Title

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ABSTRACT

This paper describes recent advances in the research program at LBL to understand the behavior of radiantly heated gas-particle suspensions. The research is investigating the use of gas-particle suspensions to absorb concentrated sunlight to supply energy for endothermic chemical reactions. The analytical section includes the description of a chemical survey, the results of optical calculations, and a summary of our heat transfer studies. The experimental section outlines the current laboratory studies of direct radiant heating that utilize a high intensity radiant source to simulate concentrated sunlight. This work is aimed at establishing a technology base supporting new applications of concentrated sunlight for the production of useful fuels and chemicals.

KEYWORDS

Solar thermal; receiver; high temperature; direct absorption; fuel; chemicals; gas; particles; heat transfer

INTRODUCTION

The development of solar thermal systems that utilize concentrated sunlight has opened up new avenues to the industrial use of solar energy. LBL has been involved for the past seven years in the development of solar thermal receivers that utilize suspended particles as solar absorbers and heat exchangers to heat gases for power and industrial process heat applications.[1] This program resulted in the design, construction [2], and successful solar demonstration [3,4] of the Mark I, Small Particle Heat Exchange Receiver (SPHER) at the solar test facility at Georgia Institute of Technology in 1982.

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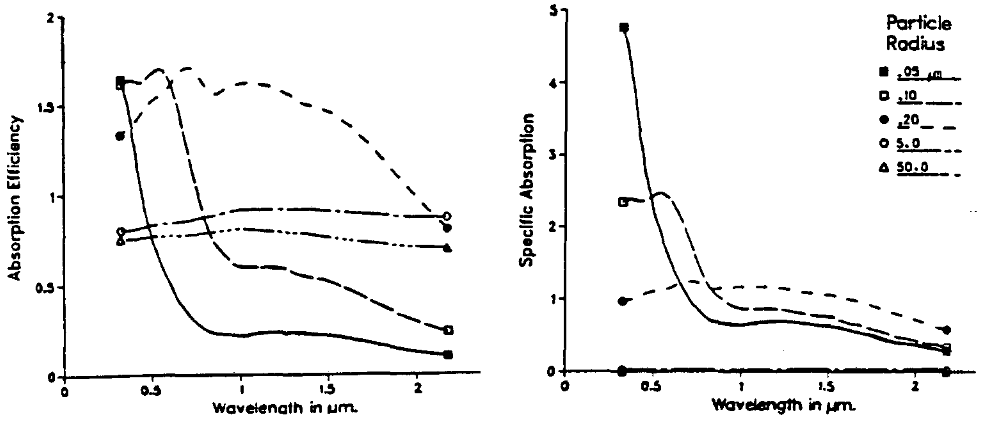
We are extending the earlier work to new methods of initiating chemical reactions. The unique combination of high direct solar flux density and high temperatures in a gas-particle suspension offers a new and unexplored environment for chemical processes. Direct radiant heating of gas-particle mixtures may be used for heating a working gas, processing chemical feedstocks or inducing chemical reactions in the suspending gas. However, before efficient and effective receiver/reactor designs can be developed it is imperative to understand the underlying physical processes. The particles must be absorbing in order to convert the radiant solar energy to thermal or chemical energy. The complex index of refraction, size, and shape of the particles have profound effects on the optical and thermal properties of gas-particle mixtures. The choice of particle size and mass loading (mass of particles per unit volume) have important effects on the size and shape of the receiver, reaction time and process conditions.

ANALYTICAL STUDIES

A survey of chemical reactions in or between gases and absorbing solids was performed. A number of suitable reactions were identified and optical, physical, and chemical data were obtained for the solids involved. Using this data, the optical properties of the particle suspensions were calculated to determine the energy absorbed by the particles. Having determined the heat input to the particles, the next task was to calculate the heat transfer between the particles and the surrounding gas to enable the determination of the temperatures and heating rates of the particles. To do this, a heat transfer model was developed that was suitable for all particle sizes treated in this work.

While direct radiant heating of small particle suspensions is similar for a wide range of particle sizes, the importance of some effects can vary considerably with particle size and mass loading. This study is concerned with particles entrained in flowing gases, e.g., having diameters of a few hundred micrometers down to submicron sizes. The optimum particle loading per volume of gas depends on the application being considered. Very low particle densities are sufficient for gas phase reactions in which the particles act as the radiant heat exchanger or catalyst for the reactions. If thermal processing of a particulate feed stock is desired, wherein the gas basically provides the transport system, much higher loading densities are appropriate. Intermediate particle loading densities are likely when it is desired to initiate reactions between the gas and particles. One of the goals of this research is to define the range of mass loading for a various applications and its effect on receiver design.

The Mie calculation may be used to determine the absorption and scattering of sunlight by spherical particles once the wavelength-dependent complex refractive index and the particle size distribution are determined. Tabulations of the refractive index were obtained from a literature search, and incorporated in a computer data base for several materials identified in the chemical survey. The absorption and scattering efficiencies (cross sectional area for absorption or scattering divided by the geometric cross section of the particle), and the specific absorption for a particle suspension (effective cross-section for absorption per unit mass) were calculated. The absorption coefficient is the product of the specific absorption and the mass of particles per unit volume. A computer program using a Mie subroutine was written to calculate the attenuation of monochromatic radiation by a suspension of particles with a known size distribution. A second computer program was written to calculate the attenuation of energy from radiant sources possessing a broad spectral distribution.



(a) (b)

Fig. 1. (a) Absorption efficiency of a single magnetite particle, and (b) specific absorption of a suspension of magnetite particles versus wavelength of the incident radiation.

Calculated absorption efficiencies are plotted versus wavelength in Fig. 1 for various particle sizes from 0.05 to 50 microns. The specific absorption for the single scattering case is plotted versus wavelength in Fig. 1. The attenuation of polychromatic radiation (in this case the solar simulator) is plotted verses the product of particle mass loading and path length for three different particle size distributions in Fig. 2. This figure permits the rough determination of the size of the receiver required to absorb a desired fraction of light within the particle suspension when the particle mass loading is specified. The information in this figure must be combined with the spatial dependence of the radiant flux pattern to determine the heat input to the particles.

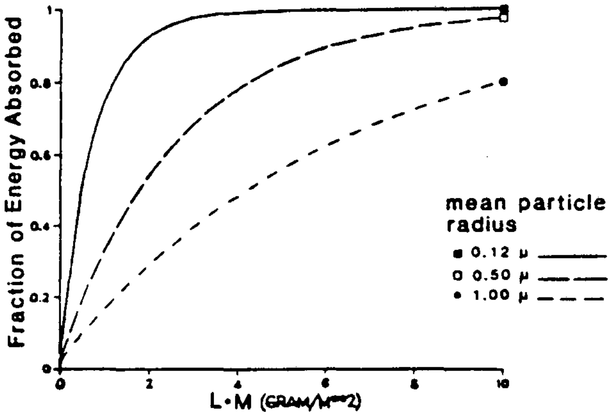


Fig. 2. The attenuation of light due to absorption from a Xenon arc lamp as it passes through a suspension of magnetite particles versus the product of particle mass loading and path length of light.

When the particles absorb radiant energy they heat and transfer energy to their surroundings by conduction, radiation, and possibly chemical reactions. The initial particle heating rate and the final temperature are determined by the heat transfer rates. The characteristics of conductive heat transfer from a particle to the surrounding gas may be broken into three regimes depending on the value of the Knudsen number (Kn), defined as λ/d, where λ is the gas molecule mean free path and d is the characteristic dimension of the particle. For $Kn < 10^{-3}$ the continuum approximation for heat transfer applies. For $Kn > 10$ free molecular flow conditions prevail and expressions based on molecular collisions apply. In the transition region, $10^{-3} < Kn < 10$, analytical modeling of heat transfer is difficult because neither the continuum nor the kinetic theory approach is strictly correct.

The particle-gas heat transfer was analyzed to obtain an expression that is valid for arbitrary Kn; in particular, it applies in the transition region. [5] The resulting expression for the heat transfer Q given by Eq. 1 below, approaches the correct limits as Kn goes to zero or to infinity.

$$Q = \frac{4 \alpha \; a \; k \; \phi (T_p - T_\infty)}{Kn + \dfrac{\phi \alpha}{(2Kn + 1)\pi}} \qquad (1)$$

α is the accommodation coefficient (a measure of how well the molecules thermally accommodate to particle temperature), k is the thermal conductivity of the gas, and ϕ is a numerical constant which depends of the internal energy of the gas molecule ($\phi = 34/75$ for monatomic gas and 48/95 for a diatomic gas). An energy balance on the particle, using this derived expression to model conduction losses, indicates that as the size of the particle decreases, it becomes increasingly difficult for the small particle to be at a temperature that is different from the surrounding gas.

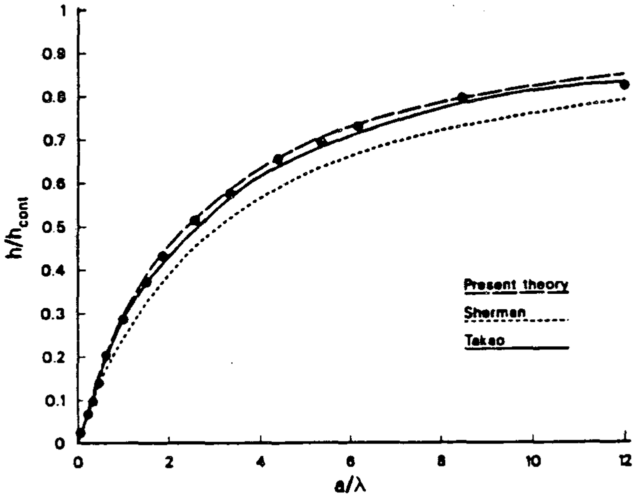


Fig. 3. The nondimensionalized heat transfer coefficient for a spherical particle as a function of the Knudsen number. The points shown on the graph are experimental data from Takao [7].

Calculations of the rate of heat transfer from Eq. (1) are in substantial agreement with experimental data from research in rarefied gas dynamics. (See Fig. 3) [6,7] Because Eq. 1 can be used to calculate the particle temperature for arbitrary Knudsen numbers, it is now possible to calculate particle temperatures for any radiant heating condition (neglecting forced convection). The present treatment provides an upper bound on radiatively heated particle temperatures of falling particles because the forced convection will tend to reduce the temperature difference between particles and gas. The primary value of the equation lies in its ability to predict the heat transfer at values of $Kn \simeq 1$ where a useful expression with an analytic basis was not previously in use.

EXPERIMENTAL STUDIES

An arc-image furnace was constructed to simulate concentrated solar radiation in the laboratory. A xenon arc lamp was mounted at one focus of a deep ellipsoid that reflected light to the other focus. A two-dimensional translational stage was constructed to provide stable mounting for the ellipsoidal reflector ensuring reproducible flux profiles. A similar, but three-dimensional translation stage was constructed to allow precise positioning of the reactor vessel at the focus of the reflector. It also serves as the mount for a scanning calorimeter used to make spatial measurements of the radiant flux. A spatial integration of these measurements was made to determine total power available in the reactor zone. The peak flux density is 4000 kW/m^2 and the total input power to the reactor is 490 Watts. The detailed three-dimensional map of the flux density was an important factor in the design of the receiver/reactor.

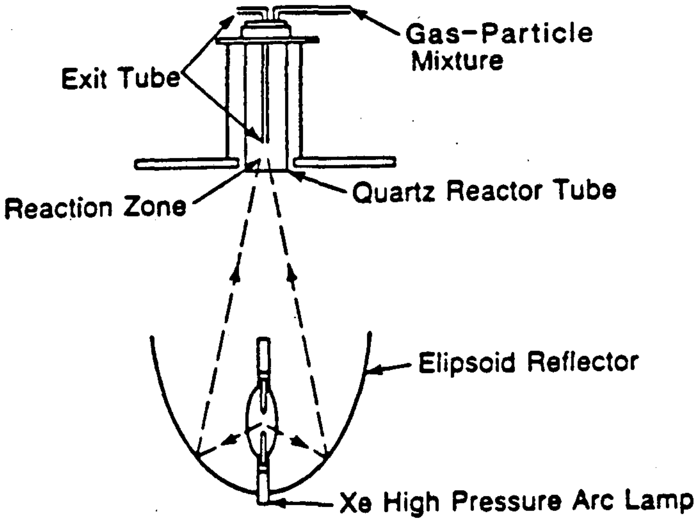


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Fig. 4. A schematic diagram of the reactor vessel placed at the focus of the arc-image solar simulator.

The gas-particle mixture enters the cylindrical reactor vessel at the top, moves in a cyclone fashion toward the bottom and is exhausted through a central tube. Light from the solar simulator passes through a flat quartz window at the bottom of the reactor vessel and is focussed just below the exhaust tube to ensure that all particles pass through the high intensity portion of the beam (see Fig. 4). A number of experiments were made to observe the heating of particle-gas mixtures in the reactor. Temperatures in excess of 1200°K were reached.

A mechanical shaker and cyclone chamber for entraining small particles in a gas stream was built. Commercially available powders of carbon, hematite, and magnetite were entrained in a gas stream and optical extinction measurements were performed on the suspensions. These particle materials were chosen for initial experimentation because of their possible roles in various reactions of interest for the production of useful fuels and chemicals. The mass loading of the particles in the suspension was determined by drawing a known volume of the gas-particle mixture through a filter and weighing the filter. Scanning electron micrographs were made to determine particle size distributions.

CONCLUSION

Earlier work demonstrated that a gas-particle mixture can act as an effective solar absorption medium for heating gas to a high temperature. Currently we are extending the small particle absorption concept to other applications, including the solar production of fuels and chemicals, and the destruction of toxic wastes. The field is entirely new and many issues still need to be addressed. We have identified and gathered data on possible reactions, calculated absorption characteristics of particle suspensions, developed a satisfactory particle to gas heat transfer model, and constructed a laboratory system to study these reactions experimentally.

REFERENCES

1. Hunt, A.J., "Small Particle Heat Exchangers," Lawrence Berkeley Laboratory report LBL-7841, 1978.
2. Hunt, A. J. and Evans, D., "The Design and Construction of a High Temperature Gas Receiver Utilizing Small Particles as the Heat Exchanger (SPHER) Phase I Report ", LBL-13755, 1981.
3. Hunt, A. J. and Brown, C. T., "Solar Testing of the Small Particle Heat Exchange Receiver (SPHER), Phase II Report," LBL-15756, 1983.
4. Hunt, A.J. and Brown, C.T., "Solar Test Results of an Advanced Direct Absorption High Temperature Gas Receiver (SPHER)," presented at the 1983 Solar World Congress, International Solar Energy Society, Perth, Australia, August 15-19, LBL-16497, 1983.
5. Yuen, W.W., Miller, F.J., and Hunt, A.J., "Heat Transfer Characteristics of a Gas-Particle Mixture Under Direct Radiant Heating," Submitted to: International Communications in Heat and Mass Transfer, LBL-18449, 1985.
6. F. S. Sherman, "A Survey of Experimental Results and Methods for the Transition Regime of Rarefied Gas Dynamics," Rarefied Gas Dynamics 3rd Symposium, Vol. II, Academic Press, New York, 1963.
7. K. Takao, "Heat Transfer from a Sphere in a Rarefied Gas," Rarefied Gas Dynamics 3rd Symposium, Vol. II, Academic Press, New York, 1963.

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