United States Patent [19]

Shofner

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[45] **Mar. 19, 1974**

[54] **SYSTEM FOR MAKING PARTICLE MEASUREMENTS**

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[52] **U.S. Cl.** **356/102,** 350/103, 250/218

[51] **Int. Cl.** **G01n 15/02**

[58] **Field of Search** 356/102, 103, 104, 204, 356/206, 23

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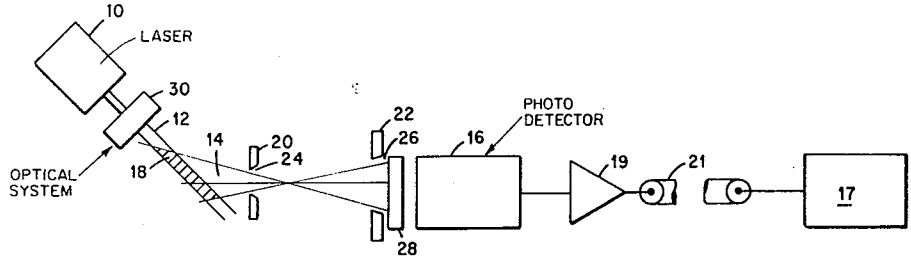
Attorney, Agent, or Firm—Fitch, Even, Tobin & Luedeka

[57] **ABSTRACT**

A system for in situ particle measurement employing light scattering. Both dry and liquid particles are measurable.

7 Claims, 4 Drawing Figures



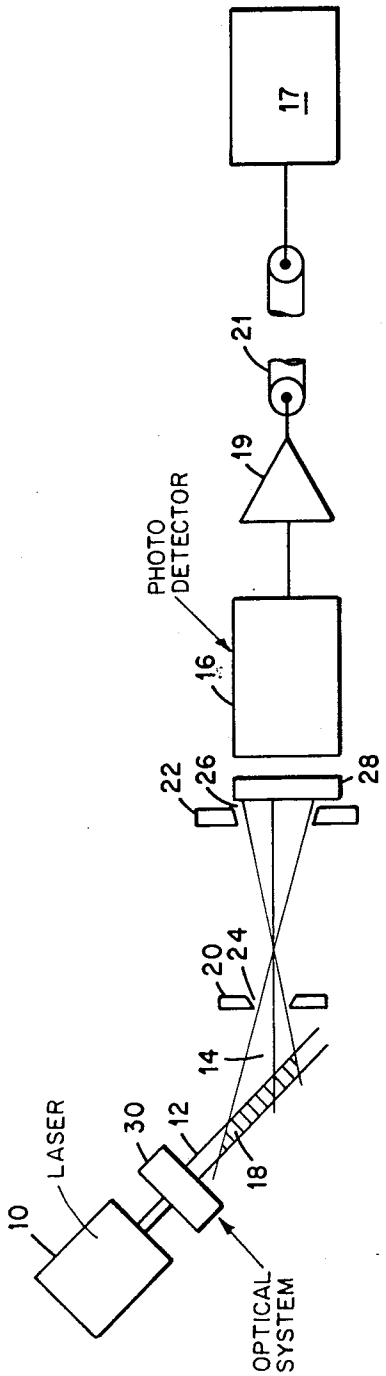

17
21
19
PHOTO DETECTOR
16
22
26
28
20
24
14
30
12
18
10
LASER
OPTICAL SYSTEM

Fig. 1

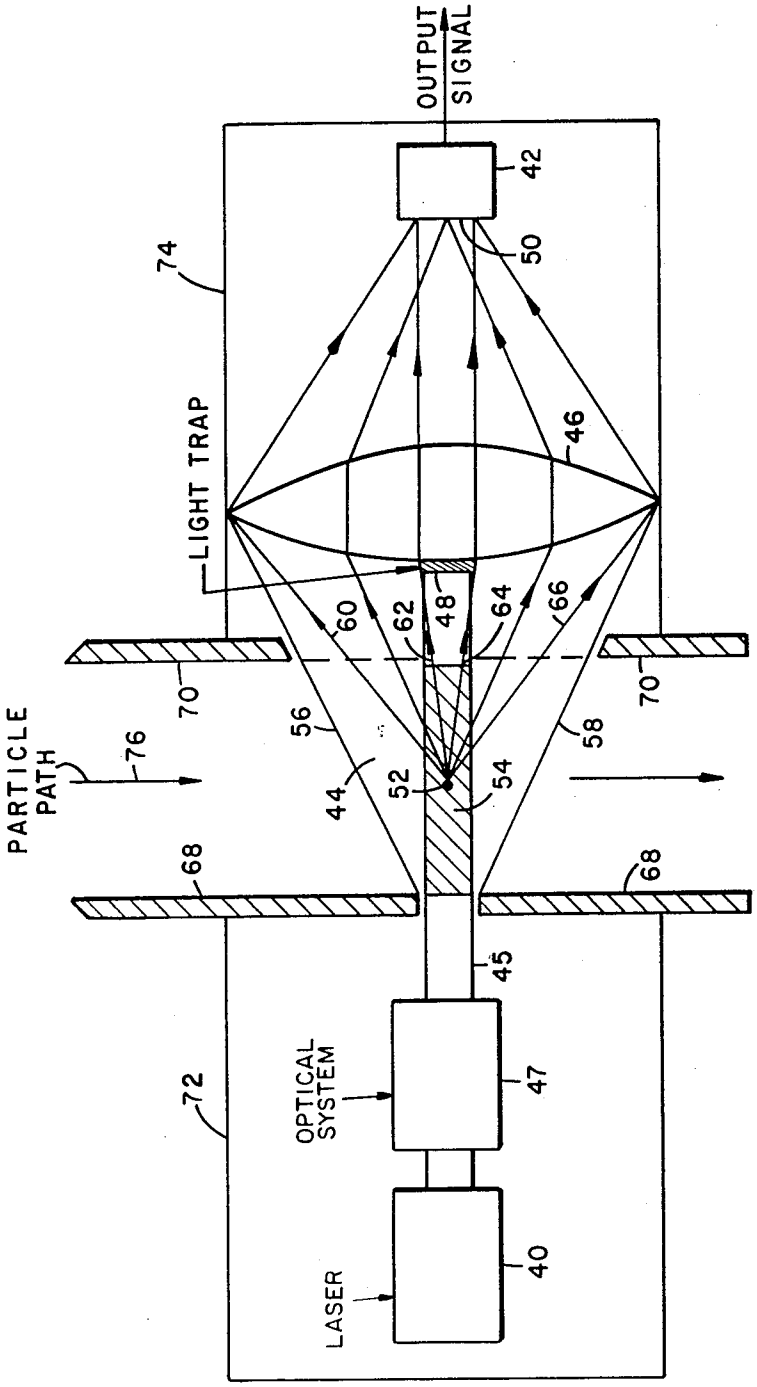

OUTPUT SIGNAL
42
50
74
LIGHT TRAP
46
60
62
48
64
66
70
70
56
58
PARTICLE PATH
76
44
52
54
68
68
45
OPTICAL SYSTEM
47
72
LASER
40

Fig. 2

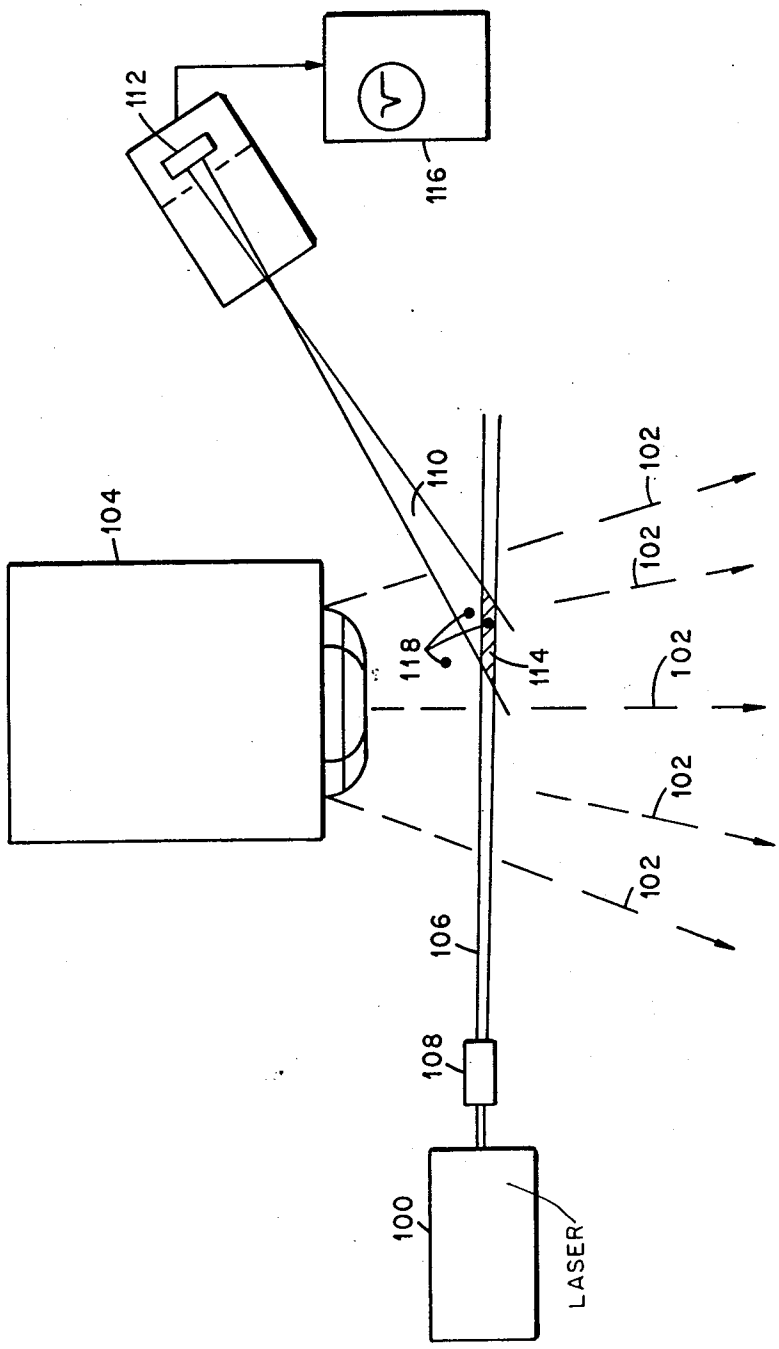


Fig. 3

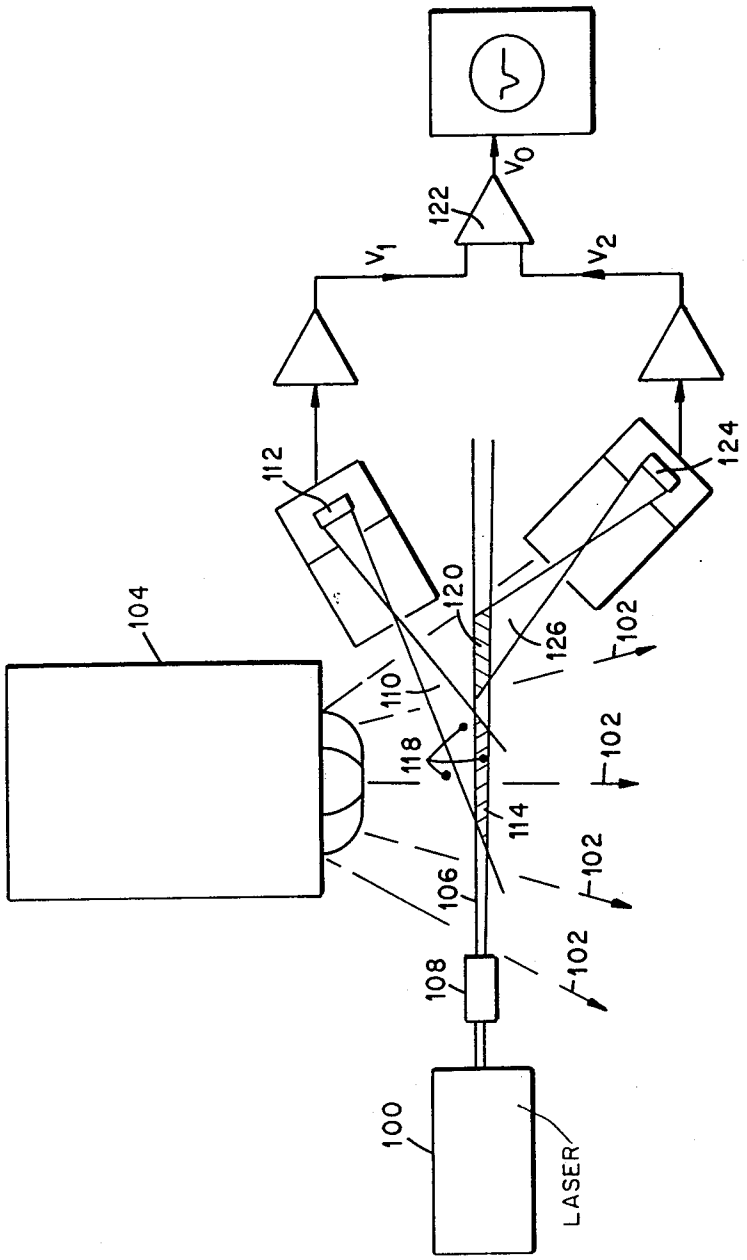

V_0
122
V_1
V_2
112
124
104
120
126
102
110
118
114
106
108
100
LASER

Fig. 4

SYSTEM FOR MAKING PARTICLE MEASUREMENTS

This invention relates to electro-optical instrumentation systems, particularly such systems for measurement of particles in various environments.

The environmental effects of atmospheric particulates are a most important part of the overall air pollution problem. It is desirable to measure the fundamentally important particle size distribution and concentration at the source and throughout the source-to-terrain transport path in order to determine transport properties, meteorological effects, and direct biological impact upon the life indigenous to the area in which the particulate is collected.

Evaporative cooling towers are one source of environmental pollution. Such evaporative cooling towers provide an attractive means for waste heat disposal. The evaporated water is pure and does not constitute a pollution problem except perhaps visual pollution in the form of fog plumes. However, cooling towers are known to emit small droplets of water, called drift, which contain the minerals of the water circulating in the cooling tower. Neither the total amount of emission, the distribution of the particle sizes, nor the quantity of mineral deposited on the environs adjacent the tower by the drift has been accurately known heretofore.

The prior art includes various instruments for measuring relatively small (less than 20 microns diameter) particles. Insofar as is known to applicant, these prior art instruments require a sample of the medium within which the particles are contained to be captured and transferred to a position within the instrumentation where the particle measurement is conducted. Other such instruments require that a portion of the particle-containing medium be drawn through the instrument under artificial flow conditions that are often quite different from the ambient or natural flow conditions.

Certain of these prior art instruments employ light scattering techniques wherein the particle or particles within the sample is impinged with a beam of light whereupon the light is scattered in all directions. It is well known that a portion of the light scattered from such particles may be directed to a detector where the detected light is converted into a measure of the particle size and, collectively, the particle size distribution. In situ particle size and distribution measurements are not known to be possible employing such prior art devices due to the requirement that the scattering volume (the volume within which the particle must be located in order to be "seen") is located internally of the device and the particle must be collected and transferred into the test device. Notably, particles of about 50 microns diameter cannot be transferred into such prior devices due to their physical size causing them to drop out or be expelled from the carrier medium during transport.

Certain other prior art devices rely upon optical or electron microscopy but these are time-consuming and therefore not applicable to in situ determinations of particle size and distribution. None of these general types of prior particle measuring systems provide satisfactory means for measuring liquid particles due to the tendency of liquid particles to evaporate and change size during transfer to the instrumentation. Moreover, such prior art systems are not capable of measuring

particles in situ within a medium which keeps the particles moving nor are they capable of "on line" monitoring of moving particles.

As a further matter, the known prior art particle measuring systems are of the "stationary" type. That is, the particles must be brought to the instrument. It is desirable that a system be provided which is amenable to being towed or carried as by an airplane or other vehicle through a cloud of particles such as a dust or rain cloud.

It is therefore an object of the present invention to provide an electro-optical system for in situ determination of particle sizes and distribution. It is a further object of this invention to provide instrumentation for accomplishing in situ particle size and distribution determinations. It is also an object to provide a system of the type described which is amenable to being towed or otherwise moved through a particle-containing medium while making particle measurements. It is also an object to provide a system of the type described wherein a particle-containing medium moves past a stationary measuring system. It is a further object of this invention to provide a method for analyzing the drift of a cooling tower. It is a further object of this invention to provide such a method wherein the drift is analyzed in situ.

Other objects and advantages of the invention will be recognized from the following description, including the drawings in which:

FIG. **1** is a representation of a particle measurement system embodying various features of the invention;

FIG. **2** is a representation of a further embodiment of the disclosed system;

FIG. **3** is a representation of apparatus employed for measuring drift; and,

FIG. **4** is a representation of a particle measurement system employing dual instrumentation.

Briefly stated, the present electro-optical system comprises a radiation (light) source whose output beam intercepts the projected acceptance geometry of a photodetector to define a scattering volume disposed between the radiation source and detector and externally of the instrumentation. Radiation from the source impinges upon a particle within the external scattering volume and is scattered by the particle. That portion of the scattered radiation which falls within the acceptance geometry of the detector and which is therefore directed toward the detector is received and converted to an electrical signal whose magnitude is related to the size of the particle. The magnitude and quantity of signals are useful in determining the distribution of particle sizes and/or the concentration of particles within the particle-containing medium.

With reference to FIG. **1**, the depicted system includes a light source **10** whose output beam **12** is caused to intersect the projected acceptance geometry **14** (comprising a cone in the depicted system) of a photodetector **16** which is disposed at an angle with respect to the beam **12**. The output from the photodetector is fed to any one of several possible devices **17** adapted to convert the signals to a usable form. For example, the output signal may be fed to an oscilloscope, a tape recorder, a digital counter, a pulse height analyzer, or a mini-computer with or without a readout. Further, the output signal may be amplified by an amplifier **19** or otherwise acted upon after it exits the photodetector

to make the signal suitable for a particular purpose such as transmission through a coaxial cable **21.**

It will be understood that the cross sectional geometry of the output beam **12** from the laser **10** may be of any of several selected geometries, but preferably is of circular cross section. Where this output beam intercepts the projected acceptance cone **14** of the detector, there is a volume defined as the scattering volume **18.** It is noted that in the Figures, only two dimensions of the scattering volume are depicted but it will be recognized that the laser beam, the acceptance cone, and consequently the scattering volume usually are each three-dimensional. For present purposes, this scattering volume refers to the volume within which a particle must be located in order for radiation from the laser to impinge on the particle and for the radiation scattered by the particle to be directed in a direction suitable for entry into the detector **16.**

In the depicted system, the projected acceptance cone **14** of the photodetector **16** is established through the use of a pair of apertures **20** and **22** whose spatial location with respect to each other and to the laser beam and photodetector, along with the size of their respective openings **24** and **26,** establish the size of the projected acceptance cone of the photodetector. As desired, additional optics, such as a narrow band filter **28,** may be inserted between the scattering volume and the detector for effecting desired changes in the radiation passing from the scattering volume to the detector prior to the entry of such radiation into the detector.

In accordance with recognized technology, the radiation emitted from the laser and impinging upon one or more particles within the scattering volume is scattered by the respective particles in all directions. A portion of the scattered radiation from each particle is directed from the scattering volume toward the detector along a path which falls within the projected acceptance cone of the detector. Such radiation portion passes through the apertures **20** and **22,** thence through the narrow band filter **28** to be received by the photodetector **16.** Also in accordance with known technology, the intensity of the radiation received by the photodetector from a particle is a measure of the size of the particle. Within the photodetector, the scattered radiation received by the photodetector from each particle is converted to an electrical signal whose magnitude is uniquely related to the intensity of the radiation scattered from the particle and therefore to the particle properties, e.g., size. Accordingly, evaluation of the electrical signal developed within the photodetector and fed therefrom as an output signal provides a measure of the particle size. Further, analysis of all of the signals from the detector provides information regarding the size distribution and concentration of the particles within the medium.

It is recognized that when employing a pulsed laser, as will be discussed hereinafter, each time the laser pulses there is a sampling of a known volume of a particle-containing medium, such volume being equal to the scattering volume of the system. From a knowledge of this scattering volume and the number of laser pulses, along with the obtained knowledge of the particle size of each particle detected and measured during a given number of laser pulses, the total number of particles per unit of volume of the particle-containing medium can be obtained as well as a determination of the size distribution of the measured particles within the particle-containing medium.

In the disclosed system, the scattering volume is located externally of the apparatus employed. That is, the scattering volume is not enclosed, but rather is exposed to ambient atmosphere. In accordance with this feature of the invention, in making a particle measurement, the scattering volume is caused to be disposed within the medium which carries the particles. That is, the particles are measured in situ by bringing the scattering volume to the particles. Such in situ measurements are not known to have been possible heretofore. By reason of this feature, in combination with a pulsed radiation source as will be described hereinafter, it is possible to make dynamic measurements of particles by disposing the scattering volume within a stream of moving particles. This capability makes the present system useful for field use either as a stationary unit or for attachment to a vehicle or airplane for making measurements of particles spread over a large area, as in a dust cloud, rain cloud or the like.

Importantly, the external scattering volume provides a means for measuring liquid particles with accuracies equivalent to the accuracies heretofore possible when measuring dry particles. Specifically, liquid particles evaporate when being transferred to the internal scattering volumes employed in the prior art, thereby becoming smaller so that the size measurement obtained is less than the actual size of the liquid particle when collected. In the present system, liquid particles are measured in situ so that a measurement of their true size is obtained.

Still further, the external scattering volume of the present system is particularly useful for measuring larger size (about 50 microns diameter and larger) particles. Withdrawing samples from a medium for transfer to a prior art system where the particles are large presents the problem of transporting the particles due to their tendency to be expelled out of the carrier medium upon change in its direction of flow or the like. Because the present system makes the particle measurement in situ, without effecting any substantial change in the flow of the particle-containing medium that will alter the condition or concentration of the particles in the medium, the present system is particulary useful in measuring large particles. This feature of the disclosed system also enhances the accuracy of the particle measurements and makes them more representative of the true conditions.

As noted hereinbefore, it is preferable that the particles pass through the scattering volume one at a time, so that each unit of intensity change registered by the photodetector represents only one particle. In the present system, such condition is obtained by adjusting the size of the scattering volume to that size which will result in one particle at a time passing through the scattering volume under the existing conditions of particle-containing medium flow and the concentration of particles in the medium. Adjustment of the size of the scattering volume is accomplished either by changing the cross sectional area or geometry of the beam (optically or mechanically), changing the size of the acceptance geometry of the photodetector (optically or mechanically), by mechanical limit means, or by a combination of these. It will be evident that other more complicated means may be employed to change the size of the scattering volume. In any event, it is emphasized that any means employed to adjust the size of the scattering volume is not to apply forces to the particle-containing

medium which effect substantial change in the particle-containing medium that alters the condition or distribution of the particles in the medium. But rather, the medium is to be kept unaltered so that the individual particles in the medium will pass undisturbed through the scattering volume.

The source of radiation for impinging on the particle under surviellance may be of several forms. One particularly suitable radiation source is a laser of the junction diode type emitting radiation having a wavelength in the infrared region of the color spectrum. One particularly useful wavelength is 9,040 A. as emitted by a gallium arsenide junction laser diode. Whereas lasers emitting radiation within the visible range are useful in certain applications, the infrared radiation is preferred because of the ready availability and relatively less cost of such lasers. The preferred junction diode laser has a peak power of at least several watts. The radiation beam from the laser preferably is initially passed through an optical system 30 designed to form a homogenous beam having sharp cut-offs. In the ideal embodiment the beam intensity is constant across the beam and zero outside. Such optical systems are known in the art. In the present system it is desirable that the beam approach the ideal beam as nearly as possible so as to obtain enhanced accuracy in resolution of the particle size and/or distribution. In the absence of such a beam, the intensity of the beam varies across the width (transversely) of the beam and a particle measured in the center of the beam will be impinged with radiation that is more intense than if the particle were impinged when it is near either of the opposite side edges of the beam as when the particle is entering or leaving the scattering volume.

The radiation emission of the laser employed in the present system is pulsed so that the radiation beam passes to the scattering volume in increments of time. The rate of pulsing is chosen in conjunction with the velocity of the particle and the cross sectional dimension of the scattering volume so that there is a single exposure of a given particle during the residence of the particle within the scattering volume. As noted hereinbefore, the present system is adapted to in situ measurements of particles and particularly suitable for measuring particles that are moving. In accordance with this feature of the system, the laser is pulsed in time increments substantially equal to the time that a moving particle resides within the scattering volume. By this means, no single particle is exposed to the light beam more than once during its passage through the scattering volume. Consequently, only one electrical signal per particle is developed by the photodetector, and each such signal representative of a particle of interest is separated from each such other signal representative of a particle of interest by at least one electrical signal that is not representative of a particle of interest, with the result that the output from the photodetector accurately reflects the size of each exposed particle.

Conventional photomultiplier detectors may be employed in the present system. A preferred detector, however, comprises a photodiode followed by a high current gain, low noise preamplifier. This photodetector is especially useful when working in the range of between about 7,000 A. and about 12,000 A. inasmuch as the usual photomultiplier detector fails to function satisfactorily in such range which includes infrared radiation.

With reference to FIG. **2**, a further embodiment of the disclosed system includes a laser **40**, spatially separated from a photodetector **42** having an annular acceptance geometry **44** developed by a convexo-convex lens **46** disposed between the photodetector and the laser. In the depicted system, the laser beam **45** is passed through an optical system **47** and enters a radiation trap **48** after it has been intercepted by the annular acceptance geometry of the photodetector and before it reaches the lens **46**. The lens **46** is oriented with its long axis disposed substantially perpendiculary to the face **50** of the photodetector so that that portion of the beam radiation scattered by a particle **52** disposed within the scattering volume **54** (cross-hatched in the Figure) of the system and which falls within the annular solid angle acceptance geometry of the photodetector is directed by the lens to the photodetector. In FIG. **2**, the lines **56** and **58** are intended to depict the outer limits of the annular acceptance geometry of the photodetector **42**. The rays **60** and **62** above the beam **45** and the rays **64** and **66** below the beam depict (in two dimension) that portion of the scattered radiation that passes to the detector **42**. It is to be recognized that the annular solid angle acceptance geometry is three-dimensional rather than two-dimensional as appears from the Figure. Accordingly, in this embodiment, a greater amount of the scattered radiation is directed to the photodetector so that an enhanced output signal is obtained from the photodetector. The system depicted in FIG. **2** is not restricted to lens as depicted but rather it will be evident that mirrors, lens of other geometries, or other configurations of optics are suitable to aid in establishing the acceptance geometry of the photodetector.

In accordance with one feature of the embodiment depicted in FIG. **2**, the scattering volume is reduced in length (laterally in the Figure) by mechanical flow plates **68** and **70** which function to block from the scattering volume any particles other than the particle to be measured. The effect of these flow plates, in combination with the instrumentation housing **72** and **74**, is to mechanically define, in part, the scattering volume **54** of the system. Notably, the flow plates do not substantially alter the ambient conditions of the particle-containing medium such as the rate of flow or particle concentration.

When using the system depicted in FIG. **2**, the flow plates **68** and **70** are aligned substantially parallel to the direction of flow of the particle-containing medium so that inertial effects cause the moving particles to move through the scattering volume along a path **76** that is generally perpendicular to the scattering volume. Thus, the scattering volume is mechanically limited in size to that volume which is suitable to cause the particles to pass through the scattering volume one at a time.

The disclosed system is particularly suitable for measuring liquid particles for the reason that the present system does not alter either the medium or the particle contained within the medium. The drift (liquid droplets) found in cooling towers has heretofore eluded measurement, both as to the size of the liquid particles and as to their concentration. FIG. **3** depicts a system suitable for measuring drift from a cooling tower. With reference to the Figure, a laser **100** is positioned adjacent the output flow (rays **102**) of a cooling tower **104**

so that the beam **106** of the laser is directed through the tower output. As desired, the beam **106** is optically treated by an optical unit **108** prior to its entry into the tower output. The beam **106** is intersected at a location within the tower output by the projected acceptance geometry **110** (conical in this Figure) of a photodetector **112** to define a scattering volume **114** disposed within the tower output. In the depicted system, the photodetector output is fed to an oscilloscope **116.**

By reason of the scattering volume **114** being disposed within the tower output and not presenting an obstruction or otherwise altering the flow from the tower, liquid particles **118** of drift (size exaggerated for clarity) move through the scattering volume unimpeded and in their "natural" state. From a knowledge of the flow of liquid particle-containing air from the tower, the size of the scattering volume **114** is selected so that one liquid particle at a time passes through the scattering volume. The beam **106** impinges on a particle at least once during its movement through the scattering volume. The beam radiation is scattered by the particle and that portion of the scattered radiation which falls within the acceptance geometry of the photodetector passes to the photodetector which develops an electrical signal that is proportional to the intensity of the received scattered radiation and representative of the size of the particle. In the depicted system, the electrical signal from the photodetector is fed to an oscilloscope **116** for observation and/or recording by conventional means.

As noted hereinbefore, through the use of a pulsed laser, there is obtained repetitive sampling of the medium, each sample volume being equal to the scattering volume. From a knowledge of the number of these samples and the number and sizes of the particles measured over the time of such sampling, the size distribution and/or concentration of liquid particles (drift) is readily obtained. Such information then becomes usable in designing cooling towers having minimum drift.

One particular problem when measuring relatively large particles in the presence of relatively high concentrations of smaller particles is that the radiation scattered by the many small particles can produce a background electrical signal at the photodetector. For example, the fog emanating from a cooling tower comprises many particles that are smaller than the liquid particles of drift. FIG. **4** depicts an embodiment of the disclosed system wherein two detectors **112** and **124** define two identical independent but closely spaced scattering volumes **114** and **120** disposed within the medium that contains the large and small particles. As the particle-containing medium moves through the respective scattering volumes **114** and **120,** the photodetector associated with each of the scattering volumes develops an electrical signal representative of the radiation scattered from all the particles disposed within such scattering volume. In the first scattering volume **114,** for example, there normally will exist not more than one large particle plus several small particles so that the resultant signal, V_1, from the first scattering volume is relatively large, it being representative of both a large and several small particles. Simultaneously, the photodetector **124** associated with the second scattering volume **120** develops a signal representative of the scattered radiation emanating from the particles within such second scattering volume. The mathematical probability of the second scattering volume containing a large particle simultaneously with there being also one in the first scattering volume is substantially less than such probability of a large particle being in the first scattering volume at the time of the measurement so that the signal, V_2, obtaining at the second photodetector is representative of the collected scattered radiation from only small particles, hence V_2 is less than V_1. This second signal, V_2, is electrically subtracted as by a differential amplifier **122** from the first signal, V_1, to obtain an output signal, V_O, which has subtracted therefrom the background signal arising from the presence of the small particles.

While the present description has included specific examples and embodiments, it will be understood that there is no intent to limit it by such disclosure, but rather, it is intended to cover all modifications and alternate constructions falling within the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. A system for particle measurement employing radiation scattering wherein there is relative movement of a particle-containing medium and particles contained therein with reference to the measurement system comprising

radiation source means emitting radiation in beam form,

photodetector means having a radiation acceptance geometry whose projection intercepts said beam of said source means,

a scattering volume disposed between said source means and said photodetector means and defined by the interception of said beam by said projected acceptance geometry of said photodetector means, said scattering volume being disposed within a medium containing the particle to be measured,

means for effecting relative movement between the particles to be measured and the scattering volume without applying forces to the particle-containing medium which effect substantial change in the particle-containing medium that alters the condition or ditribution of the particles in the medium, and

means pulsing said light source means at a rate that results in illumination of said scattering volume not more than once during each time period equal to the time period required for a particle to traverse said scattering volume in a direction generally parallel to the direction of movement of said particle-containing medium under the then existing conditions of particle movement through said scattering volume and at least once during the interval between the exit of an illuminated particle from said scattering volume and the entry of a further illuminated particle into said scattering volume, whereby the particle to be measured moves substantially undisturbed through said scattering volume and while disposed within said scattering volume is impinged by said beam and scatters a portion of said beam toward the photodetector means to cause said photodetector means to develop an electrical signal that is proportional to the intensity of the radiation scattered to said photodetector means by said particle and each such output electrical signal that is representative of a particle of interest within said scattering volume is separated from each other such signal representative of a particle of interest

by an output electrical signal that is not representative of a particle of interest.

2. The system of claim 1 wherein said radiation source comprises a laser.

3. The system of claim 1 and including means for adjusting said scattering volume to a size such that under the conditions of flow of the particle-containing medium the particles within the medium move through the scattering volume one at a time.

4. The system of claim 1 wherein the particle to be measured is a liquid particle.

5. The system of claim 1 wherein the major dimension of the cross section of the particle to be measured is larger than about 50 microns.

6. A method for making in situ measurements of particles moving along a path comprising the steps of

projecting a beam of radiation into a particle-containing medium,

positioning a photodetector means at a location distant from said radiation beam,

aligning said photodetector means with respect to said beam whereby the projected acceptance geometry of said photodetector means intercepts said beam at a location within the particle-containing medium to define a scattering volume,

effecting relative movement between the particle to be measured and the scattering volume without applying forces to the particle-containing medium which effect substantial change in the particle-containing medium that alters the condition or distribution of the particles in the medium,

admitting said beam of radiation to said scattering volume in pulses timed to illuminate said scattering volume not more than once each time period equal to the time period required for a particle to traverse said scattering volume in a direction generally parallel to the direction of movement of said particle-containing medium under the then existing conditions of particle movement through said scattering volume and at least once during the interval between the exit of an illuminated particle from said scattering volume and the entry of a further illuminated particle into said scattering volume, whereby the particle to be measured moves substantially undisturbed through said scattering volume and while disposed within said scattering volume is impinged by said beam and scatters a portion of said beam toward said photodetector means to cause said photodetector means to develop an electrical signal that is proportional to the intensity of the radiation scattered to said photodetector means by said particle and each such output electrical signal that is representative of a particle of interest within said scattering volume is separated from each other such signal representative of a particle of interest by an output electrical signal that is not representative of a particle of interest.

7. A system for measuring relatively large particles employing radiation scattering wherein there is relative movement of a particle-containing medium with reference to the measurement system and said medium contains large and small particles comprising

a radiation source means emitting a radiation beam directed into said particle-containing medium,

a pair of photodetector means each having a radiation acceptance geometry whose projection intercepts said beam at spaced apart locations within said particle-containing medium,

a plurality of scattering volumes disposed between said source means and respective ones of said photodetector means and defined by the interception of said beam by the respective projected acceptance geometries of said plurality of photodetector means,

means for effecting relative movement between said particle-containing medium and said scattering volumes without applying forces to the particle-containing medium which effect substantial change in the particle-containing medium that alters the condition or distribution of the particles in the medium, whereby the particles in said medium move substantially undisturbed through said scattering volumes and while disposed within said scattering volumes are impinged by said beam and scatter a portion of said beam toward respective ones of said photodetector means to cause said plurality of photodetector means to develop respective electrical signals that are proportional to the intensity of the radiation scattered to each such photodetector means by said particles, said signals being developed substantially simultaneously by said photodetectors so that the mathematical probability of a large particle appearing in one of said scattering volumes at the time of measurement is substantially less than the mathematical probability of a large particle appearing simultaneously in the other of the scattering volumes and the signal developed by that photodetector whose scattering volume contains a large particle is greater than the signal developed by the other photodetectors, and

means electrically subtracting the smaller of said signals from the larger signal.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,797,937 Dated May 13, 1974

Inventor(s) Fredrick M. Shofner

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 5, line 13, change "laser diode" to -- diode laser --

Signed and sealed this 17th day of September 1974.

(SEAL)
Attest:

McCOY M. GIBSON JR.
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents

50 (10-69)

USCOMM-DC 60376-P69
☆ U.S. GOVERNMENT PRINTING OFFICE : 1969 O—366-334.