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MEASUREMENT OF THE TRANSMISSIVITY OF A CARBON-PARTICLE-SEEDED NITROGEN JET

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ABSTRACT

An experiment was conducted to measure the transmissivity of a flowing stream of nitrogen gas that had been seeded with nominal 0.009-micron carbon particles. The seed density and light-beam wavelength were the variables of the experiment. Seed density was varied from 10^{-5} to 10^{-4} g/cm^3. Wavelength was varied from 200 millimicrons to 3500 millimicrons. The results are presented as a ratio of transmitted to incident light intensity, and as an absorption cross section. Scattering is assumed to be unimportant. The experimental results show that the absorption cross section decreases as the seed density increases. This is attributed to particle agglomeration. The measurements also show that, for all practical purposes, the absorption cross section is independent of wavelength for wavelengths from 200 to 3500 millimicrons.

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SUMMARY

An experiment was conducted to measure the transmissivity of a flowing stream of nitrogen gas that had been seeded with nominal 0.009-micron carbon particles. A commercial powder known as Carbolac was used for seeding. All measurements were made at 1 atmosphere (1×10^5 N/m^2) pressure and room temperature. The measurements were made by passing a beam of light from an external source through the seeded gas stream, and then determining the intensity of the transmitted beam with a spectrophotometer.

The seed density and light-beam wavelength were the variables of the experiment. Seed density was varied from 10^{-5} to 10^{-4} gram per cubic centimeter. Wavelength was varied from 200 to 3500 millimicrons. The nitrogen flow rate was 50 cubic feet per hour (390 cm^3/sec), and the path length was 1.27 centimeters for all tests. The results are presented as a ratio of transmitted to incident light intensity, and as an absorption cross section. Scattering is assumed to be unimportant.

The experimental results show that the absorption cross section decreases as the seed density increases. This is attributed to particle agglomeration. The measurements also show that for all practical purposes, the absorption cross section is independent of wavelength for wavelengths from 200 to 3500 millimicrons. At a seed density of 10^{-5} gram per cubic centimeter, the absorption cross section is between 17 000 and 19 600 square centimeters per gram. At a seed density of 10^{-4} gram per cubic centimeter, the absorption cross section is between 10 800 and 13 000 square centimeters per gram.

INTRODUCTION

The presence of small, opaque solid particles in a transparent gas can cause a large increase in heat transfer to the gas if the heat source is hot enough to radiate a large portion of its thermal energy. In gas-core reactor concepts (ref. 1), the heat source would be a nuclear fuel in either a liquid or a gaseous state. The heat sink is a transparent gas that flows around the gaseous fissioning material. If small, absorbing particles are added to the gas, then the heat could be transferred in the form of thermal radiation. This could lead to efficient heat transfer, and at the same time provide a means for shielding the solid structure from thermal radiation. The anticipated core temperatures range from 50 000° to 60 000° R (27 777.8 to 33 333.3 K), and temperatures in the nozzle exhaust may exceed 15 000° R (8333.3 K). Hydrogen gas is transparent to radiation at temperatures below 10 000° R (5555.6 K). The necessity for seeding the low-temperature hydrogen to effectively absorb radiant energy is apparent. Estimates based on the calculated emissivity of dispersed carbon particles indicate that small concentrations of seed material should make hydrogen sufficiently opaque to protect the reactor walls. It is, therefore, of interest to be able to predict the absorptivity of transparent gases that contain clouds of particles. This report describes an experimental measurement of the absorptivity of carbon particles in a flowing stream of transparent nitrogen. Measurements can not easily be made at the high temperatures associated with the advanced gas-core nuclear reactors. Therefore, the studies were made at room temperatures and can be used as a first estimate in heat-transfer predictions.

In 1908, Gustav Mie derived the basic equations describing the interaction between a plane, monochromatic wave of electromagnetic energy and a sphere that is surrounded by an infinite, nonconducting medium. These equations are still used to make theoretical calculations of absorption and scattering of light by particle clouds. Some calculations using these equations for carbon are presented in references 2 and 3. Theoretical absorption and scattering cross sections are presented in reference 4 for 15 materials of interest for seeding the coolant in a gas-core reactor. References 5 and 6 present calculated absorption and scattering coefficients for a number of metallic particles, as well as some measured refractive indexes.

The theory is helpful in predicting the general influence of such parameters as wavelength and particle size. When applying this theory to a cloud of real particles, however, the sizes and shapes are unknown. For example, particles are not perfect spheres, they are not all of the same size, and they tend to stick together, or agglomerate. All of these imperfections can have a significant effect on the optical behavior of a real particle cloud. Thus, experiments are necessary to determine the absorbing power of real particle clouds.

Two kinds of experiments have been reported. One type of experiment has involved radiant heating of a gas that contains small solid particles. The other kind of experiment has been aimed at more basic measurements of absorption cross sections of various particles, generally at room temperature.

Reference 7 reported a significant increase in total heat transfer to the seeded gas when carbon dust was added to the air stream flowing around a glass-enclosed arc. This arc test gave an average absorption cross section of 22 800 square centimeters per gram for 0.027-micron-diameter carbon particles at carbon seed densities from 0.5×10^{-5} to 1×10^{-5} gram per cubic centimeter. The absorption cross section σ is calculated from the equation $I/I_0 = e^{-\sigma\rho_c L}$. (Symbols are defined in the next section.)

Reference 8 describes the heating of seeded air as it flows through a radiation furnace. A new furnace design has extended these results to where over half of the heat transfer is by thermal radiation (ref. 9). Using a flash lamp to heat seeded hydrogen and helium, reference 10 measured an absorption cross section of 4700 square centimeters per gram for 1-micron carbon particles with a density of 10^{-4} gram per cubic centimeter.

For carbon particles dispersed in water, reference 11 reports spectral absorption cross sections from 6000 to 14 000 square centimeters per gram with Carbolac powder 0.009 micron in diameter. These measurements indicated no variation with wavelength of the incident light over the range from 200 to 1000 millimicrons. The carbon seed density ranged from 10^{-6} to 10^{-4} gram per cubic centimeter. Reference 12 used aerodynamic shear forces to decrease agglomeration and measured extinction cross sections from 10 000 to 58 000 square centimeters per gram for Carbolac powder dispersed in flowing helium and nitrogen. Measurements were made at four wavelengths between 255 and 550 millimicrons for carbon seed densities of 8×10^{-5} gram per cubic centimeter in nitrogen and 1.6×10^{-5} gram per cubic centimeter in helium. No strong dependence on wavelength was found. The main difficulty with pneumatic dispersion employing shear forces is that it requires large amounts of flowing gases. Therefore, the production of very dense clouds of suspended particles is difficult.

Reference 13 reported an absorption cross section of 20 000 square centimeters per gram for 0.009-micron-diameter Carbolac in flowing nitrogen. Wavelength ranged from 110 to 800 millimicrons. The measurements were made at temperatures from 70° to 1500° F (294 to 1090 K), and no temperature effect was found. Particle density varied from 0.6×10^{-5} to 2×10^{-5} gram per cubic centimeter. This is the first experimental indication that the absorption cross section of carbon powder is independent of temperature, at least up to 1500° F (1090 K). This fact increases the usefulness and applicability of measurements made at room temperature.

It is the purpose of the experiment reported herein to extend the wavelength range of these previous measurements and to investigate the effect of a systematic variation of particle seed density on the absorption cross section. No special devices or procedures were used to prevent particle agglomeration. Commercially available Carbolac powder was used to seed a flowing nitrogen stream. The powder had a "nominal" diameter of 0.009 micron. The actual particle cloud, of course, was made up of some unknown distribution of sizes.

The absorption cross section was determined by measuring the attenuation of a beam of light passed through the seeded gas stream. A spectrophotometer was used to measure spectral transmissivities over a wavelength range from 200 to 3500 millimicrons. Seed densities from 10^{-5} to 10^{-4} gram per cubic centimeter were investigated. All results are presented either as a transmissivity or an absorption cross section.

SYMBOLS

d	diameter, cm
I	transmitted light intensity, W/cm^2
I_o	incident light intensity, W/cm^2
L	path length, cm
r	radius, cm
z	dimensionless transverse position
ρ	density, g/cm^3
σ	absorption cross section, cm^2/g
λ	wavelength, cm

Subscripts:

c	carbon
p	particle

APPARATUS AND PROCEDURE

The experimental apparatus and the data-taking operation are described in this section. The experimental setup was composed of two main components. One of these was the equipment necessary to produce a steady, uniform stream of nitrogen gas containing a known concentration of Carbolac powder. The other experimental subsystem was the optical instrumentation used to measure transmissivity at wavelengths between 200 and 3500 millimicrons. The overall experimental arrangement is shown in figure 1.

Seeded-Gas System

The particle-carrying gas stream was produced by flowing metered nitrogen gas through a powder feeder, then through a nozzle where the measurements were made.

A cross section of the nozzle is shown in figure 2. The Carbolac particles were added to the nitrogen with a Thermal Arc powder feeder. The carbon particles are stored under pressure in a vibrating container. A variable-speed screw feed is used to inject the powder into a high-speed jet of nitrogen gas. The seeded gas then passes through a vortex flow mixer, where a reasonable deagglomeration is provided.

The seeded nitrogen stream flowed from the seeder through a 5-foot (1.524-m) length of 1/2-inch- (1.27-cm-) inside-diameter tubing into a nozzle. The nozzle was developed to provide a uniform stream of seeded gas of a known diameter of 1/2 inch (1.27 cm). The nozzle assembly is shown in figure 2. A slot near the end of the nozzle was used to allow passage of a light beam through the gas stream.

No attempt was made to measure particle diameter. The particles used are characterized by the manufacturer as being 0.009 micron in diameter. Insofar as no specific effort was made to reduce agglomerates, the average size of a particle in these experiments was considerably larger than 0.009 micron. Even if there were no agglomeration, there is some distribution of particle sizes. Figure 3 (taken from ref. 14) shows a typical size distribution of channel black, the kind of powder used in these experiments. A number for particle diameter or size distribution was not required for any data reduction.

Some preliminary transmission measurements were made to determine how uniformly the nitrogen jet was seeded. A light beam was passed through the seeded jet, normal to the flow direction, at various transverse positions. Thus, the path length through the seeded stream was some chord across a circular cross section of the flowing gas. Figure 4 shows the result of such a chordal traverse. The seed material appears to be uniformly distributed, since no dissymmetries are apparent. It is possible, of course, that some axisymmetric variation of seed concentration was present.

If the seed were uniformly dispersed, then the transmissivity should vary in some particular way with tranverse position. Algebraic manipulation of Beer's law of transmissivity easily discloses that on a semilog plot the line relating transmissivity to transverse position should be an arc of a circle. Figure 5 shows a replot of the data of figure 4 on semilog coordinates. The data can be fitted with an arc of a circle over a substantial portion of its width. This shows that the seed material was dispersed uniformly throughout the nitrogen gas stream.

In addition to the distribution of powder, it is necessary to know the absolute concentration of seed in the nitrogen stream. The concentration was controlled by adjusting the seeder feed drive speed. The nitrogen flow rate was constant. A calibration curve of weight flow rate of carbon powder as a function of the speed-control setting was obtained gravimetrically. The carbon powder was removed from the gas stream for a known length of time by passing it through a filter bag which trapped the particles but let the nitrogen pass through. The weight of the filter bag was substracted from the total weight to obtain the weight of carbon powder. Figure 6 shows the calibration curve, with each data point representing an average of four runs. All of the measurements were performed at a predetermined setting of the seeder speed control and a constant gas flow rate. Figure 6 was used to determine the weight flow rate of seed material in subsequent experimental runs.

Optical Instrumentation System

The optical system consisted of a light source, mirror system, and recording spectrophotometer. This system is illustrated schematically in figure 1.

The light source used was a quartz iodide lamp that has recently been recommended by the National Bureau of Standards as a new standard of irradiance. It is a 200-watt lamp that has a coiled-coil tungsten filament. The filament temperature is 3000 K. The lamp was stable over a spectral range from 250 to 2600 millimicrons. The lamp provided a very bright, steady light source for these experiments.

Reverse optics were used so that the light source could be located outside the spectrophotometer. The light was collected by mirrors, chopped, and then passed through the flowing gas stream. The transmitted beam was then collected and focused on the slit of the spectrophotometer. The chopped signal was rectified in the spectrophotometer internal circuitry. The three spherical mirrors used to reflect and focus the light beam are shown in figure 1. The chopper operated at 480 hertz.

A Beckman model DK1A spectrophotometer was used to measure the spectral intensity of the transmitted light beam. Slit width between 10^{-3} and 10^{-2} centimeter was used for all experiments. This small slit width allowed adequate resolution. The spectrophotometer utilized a monochromator and either a lead sulphide detector or a photomultiplier tube. The effective spectral range of the instrument was from 200 to 3600 millimicrons. The single-beam mode of operation used in these tests proved to be quite satisfactory. No diffiuclties were encountered due to stray light because the spectrophotometer was tuned to respond only to the chopped-light frequency.

Data Reduction

The basic data of a run consisted of a seeder speed setting and two traces of lamp intensity as a function of wavelength (one trace with seeding of the carrier gas and one trace without seeding). From these two traces, transmissivity as a function of wavelength is obtained.

The seeder speed setting was used to obtain a seed flow rate from figure 6. This weight flow rate of seed and the known, constant nitrogen flow rate of 50 standard cubic feet per hour (390 cm^3/sec) were used to compute the seed density in the flowing gas stream.

Transmissivity data are presented at a selected wavelength as a function of seed density. The choice of wavelength was rather arbitrary, since no strong influence of wavelength was found. Therefore, the monochromatic transmissivities are shown at the wavelength of maximum light-source intensity, 550 millimicrons.

Some of the data are presented in the form of a cross section. It is assumed that scattering was not important in these experiments (ref. 11). The cross section is calculated from the ratio of transmitted light intensity to incident light intensity according to the following equation:

$$\frac{I}{I_o} = e^{-\sigma \rho_c L} \tag{1}$$

The carbon density ρ_c is in grams per cubic centimeter. The path length L for these experiments was 1.27 centimeters. This gives the absorption cross section σ in units of square centimeters per gram.

RESULTS AND DISCUSSION

The discussion of the results obtained is divided into three topics. The first topic is the effect of seed density on transmissivity at a wavelength of 550 millimicrons. Next, the variation of transmissivity with wavelength, at constant seed density, is discussed. Finally, the absorption cross section over the entire range of both wavelength and seed density is presented. Seed with a particle size of 0.009 micron was used throughout the investigation.

Effect of Seed Density

Seed density was varied by holding gas flow rate constant and increasing the amount of seed material. The ratio of transmitted light intensity to incident light intensity was measured for seed densities ranging from 10^{-5} to 10^{-4} gram per cubic centimeter. These measurements were made with monochromatic light at a wavelength of 550±3 millimicrons. This wavelength corresponds to the maximum brightness of the light source. Subsequent measurements showed that these results are a good representation of what happens over the entire wavelength range that was investigated (200 to 3500 millimicrons).

The experimental results are shown in figure 7. As the seed density is increased from 10^{-5} to 10^{-4} gram per cubic centimeter, the percent of incident light that is transmitted decreases from 78 to 21 percent. This is somewhat to be expected, since equation (1) shows that transmissivity varies exponentially with seed density, if path length and cross section remain constant.

Since path length is constant, the data should fall on a straight line if the absorption cross section is constant and equation (1) holds true. This is almost the case. The solid faired curve does not differ greatly from a straight line (shown dashed). The fact that the solid line curves means that an absorption cross section calculated from equation (1) would vary with seed density.

The absorption cross section is shown in figure 8 as a function of seed density. The absorption cross section decreases as concentration increases. For a seed density of 10^{-5} gram per cubic centimeter, the absorption cross section is 18 000 square centimeters per gram. For a seed density of 10^{-4} gram per cubic centimeter, the absorption cross section is 12 600 square centimeters per gram. The decrease of absorption cross section with an increase of density is consistent with the assumption that particle agglomeration is the cause. At higher seed densities, particles are closer together and, therefore, more likely to stick together at the same gas flow rate. It seems probable that agglomeration is the reason for the observed variation of absorption cross section.

Effect of Wavelength

The transmissivity of Carbolac powder for wavelengths ranging from 200 to 3500 millimicrons is shown in figure 9. The path length is constant at a value of 1.27 centimeters. Results are shown for four constant seed densities ranging from 10^{-5} to 10^{-4} gram per cubic centimeter. There is no important variation of transmissivity with wavelength. There is some slight spectral dependence from 200 millimicrons up to 600 millimicrons. The general conclusion is that the absorption cross section of Carbolac powder is independent of wavelength over the range studied. This conclusion is in agreement with the results reported in reference 12 over the wavelength range from 255 to 550 millimicrons and in reference 13 over the wavelength range from 110 to 800 millimicrons.

The small variation of transmissivity in the near-ultraviolet wavelength range was investigated in more detail to be sure it was a real effect. Figure 10 shows the results for short wavelengths ranging from 200 to 600 millimicrons. The variation does seem to be a real one, but it is weak and of no practical importance to the energy absorption process.

Absorption Cross Section Over Entire Experimental Range

All of the data shown in figure 9 were reduced to absorption cross section values. They all fall within the band shown in figure 11. The variation of absorption cross section at constant density is due to the effect of wavelength. Figure 11 shows that the effect of seed density on the absorption cross section is greater than that of wavelength in the ranges studied.

At a seed density of 10^{-5} gram per cubic centimeter, the absorption cross section varies from 17 000 to 19 600 square centimeters per gram for wavelengths ranging from 200 to 3500 millimicrons. At a seed density of 10^{-4} gram per cubic centimeter, the absorption cross section varies from 10 800 to 13 000 square centimeters per gram for the same wavelength range.

CONCLUSIONS

The ratio of transmitted to incident light intensity was measured for a flowing stream of nitrogen gas that contained Carbolac powder. The path length was 1.27 centimeters and the nitrogen flow rate was 50 cubic feet per hour (390 cm^3/sec) for all runs. Seed density was varied from 10^{-5} to 10^{-4} gram per cubic centimeter. The normal particle size used throughout the investigation was 0.009 micron. A spectrophotometer and an external light source were used to measure transmissivity at wavelengths ranging from 200 to 3500 millimicrons. Some of the results are presented in the form of an absorption cross section. Scattering was assumed to be unimportant, so all attenuation is attributed to absorption. No special attempt was made to prevent particle agglomeration. The results of this experiment indicate the following conclusions for Carbolac powder over the wavelength and seed density ranges studied.

1. Absorption cross section decreases as seed density increases. The probable reason is that there is more particle agglomeration at a density of 10^{-4} gram per cubic centimeter than at 10^{-5} gram per cubic centimeter.

2. There is no important variation of absorption cross section with wavelength. There is a slight but measurable variation in the near-ultraviolet wavelength region.

3. At a seed density of 10^{-5} gram per cubic centimeter, the absorption cross section is between 17 000 and 19 600 square centimeters per gram.

4. At a seed density of 10^{-4} gram per cubic centimeter, the absorption cross section is between 10 800 and 13 000 square centimeters per gram.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 8, 1968,
122-28-20-17-22.

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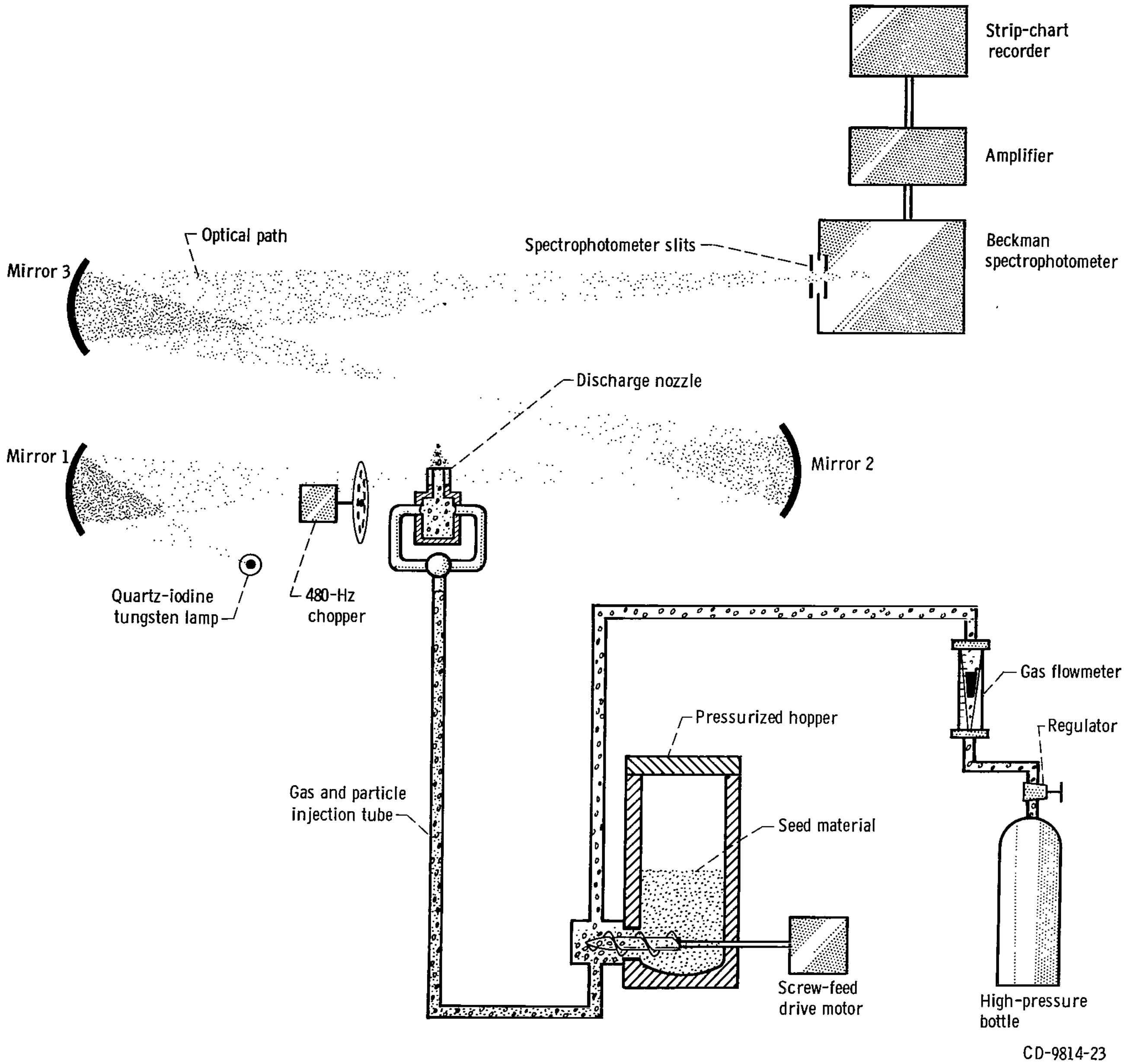

Figure 1. - Schematic diagram of optical system and particle seed device.

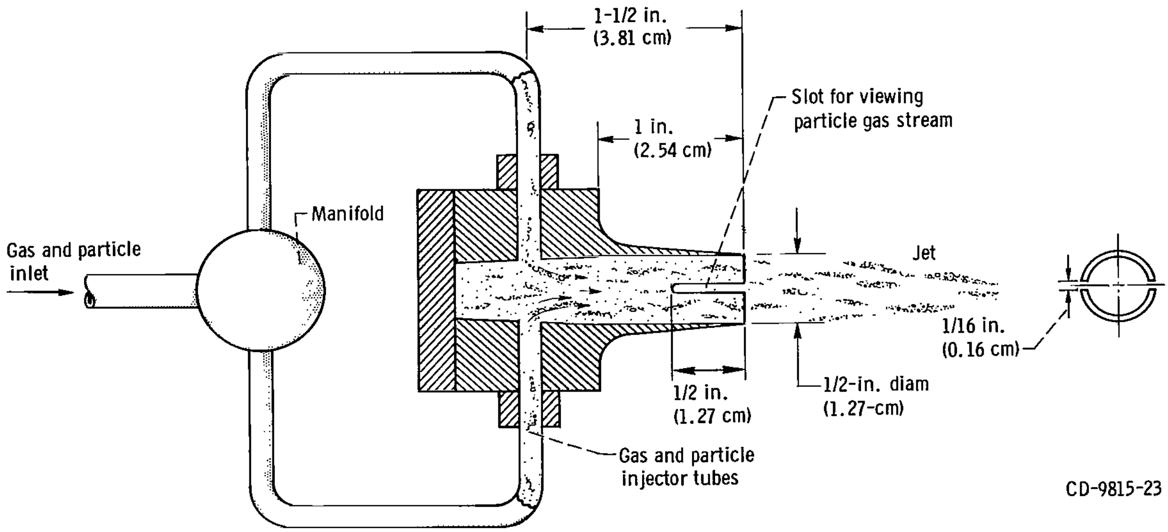

Figure 2. - Nozzle assembly and light-path slot.

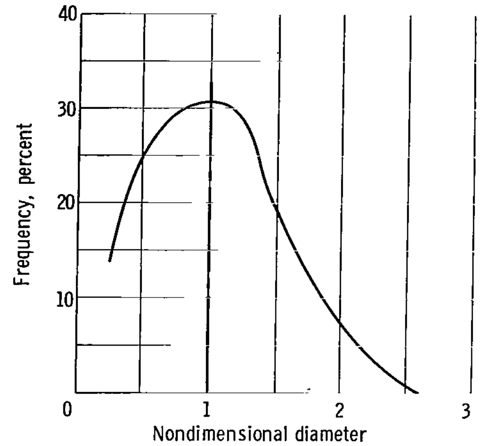

Figure 3. - Typical size distribution of channel black.

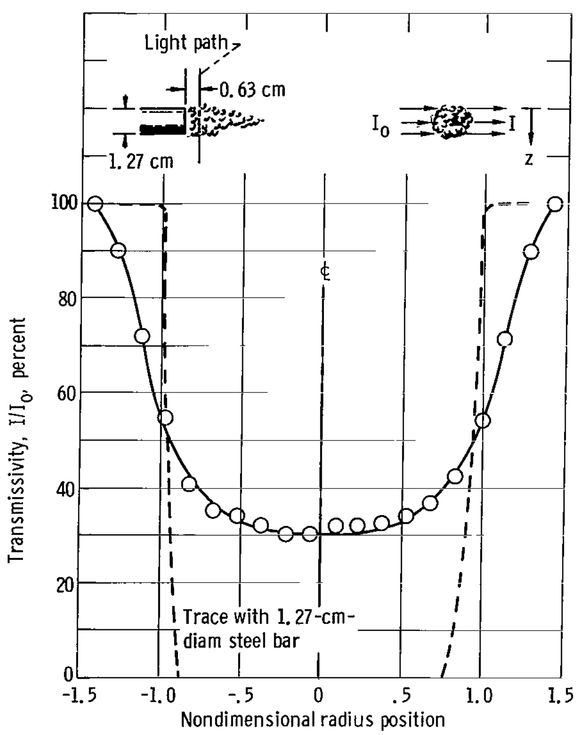

Figure 4. - Symmetry of Carbolac-seeded nitrogen jet.

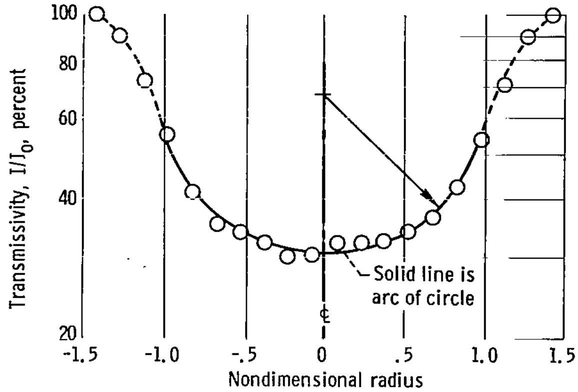

Figure 5. - Uniformity of Carbolac-seeded nitrogen jet.

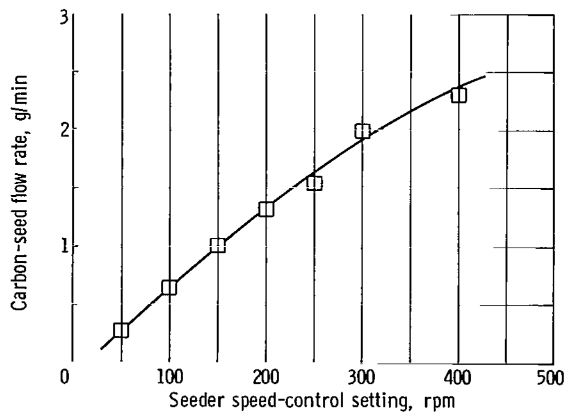

Figure 6. - Seeder calibration curve for Carbolac powder. Each data point represents an average of four runs.

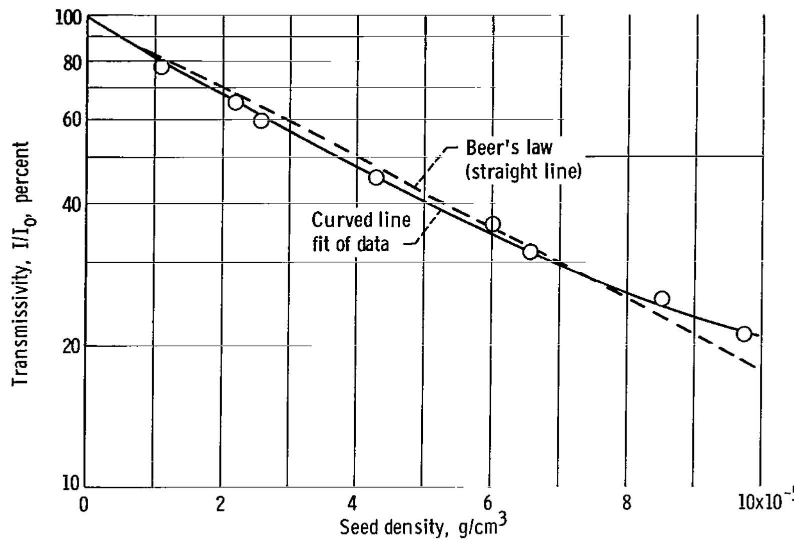

Figure 7. - Applicability of Beer's law to Carbolac powder at wavelength of 550 millimicrons for path length of 1.27 centimeter.

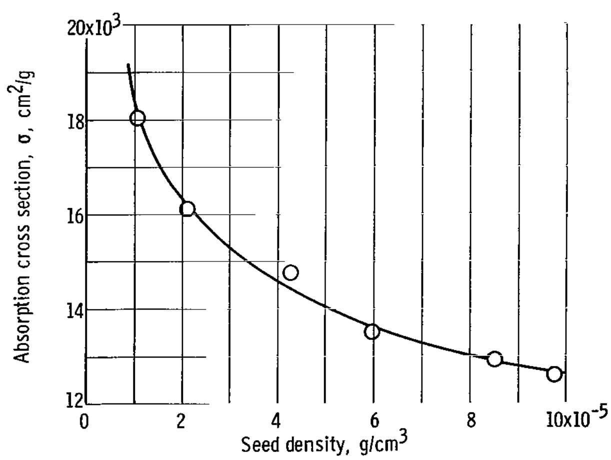

Figure 8. - Effect of seed density on absorption cross section at wavelength of 550 millimicrons.

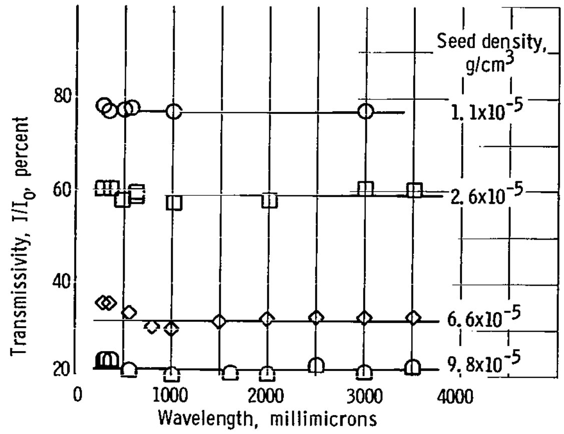

Figure 9. - Spectral variation of Carbolac transmissivity for path length of 1.27 centimeters.

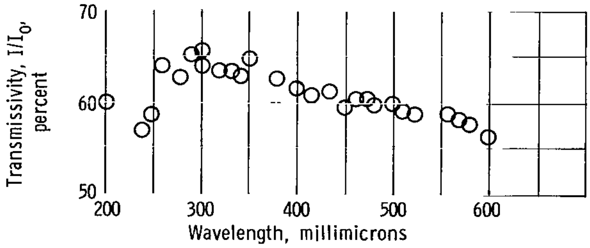

Figure 10. - Short-wavelength transmissivity of Carbolac for density of 2.5×10^{-5} gram per cubic centimeter and path length of 1.27 centimeters.

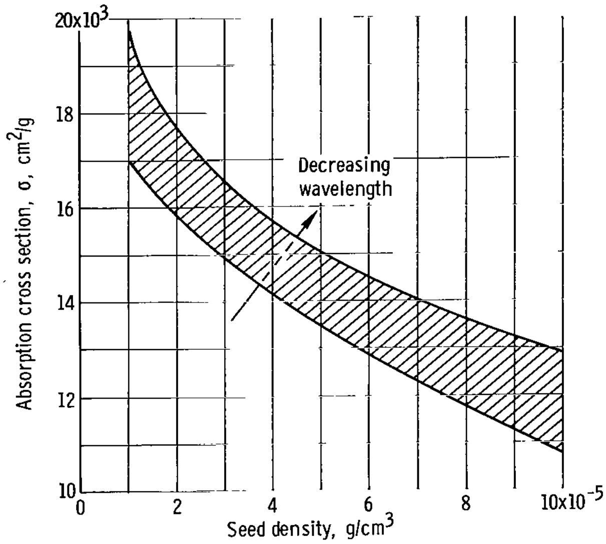

Figure 11. - Absorption cross section of Carbolac powder for all wavelengths from 200 to 3500 millimicrons.

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