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PULSED HOLOGRAPHY OF RAPIDLY MOVING DUST PARTICLES

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* microns

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ACKNOWLEDGMENTS

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Pulsed Holography of Rapidly Moving Dust Particles

I. Introduction

Visual access to various processes involving small particles has been made possible in recent years through pulsed holography. High velocity particles carried in wind tunnel air flows have been counted and sized [1,2]. Resolution in the 5-20 μm range has been obtained. The combustion of 50 μm coal particles has been observed for the first time with a resolution of 3 μm,[3] thus yielding insight into the combustion processes. While the in-line geometry is the simplest to arrange, it has been shown that off-axis geometry yields less noisy and higher resolution holograms.

A process involving small particles that has not yet been visualized is that of impacting. Neither the possible fragmentation of an impacting particle, nor the cratering of the impact surface has been observed in order to develop an adequate model of such microscopic impacts. In order to observe the details of such a process very high resolution must be achieved.

The purpose of the present work is to further develop the necessary techniques of optical holography so as to observe such impacts. In a previous study[4] static particles in 10-50 μm range were the objects in off-axis and in-line geometry holograms, in order to determine the optimum optical system to use to maximize resolution. It was found that an off-axis geometry with a 10X magnification prior to recording will yield resolution to less than 3 μm. Double exposure holograms made to simulate the technique for measuring individual particle velocities display a significant loss of contrast, in many cases making identification of corresponding image pairs impossible. Image subtraction was successfully used to restore contrast. Although the technique is feasible in CW holography the conditions necessary to obtain subtraction are very difficult to control.

The research reported here is an extension of the previous work to pulsed holography of rapidly moving particles. The ultimate goal is to observe a particle impact. The particle's velocity is to be measured, hence double exposure holograms are to be made. This means that the loss of contrast produced in such double exposures is to be dealt with. Also, since interest is focused on the particle and on the fragments produced in the impact, resolution is to be as high as is feasible.

To deal with the contrast loss, image subtraction has been effected by using a Pockel's cell to change the phase in the reference beam during the second exposure. By using a recording geometry similar to that employed in the earlier work, resolution to a few microns has been obtained again and image smearing due to particle motion has been found to be negligible for the velocity range obtainable with the apparatus used.

During the course of the experimental work two things occurred which were unexpected. First, occasionally image subtraction occurred spontaneously due to turbulent air flow from the nozzle used. Second, apparent flow was observed around particles carried by the air stream due to the fact that there was a velocity differential between the particles and the stream.

II. Theory

It has been clearly established that magnification of micron sized objects prior to hologram recording is a necessity to obtain optimum resolution.(3) Of course the magnification system will be an additional factor to consider in optimizing resolution. In the present work the dust and carrier stream could be located virtually anyplace with respect to an optical system, so a short focal length magnifier was used. Of course inexpensive, well corrected, and high resolving power optics is readily available. For the work reported here a Gaertner 10X eyepiece was used. In the back focal plane there is a 1.25 cm field of view, thus making it possible to make hologram recordings simultaneously of the nozzle tip and a 1 cm particle field. The nozzle provided a convenient scale for measuring particle sizes and velocities. Based upon physical measurements of the eyepiece, a theoretical 0.7 μm resolution is possible for particles in the back focal plane. However, bench tests show that other factors limit resolution to about 2 μm. This is the first factor involved in smearing of holographic images.

The second factor, and one that is anticipated to be the more important one, is that of particle motion during recording. During a typical recording time of 20 ns., particles will travel a distance of .02v μm where v is in meters per second. Thus 100, 200, 300 m/s particles will produce images smeared by equivalent amounts of 2, 4, 6 μm, respectively. Therefore, at the higher particle velocities, smearing due to particle motion dominates. However, in fact such velocities were not obtainable with the equipment used, so that the factors of magnifier resolving power and particle motion were comparable.

As has been elsewhere shown[4,5] contrast loss is a rather serious problem in double exposure holograms. Restoring contrast may be accomplished by introducing a 180° phase change in either reference or object beams during the second exposure. A number of methods have been proposed,[6] and at least two have produced good results.[4,5] In the present work a novel method has proved quite successful. This is to effect the phase change by triggering a second Pockel's cell exterior to the laser cavity during the second exposure.

The idea is rather simple. A Pockel's cell is normally used within the laser cavity in conjunction with the linearly polarized laser pulse and a Brewster stack to rotate the plane of polarization of the pulse. The rotation of this plane is produced when the Pockel's cell crystal is rendered biaxially birefringent by an axial electric field. Figure 1(a) shows the incident and transmitted polarizations when no axial electric field exists. Figure 1(b) shows the ordinary and extraordinary axes, the incident and transmitted polarizations when an appropriate axial electric field is applied. Effectively the extraordinary wave suffers an additional 180^{o} phase change in passing through the crystal under the applied field (triggered) condition. The recombination of ordinary and extraordinary waves upon exiting the crystal produces the desired 90^{o} polarization rotation required for Q-switching.

This mode of operation of the Pockel's cell may be used to advantage to produce a 180^{o} polarization rotation, or equivalently, a 180^{o} phase change in, say, the reference beam. A perspective view of the Pockel's cell is shown in Figure 2 for arrangement to produce subtraction. In Figure 2(a) is shown the entering and exiting polarization before triggering and in Figure 2(b) is shown the ordinary and extraordinary axes, the entering and exiting polarizations during triggering.

III. Description of the Equipment

The laser system used was a Korad Holocamera Model K1200 QDH,KHCL. This system is capable of producing two 20 ns pulses separated by nominally 10 μs to 100 ms and having combined energies of 10 J. It is specifically designed to be mobile and consequently employs a folded optical system.

The energy output was much greater than that necessary for the present work, so the system was modified by removing the two amplifier heads. The output was thus reduced to the order of 100 mJ. ND filters were then used to make final adjustments in the energies of the reference and object beams. The laser geometry is shown schematically in Figure 3.

In order to measure the pulse separations in the double pulsing mode a fast vacuum photo diode and a 50 MHz storage oscilloscope were employed. At the same time, the relative heights of each pair of pulses were routinely recorded. A typical oscilloscope trace is shown in Plate 1. The maximum time resolution of this detection system was about 2 μs - comparable to the minimum pulse separation obtainable with the laser system.

The abrasive dust was given its high velocity in a S. S. White Airdent dental trimmer. This machine is the type used in orthodontal and dental work as a small "sand blast" unit. Nitrogen gas at high pressure is passed through a regulator to reduce the pressure to the range 20-130 psi. The dust is held in shakers which feed the particles into a venturi in the gas flow. The gas and entrained particles may be passed through a variety of nozzles.

The nozzle actually used in this study was cylindrical with ID 525 μm and OD 1060 μm. A quick check of the dental trimmer at the Applied Research Laboratory of the Pennsylvania State University using LDV indicated that the trimmer was capable of producing velocities in the range of 100-125 m/s. The results were somewhat ambiguous because of the rather large particles employed (60-125 μm). It was hoped that higher velocities would occur, but this did not turn out to be the case.

IV. Procedure

As a check on the particle sizing done using the holograms and comparison with the nozzle size, a number of particles were sized using a standard measuring microscope. Typical results are shown in Table 1. It can be seen that the smallest particle dimension was about 50 μm and the largest was 185 μm. The particles are alumina purchased from a dental supplier and are appropriately angular for abrasive work.

After the particles were characterized the optical system was properly aligned for holographic work. Using a series of "burns" produced by the pulsed laser on exposed Polaroid film, a gas laser was aligned with the pulsed beam. In the usual way this laser was then used to position, aligned, and focus the pinhole filters. Collimating lenses were chosen to produce beams of the appropriate diameters. The object beam was thus made one half inch in diameter - approximately the same as the field of the magnifier used in constructing the holograms. Also the reference beam was made about 1½ inch in diameter. The pinhole filters used consisted of 35 μm pinholes and 10X microscope objectives.

A microscope slide cover glass was introduced into the reference beam to remove a portion of the beam for diagnosis with the photodetector and oscilloscope. The bank voltages for the flash lamp and for the Pockel's cells were then adjusted to produce the best film exposure. The pulse heights were recorded from the oscilloscope trace. Before making exposures, pulse heights were checked to assure adequate pulse energy.

A ratio of 2:1 in reference to object beam intensities was employed in constructing the holograms. This ratio was achieved by using N. D. filters in the reference beam.

By careful adjustment of the bank voltages and pulse delay generator equal pulses could be produced to about 1.6 μs, though the system was designed for a minimum of 10 μs separation. Actual pulse separations used varied in the range 1.6 to 10 μs. Shorter separations are necessary at the higher velocities. For example, a 100 m/s particle travels 100 μm per μs. Thus, in 10 μs the particle will move such a great distance that it becomes difficult to identify image pairs in a double exposure. However, in 2 μs the same particle would only travel 200 μs, or about two or three particle diameters.

V. Results

Particle velocity measurements were made using a measuring microscope and reconstructed holograms. The separations of particle images in double exposures were compared with the known diameter of the nozzle then multiplied by the appropriate scale factor to give displacements in microns. Of course, not all image pairs were precisely in the image plane of the nozzle (especially far from the nozzle). The magnification produced by the premagnifier is thus not the same for all particles. The divergence angle for the nozzle was determined by directing the jet at a glass slide at known distances. The sizes of the abrasion patterns were then used to determine that this angle is about 30°. This means that particles may move off the nozzle axis by as much as 0.5 mm at a 2.00 mm distance from the exit.

Now, the premagnification used in constructing the holograms was 6X.

Using geometrical optics, it follows that

$$\Delta m/m = m\Delta p/f$$

where m is the lateral magnification, f is the effective focal length of the magnifier and p is the object distance. Thus, with a focal length of 15 mm, a 0.5 mm variation in p produces a change in magnification of 1.2. This means that actual magnification at this axial distance (2.0 mm) from the nozzle may vary by 20%.

Because of this consideration, either axial particles only must be considered, or the off axial displacements of the particles must be measured to determine correct particle velocities. The former was chosen as the simpler. For these magnifications we have approximately

$$\Delta q/q = m\Delta p/f$$

where q is the image distance from the premagnifier. If variations of q for particles considered are kept less than 10%, then variations in m will not be larger than 10%.

Figure 4 shows particle velocities measured from double exposure holograms as a function of the square root of the pressure. Two observations may be made concerning these results. First, the maximum particle energy is proportional to the pressure drop in the carrier gas as expected. Second, there is a considerable range of particle velocities below the maximum. The reason for this is two-fold. First, the particles are quite large compared with the orifice through which they must pass. Thus they must lose considerable energy through wall impacts. Second, the gas flow is turbulent virtually throughout the pressure range used. Using the particle velocities from Figure 4, the nitrogen flow velocity is at least 20 to 110 m/s. The corresponding Reynolds number range for this nozzle is 1400 to 7500 indicating fully developed turbulence at the higher pressures. This turbulence is expected to cause variations in the velocities of particles carried in the flow.

Photographs were made of a number of holograms for purposes of the following discussion. These were made using an SLR camera with a micro, or close-up lens. To obtain adequate magnification, photographs were made through the same type of magnifier as used constructing the holograms. The camera was focused on infinity and positioned axially to give the sharpest image.

Plate 2 shows a typical image obtained in this work. The "projectile" is a 55 x 135 μm particle emerging from the nozzle under 30 psi pressure, indicating a velocity of 20 to 60 m/s. Resolution is evidently between 5 and 10 μm. Similarly, Plate 3 shows two particles with typical dimensions of 100 μm with roughly 20 to 60 m/s velocities. Again resolution is better than 10 μm. It is difficult to estimate resolution because it is not of course known how sharp the corners of these particles "actually" are. In fact, resolution may be as low as 2 or 3 μm if one could actually use the Rayleigh criterion. It does seem, however, from both of these photographs that there is a slight smearing of the images. Plate 4 shows two particles at a nitrogen pressure of 120 psi or maximum velocity of 100 m/s. Except for a slightly out of focus photograph and the circular artifact produced by by a bubble in the emulsion, the resolution is essentially the same as that obtained with the lowest velocities recorded. Resolution is under 10 μm and smearing is essentially that produced by the magnifying lens.

In Plate 5 is shown typical results with these semi-transparent particles in double exposures. Two particle pairs are shown for 70-100 μm particles. These exposures were made under precisely the same conditions as the single exposures and high contrast film was used to photographically enhance the contrast. In spite of this, the significant loss of contrast is apparent. In this case the pulse separation was 6 μs and the velocities on the order of 30 m/s. Rotation of one of the particles is evident corresponding to rotation of about 40,000 revolutions per second. It is this loss of contrast we wish to eliminate.

Plate 6 is a particularly noise free hologram of a 50 x 70 μm particle traveling at perhaps 50 m/s. Here the semi-transparent nature of the particles is captured and resolution is on the order of 6 or 7 μm.

Now we consider results on the subtraction process. Anything that changes the phase of either the object wave or the reference wave by 180° between double exposures will produce image subtraction. This may be either a controlled phase change in the reference beam via a Pockel's cell, or by a phase change introduced into the object beam via an optical path length change. The second may be produced by turbulent flow in which random fluctuations in the gas density, hence in index of refraction, occur. As has been pointed out,[3] it is difficult to produce much such phase change across a 100 μm region. However, with the nozzle employed in this work the region is 500 μm thick at the nozzle, 1500 μm thick one nozzle diameter further into the flow, etc. And the density fluctuations will occur on the time scale of the pulse separations since they are carried with the flow.

This problem of turbulent flow, particularly at higher gas pressures, tends to confuse efforts to control subtraction. For example, Plate 7 shows subtraction occurring naturally at 90 psi. Here the pulse separation was 3.3 μs, giving a particle velocities ranging from 90 m/s to 120 m/s. The larger particles are moving more slowly. Image pairs are fairly easy to identify and separations are easy to measure. Plate 8 shows an even worse situation. Here turbulence in the gas flow is evident, but more significant is the extreme distortion produced in the particle images by that flow. Pairs can be identified only with some difficulty (arrow pairs) and it almost seems as though there is flow around the particles. While this is likely, it is unlikely that such flow would be visible because of the small dimension of the particles.

Plate 9 shows a typical example of the effect of controlled subtraction via an external Pockel's cell. As usual, the background is dark and the particles are white. (For obvious reasons this contrast reversal occurs in the subtraction process.) It is clear, moreover, that the laser triple pulsed in this instance, thus producing the close "ghost" image. Again resolution is very good as is seen with the in focus particle nearest the nozzle. This particle is approximately

125 x 25 μm traveling at 40 m/s and resolution is better than 5 or 6 μm. This Plate should be compared with Plate 5 - typical of double exposure without subtraction.

Because of the wide variation in particle velocities with such a nozzle, double exposures must be used to investigate impacts if the particle velocity is to be evaluated to within 30% accuracy. If subtraction is not also used, then, because of loss of contrast, details of the impacts will be lost.

Finally, Plate 10 shows what happens when controlled subtraction is attempted and the flow is very turbulent. Here the pressure is 120 psi and the pulse separation is 2 μs, giving particle velocities around 80 m/s. The gas turbulence is evident in the background with cells typically 200 μm in size at this point. This turbulence causes extreme distortion in the images, and consequently subtraction is not effective.

VI. Summary

Off-axis image plane holograms have been constructed of abrasive alumina particles with major lengths up to 185 μm and minor lengths down to 25 μm. Single exposure holograms display resolution to dimensions on the order of 6 to 10 μm. The largest factor limiting resolution is the image systems used in recording, with perhaps the second factor being the turbulent flow observed in the carrier gas. Of minor importance is the motion of particles during the 20 ns exposures.

Here resolution may be improved by a factor of two by using a larger aperature imaging system and by reproducing precisely the recording geometry in the reconstruction. However, resolution has been obtained which is adequate to observe particle fragments in impact processes - one of the major goals of this work.

Particles have been sized and their velocities measured as a function of carrier gas pressure. It has been found that, for the device used to produce high velocity particles, turbulence and the interaction of the particles with the nozzle produce a rather wide velocity spread. This means that when impact is studied, velocities will have to be measured for each impact event to correlate results with velocities. Unfortunately, the double exposures required for velocity measurement suffer contrast loss. However, at least if the flow is not fully turbulent, image subtraction restores significantly the contrast. The method used here - that of a Pockel's cell in the reference beam triggered during one of the two exposures - has proved very successful. This was a second goal of this work.

Image smearing due to particle travel during a single exposure was not observed. The particle velocities obtainable with the dental trimmer were not as high as desired by at least a factor of two. However, even if such velocities had been obtainable, as it turns out, particle images would have been of poor quality because of the turbulence. To go to higher velocities, we must use a larger nozzle - not a possibility with the dental trimmer used.

The goals set for this work have been met. Good resolution has been obtained on 100 m/s particles and double exposures have been enhanced through image subtraction. These results will now be used to study impact events. Resolution needs to be improved by about a factor of two, but this will not be difficult to accomplish with slightly improved premagnifier optics. Considerable insight into abrasion processes are anticipated. As an extension of this work on image subtraction, this technique will be applied to macroscopic processes in which only changes with time are of interest.

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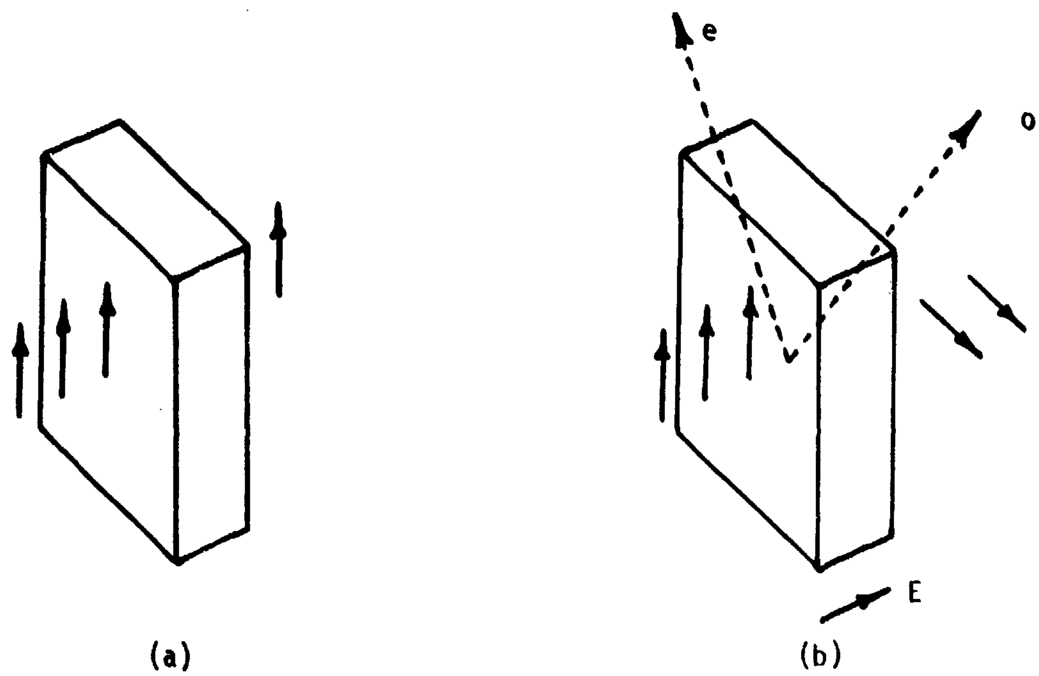

Figure 1. (a) Incident and transmitted polorization for Pockel's cell in normal orientation with no applied electric field (b) Same as (a) but with applied electric field, E, and showing ordinary and extraordinary axes.

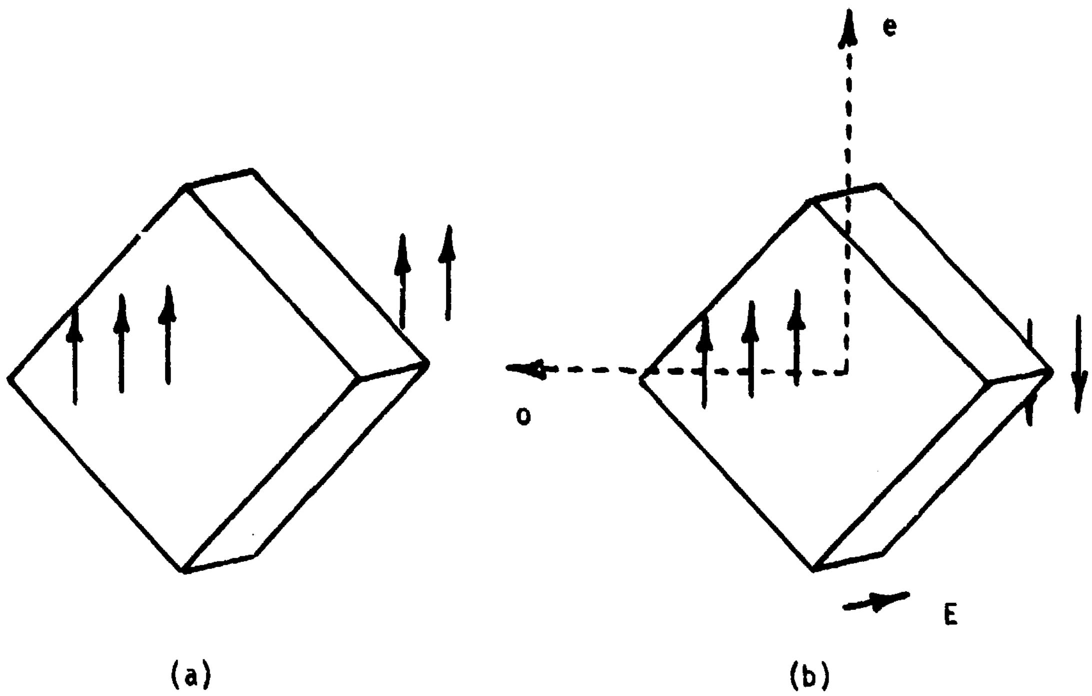

Figure 2. (a) Incident and transmitted polarizations for Pockel's cell in orientation used for substraction with no applied electric field. (b) Same as (a) but with applied electric field, E, and ordinary and extraordinary axes shown.

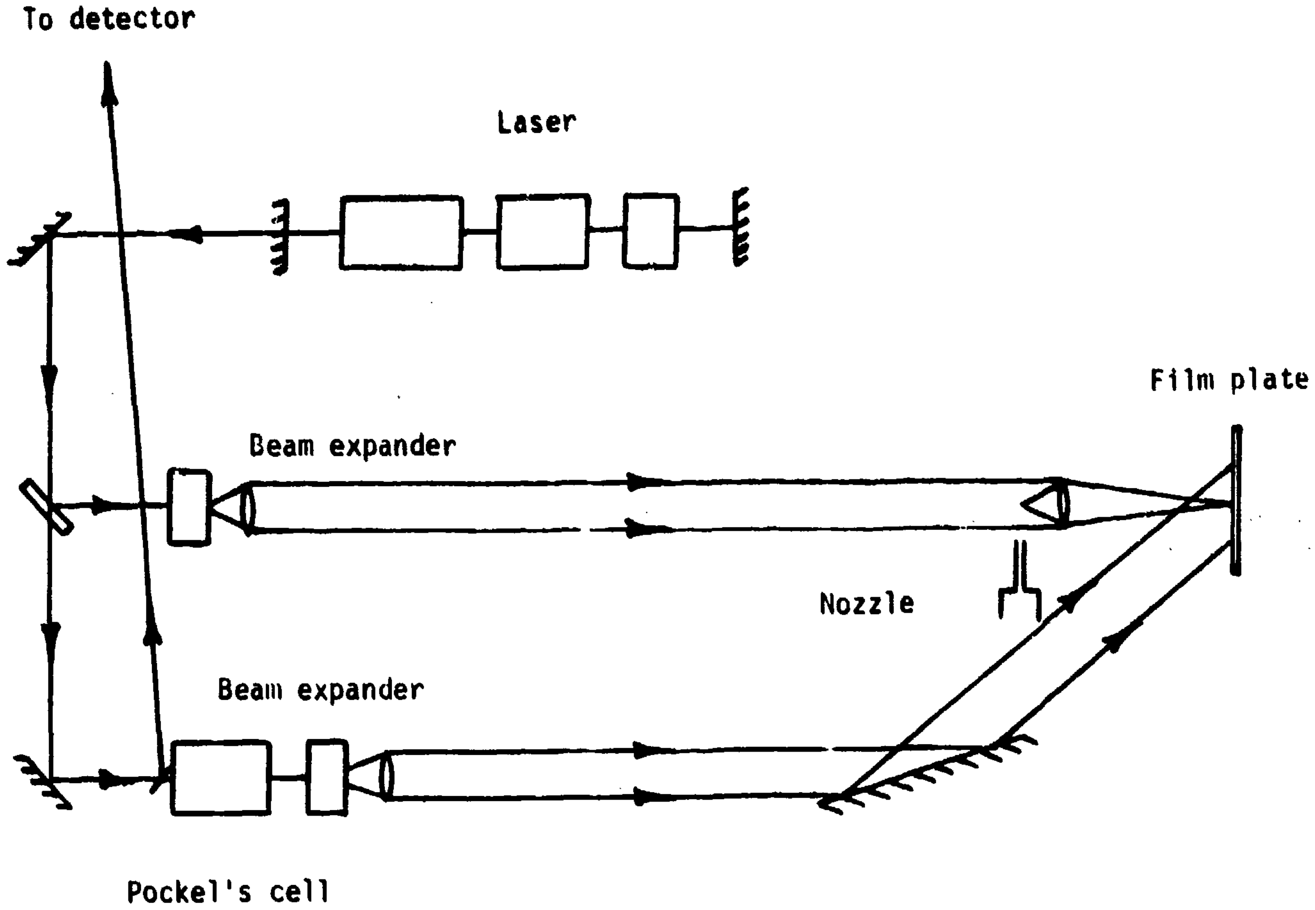

Figure 3. Schematic of holocamera geometry used to construct image plane holograms of dust

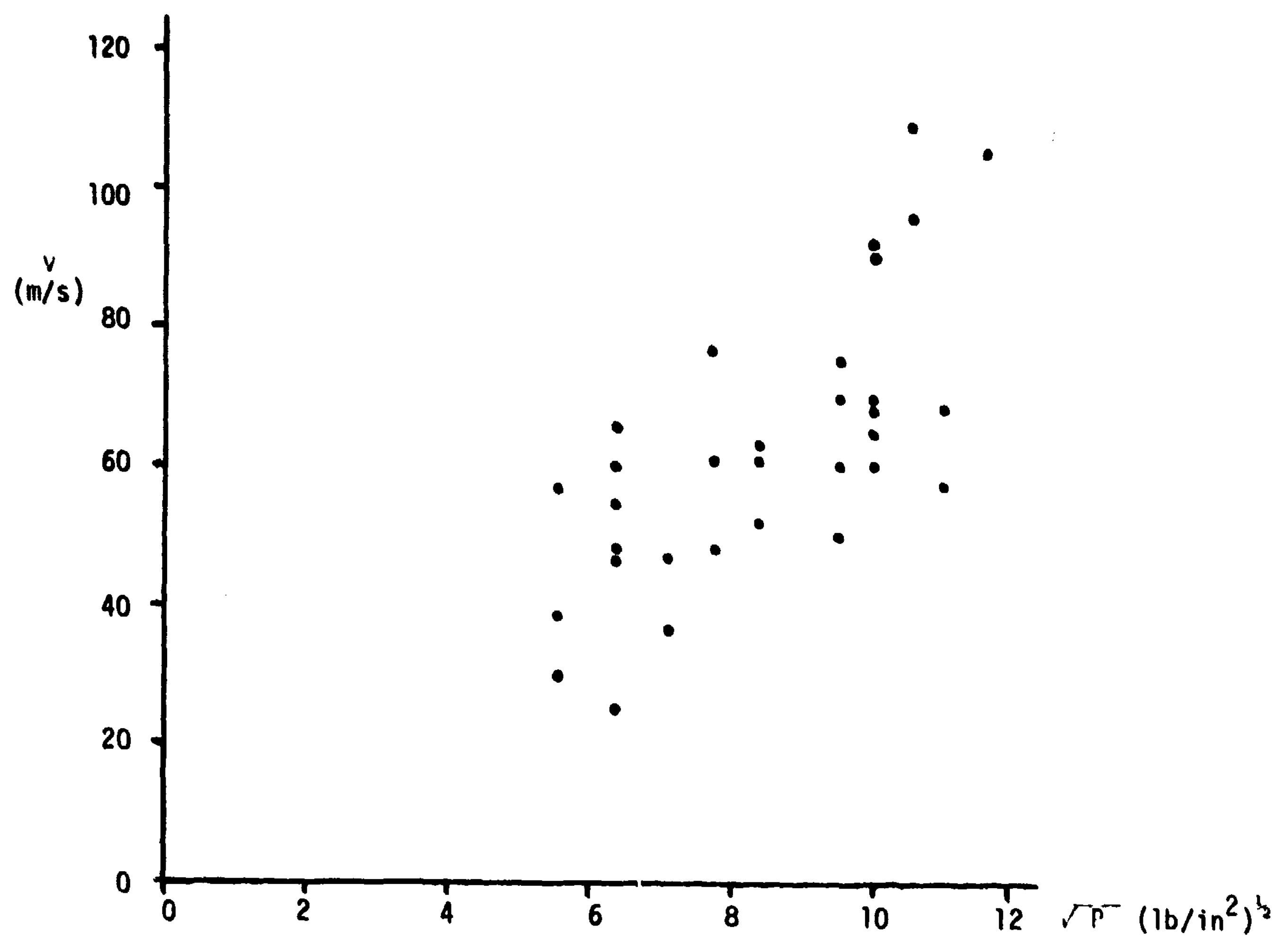

Figure 4. Measured particle velocities as a function of square root of gas pressure

Max. dim. (μm)	Min. dim. (μm)
105	50
85	75
175	90
125	75
125	65
75	70
125	65
185	75
175	50
165	60

Table 1. Typical particle sizes obtained from microscopic measurements.

Plate 1

Plate 2

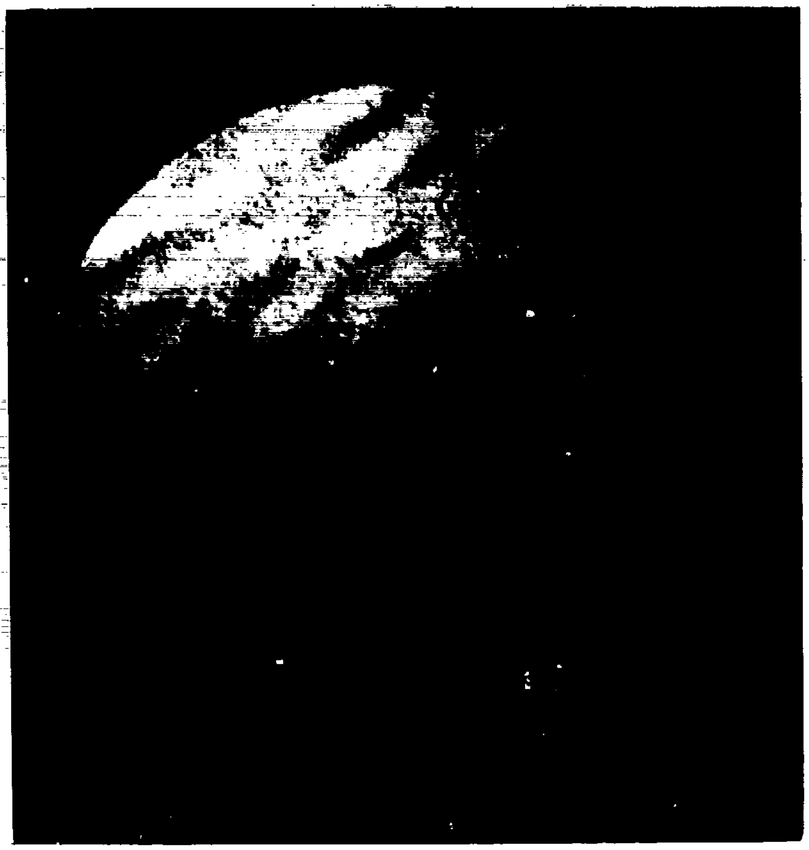

Plate 3

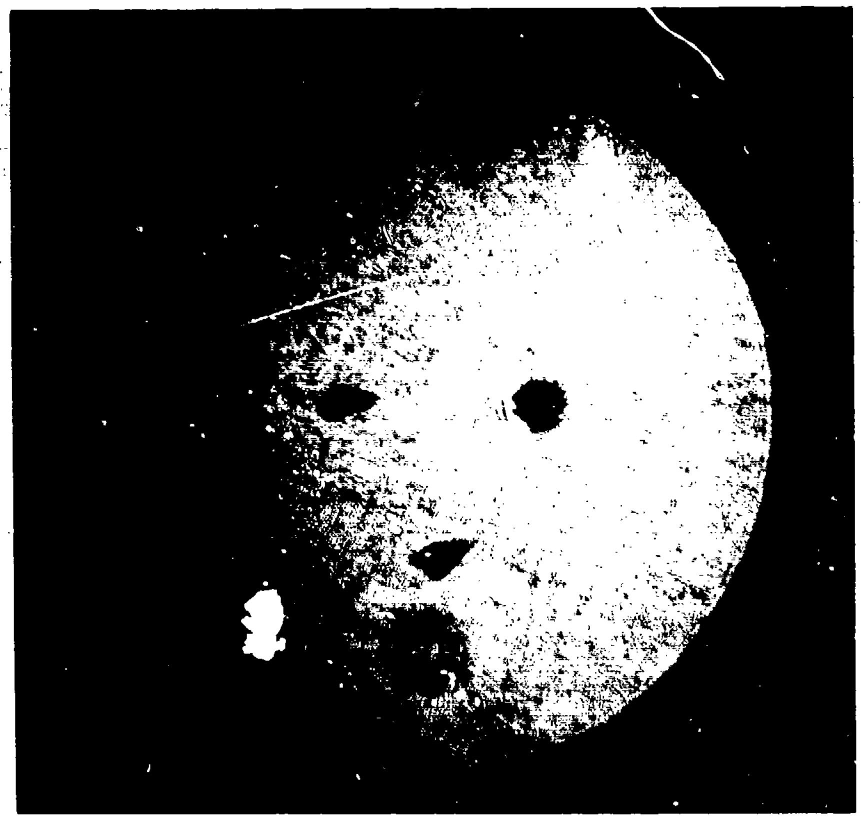

Plate 4

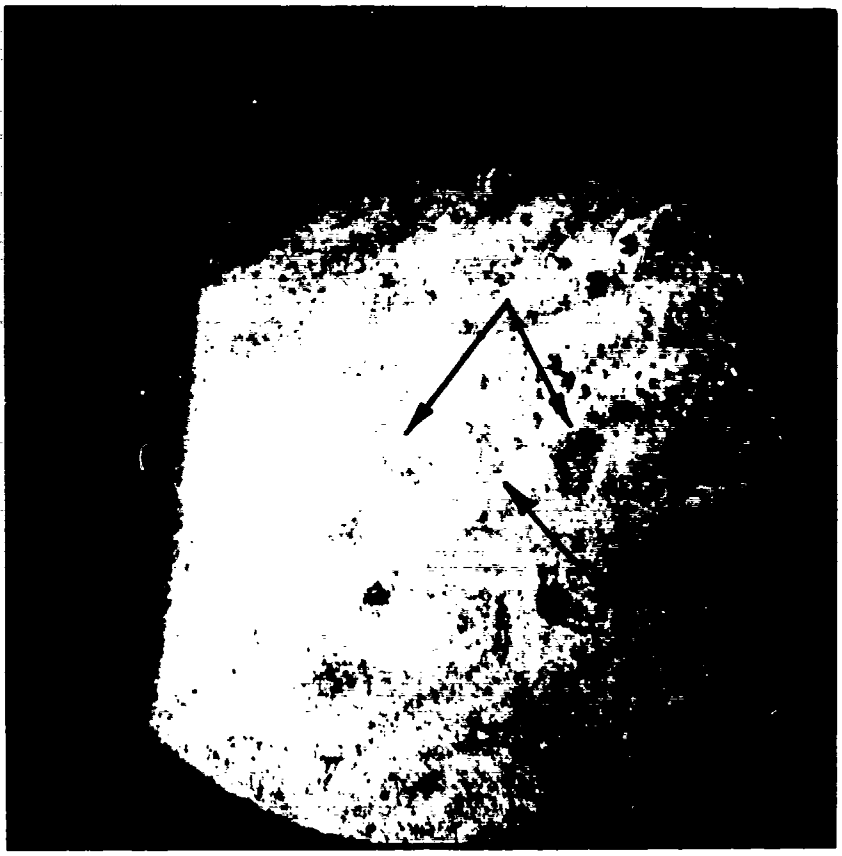

Plate 5

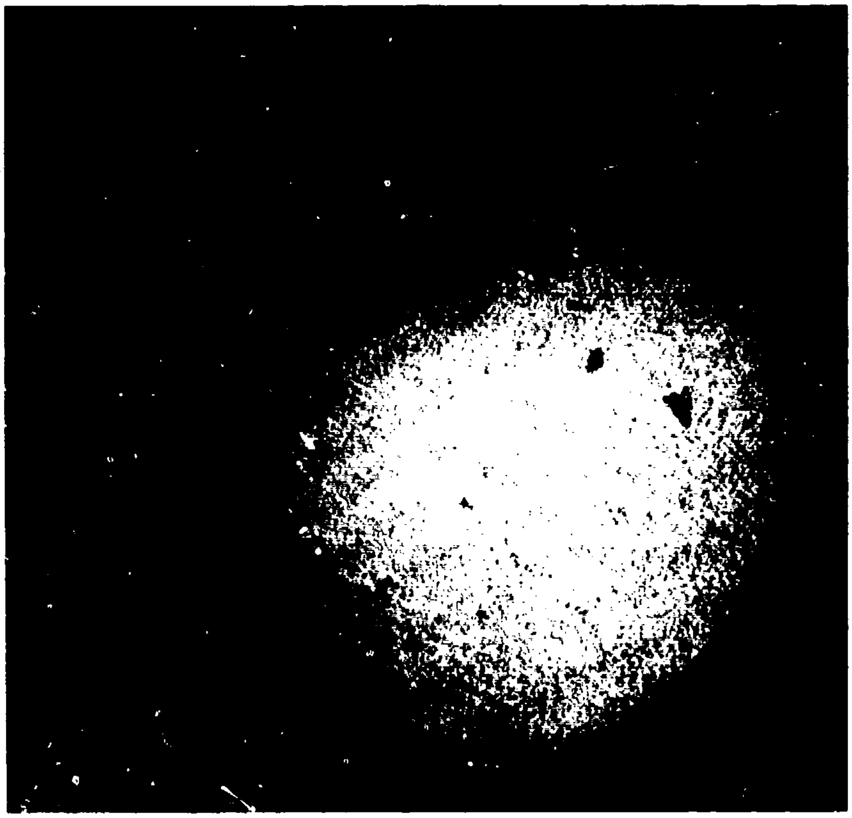

Plate 6

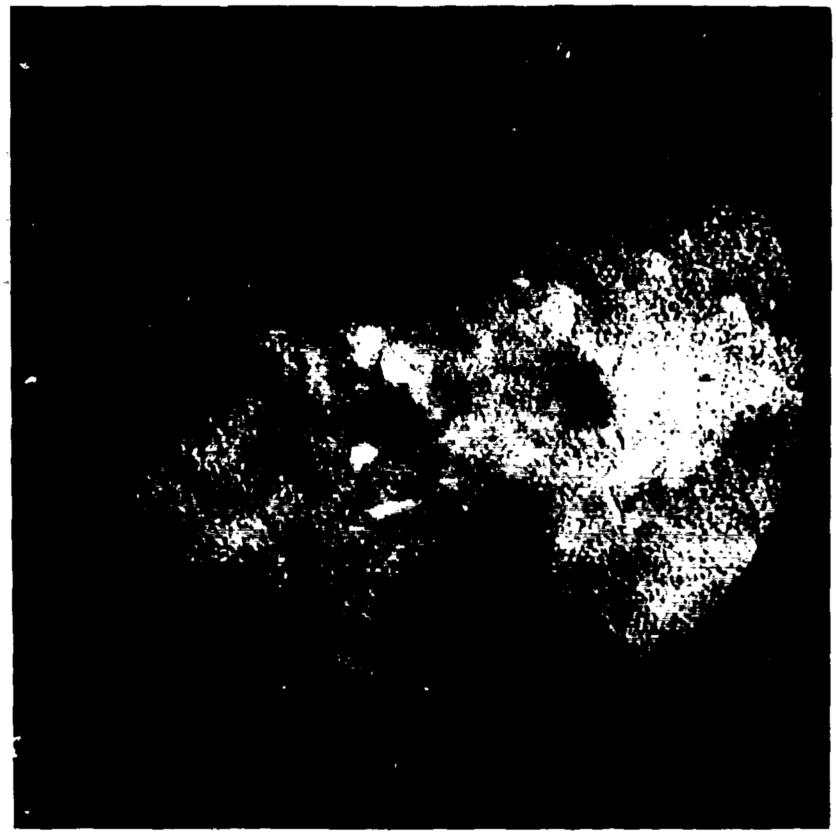

Plate 7

Plate 8

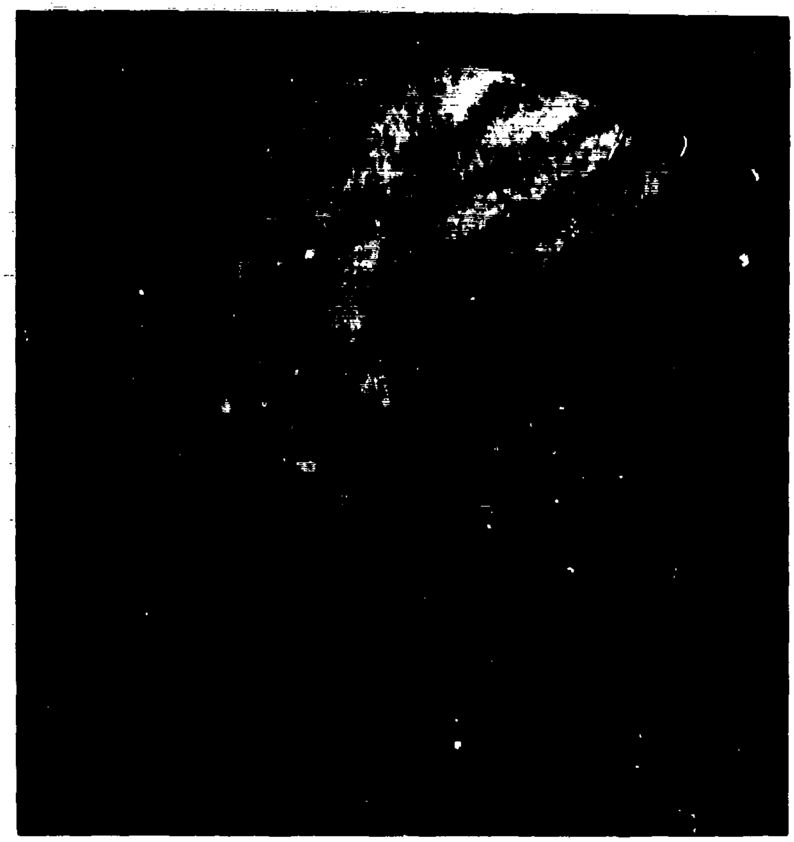

Plate 9

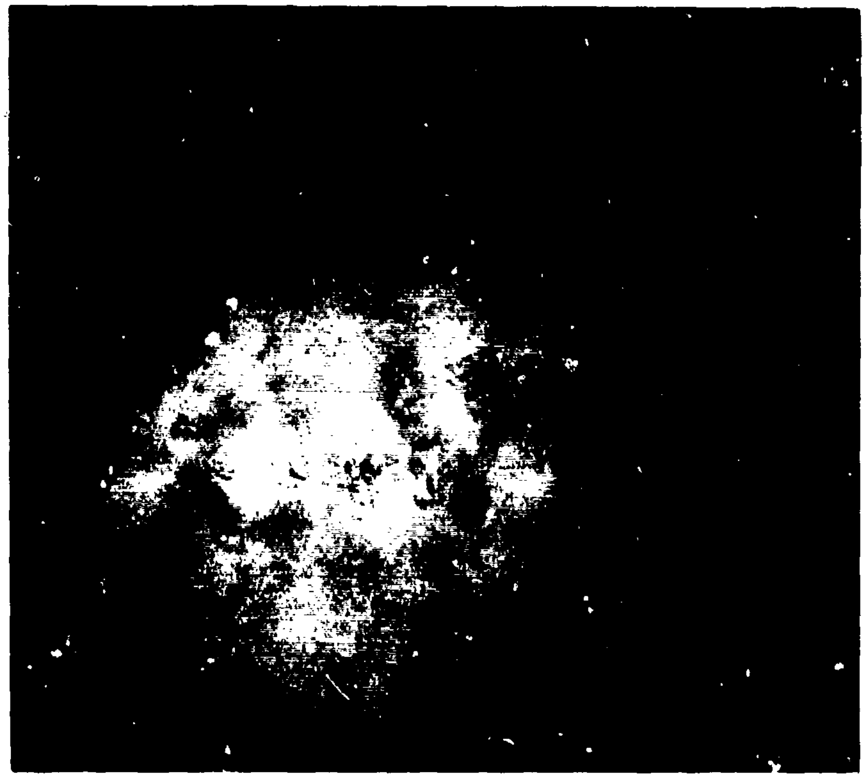

Plate 10