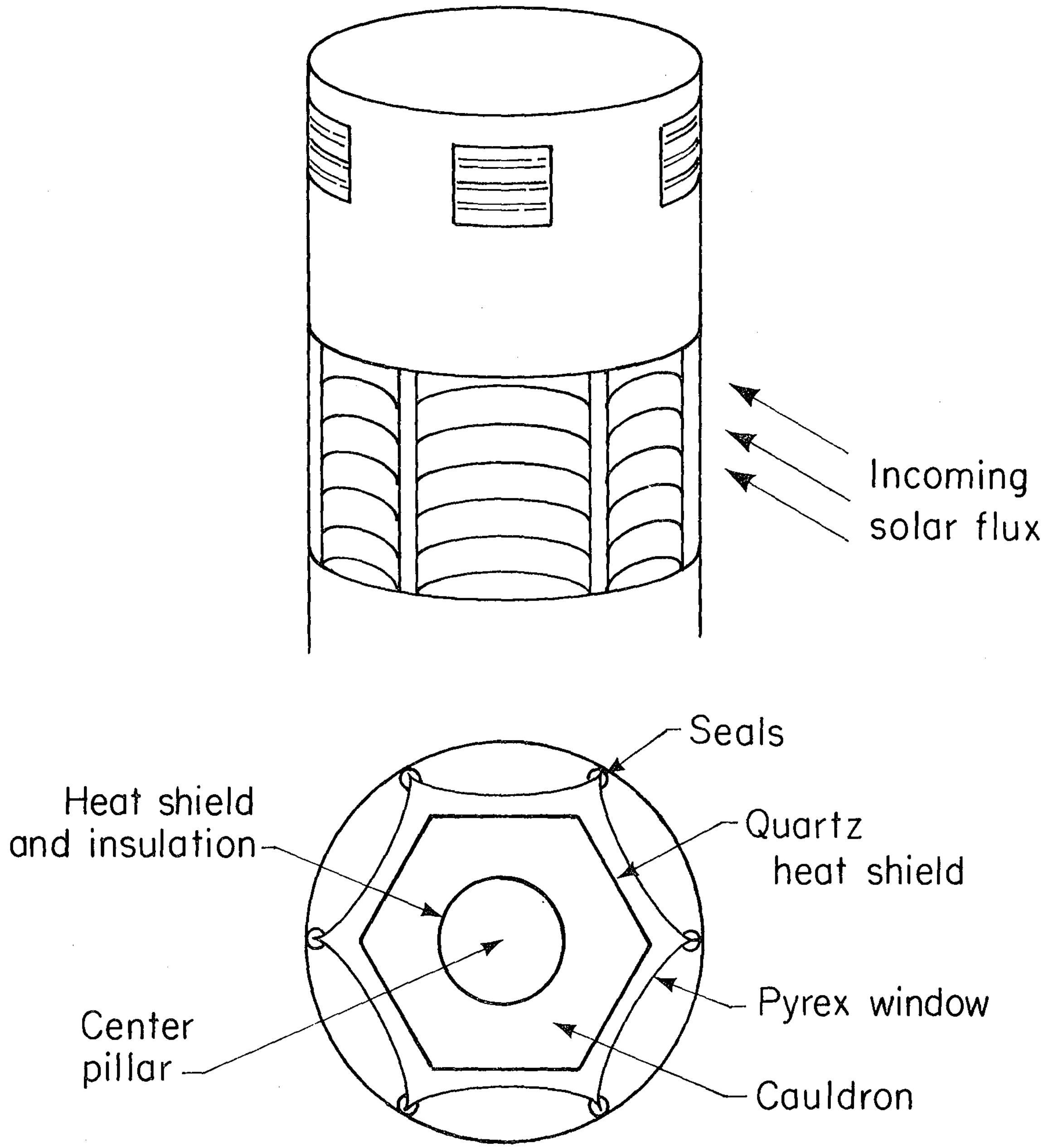

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Figure 4. Conceptual design of a heating chamber to be illuminated from all sides.

Particle build-up on the window is not likely to be a serious problem since the particles are so small they move with the gas stream. In addition, the particle injectors can be positioned so that a sheath of particle-free air is adjacent to the window. If the particles do reach the window and adhere they would quickly be heated to vaporization or combustion temperatures since they are in the region of maximum solar flux.

The walls of the heat exchanger perform a passive function. The particle densities will be such that most of the radiation will be absorbed before reaching the walls. It is desirable to reflect any sunlight that does hit the walls so that it has a further chance to be absorbed by the small particles. This reflective capability would also serve to reflect the incident solar radiation back out of the cavity during throttling down or if insufficient particles are injected into the gas stream.

System Considerations

The SPHER may be used to heat gas for use in either an open or a closed Brayton cycle. The open cycle operates by drawing in ambient air, using it as the working fluid, and discharging it again to the atmosphere. This once-through process avoids the need for the large cooling towers that are 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 advantage of the closed cycle is that it usually operates at higher pressures and energy densities, resulting in a decrease in the size of the rotating machinery. The following discussion deals primarily with the application of SPHER to the open cycle system.

An important question in the analysis of solar-electric production is determining the optimum size for the collector-receiver module. The size for a solar-hybrid power plant incorporating a SPHER has not yet been determined. The basic receiver may be scaled to nearly any size, but for an electric power plant of the type discussed here the probable module size is between 10 and 100 Mw electric.

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 six and 80% recuperation of the exhaust heat. For a gas temperature of 980C° the plant efficiency would be about 36%*. The volume gas passing through the plant would be about 220,000 cubic meters per hour. At these flow rates the amount of carbon needed is only about 10 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.

The electrical requirements for the high intensity arcs have not yet been determined in detail but will be of the order of a few kilowatts, or less than 0.1 percent of plant output. There will be some power required to cool the windows but this should be quite modest if a heat shield is used.

The SPHER concept may be used in a closed cycle Brayton system. In this case however, a combination of particles and working gas must be found to prevent the accumulation of particles in the loop. This would be necessary since new particles would have to be added to make up for the loss in absorption due to 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 the 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.

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*This would be increased by about 10%, and the amount of gas and particles used would decrease by about 40%, if a reheat stage is added.

THE SMALL PARTICLE HEAT EXCHANGER FOR DISTRIBUTED SOLAR APPLICATIONS

Introduction

The discussion in this section will treat the application of the small particle heat exchanger to solar collection systems that utilize linear trough-type concentrators or flat (or curved) plate collectors with no concentration. Almost all the considerations of the optical, physical and thermal characteristics of the particles are identical to those in the preceding section. This discussion will therefore be limited to the system considerations and how they impact the choice of particles and operating conditions.

The Use of the SPHER CONCEPT in a Linear Solar Collector

The linear trough collection systems operate at lower flux concentrations and have higher losses than two dimensional focusing systems. Therefore, they are usually limited to lower temperatures. Other factors that limit the maximum achievable temperatures are the decomposition temperature of collection fluids, and the stability of low cost selective coatings used to decrease infrared radiation losses. Higher operating temperatures are available with the same geometries by decreasing the fluid flow but are limited by the above considerations and the increasing thermal losses.

The SPHER receiver design consists of two concentric pyrex pipes at the focus of a linear trough system. The space between the pipes may be either vacuum or flowing air depending on the application. The use of vacuum would provide higher temperatures. The flowing air could be of intermediate pressure, allowing higher pressures in the inner tube to be achieved. If pyrex pipe were used at moderate pressures, maximum temperatures of the order of 500°C could be reached. This is about 200°C higher than current designs.

The system would operate in a similar fashion to that described earlier. The particles would be chosen to combust or vaproize at lower temperatures and the heating would occur along the length of the pipe. The flows and particle densities are adjusted to ensure that particles are present in the last portion of the pipes.

Small Particle Gas-to-Gas Heat Exchange

A possible non-solar application of the small particle heat exchanger concept is to gas-to-gas heat exchangers. These types of heat exchangers have limited application because they usually have significant temperature drops. This limits the situations in which they can be used to those where large temperature changes are tolerable or desired. To obtain small temperature drops entails using heat exchangers with very large surface areas. Small particle suspensions have the ideal properties for this purpose because of the large surface area for a small volume of material.

The effectiveness of small particles for this application will depend on the desired operating temperature. Since the heat exchange depends on radiative transfer, the temperature must be high enough for a substantial amount of the heat energy to be in the form of radiation. Table II indicates that at 1500°K roughly one tenth of the energy acquired by carbon particles (at 6 atmospheres pressure) is given up in the form of radiation. Since gases by themselves are generally not good radiators at these temperatures,the particles would dominate the radiative transfer process. At higher temperatures and lower pressures the particles will be even more effective at radiating the heat in the gas particle mixture.

Figure 5 illustrates one way a small particle heat exchanger could be arranged. The design resembles a conventional tube and shell type except that the tubes are transparent to radiation of wavelength corresponding to the black body peak at the desired operating temperature. If high pressures are desired, the higher pressure side should be in the drum to keep the tubes in compression. The high temperature side can be on either side although the details of the tube spacing and diameter may vary. More detailed heat transfer calculations are underway and will quantify the performance gains over conventional systems.

Several applications of small particle heat exchangers for this purpose can be identified. Closed cycle Brayton engines must transfer heat energy to the working gas. If the heat results from combustion or is carried by a gas there is a need for an efficient gas-to-gas heat exchanger. Modern fluidized bed combustions units utilizing Brayton cycles must use extensive high temperature filtration to remove the particles from the gas stream before passing it through the turbine. The combustion process must be carried out at high pressures which for large fluidized beds means that the vessels become very heavy. An efficient gas-to-gas heat exchanger would allow lower pressures that would simplify the design and eliminate the need for the high temperature filtration. Other possible applications include transferring heat to the working gas in a Stirling cycle engine and recovering heat from hot stack gases.

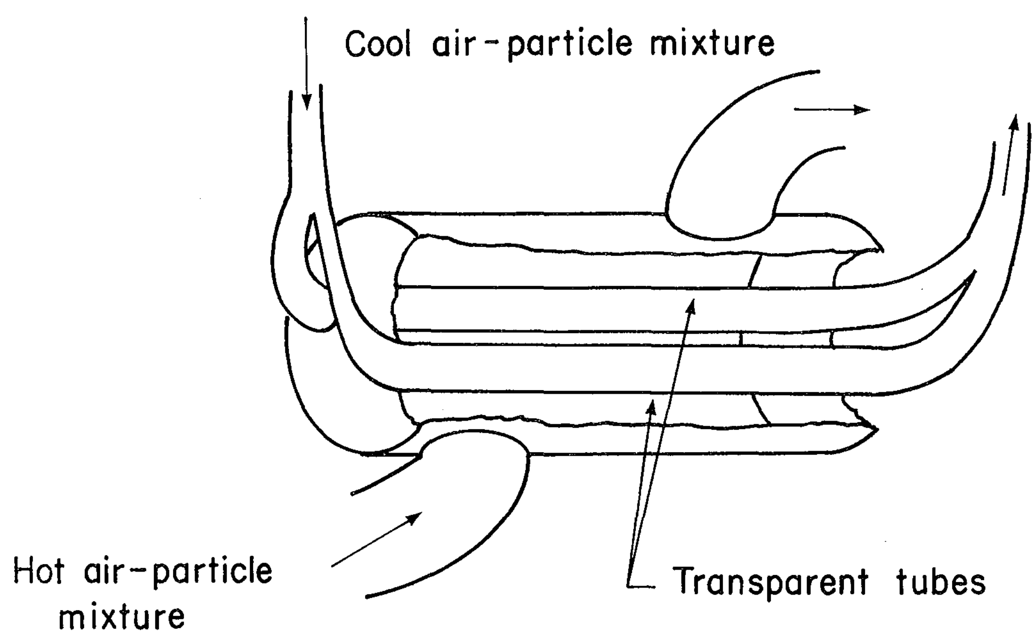

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Figure 5. Possible arrangement of a high temperature gas to gas heat exchanger.

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