United States Patent

Elking et al.

[15] **3,661,460**

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[54] **METHOD AND APPARATUS FOR OPTICAL ANALYSIS OF THE CONTENTS OF A SHEATHED STREAM**

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[21] Appl. No.: **67,819**

[52] **U.S. Cl.** ....**356/36**, 250/218, 250/222 PC, 356/102, 356/208, 356/246

[51] **Int. Cl.** **G01n 1/00**, G01n 15/02, G01n 21/06

[58] **Field of Search** ....356/36, 39–40, 356/102–104, 134, 201, 207–208, 246; 250/218, 222 PC

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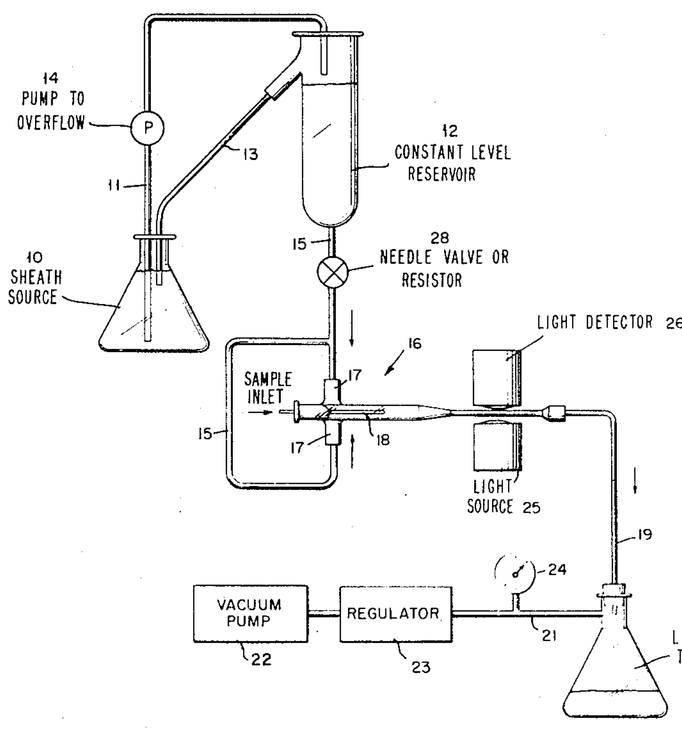
[57] **ABSTRACT**

There is provided a method and apparatus for optical analysis by photometry of a substance flowing in a liquid stream within a coaxial sheath stream of a transparent liquid. The sheath stream, flowing in the same direction, entrains the inner stream so as to confine it concentrically. A photometer is used which includes a light source on one side of the sheathed stream in a position to direct light onto the inner stream which is cylindrical, the outer or sheath stream also being cylindrical. The photometer also includes a light detector externally of the sheathed stream in an angular position to detect the photometric results of impingement of light on the contents of the inner stream. Refraction of light at the interfaces of the sheath stream is compensated by varying the radius of the inner stream through the control of the flow of one stream with reference to the other.

The concept also includes the narrowing of the sheathed stream to a very small diameter in which it is confined by a wall structure in the area of examination.

19 Claims, 6 Drawing Figures



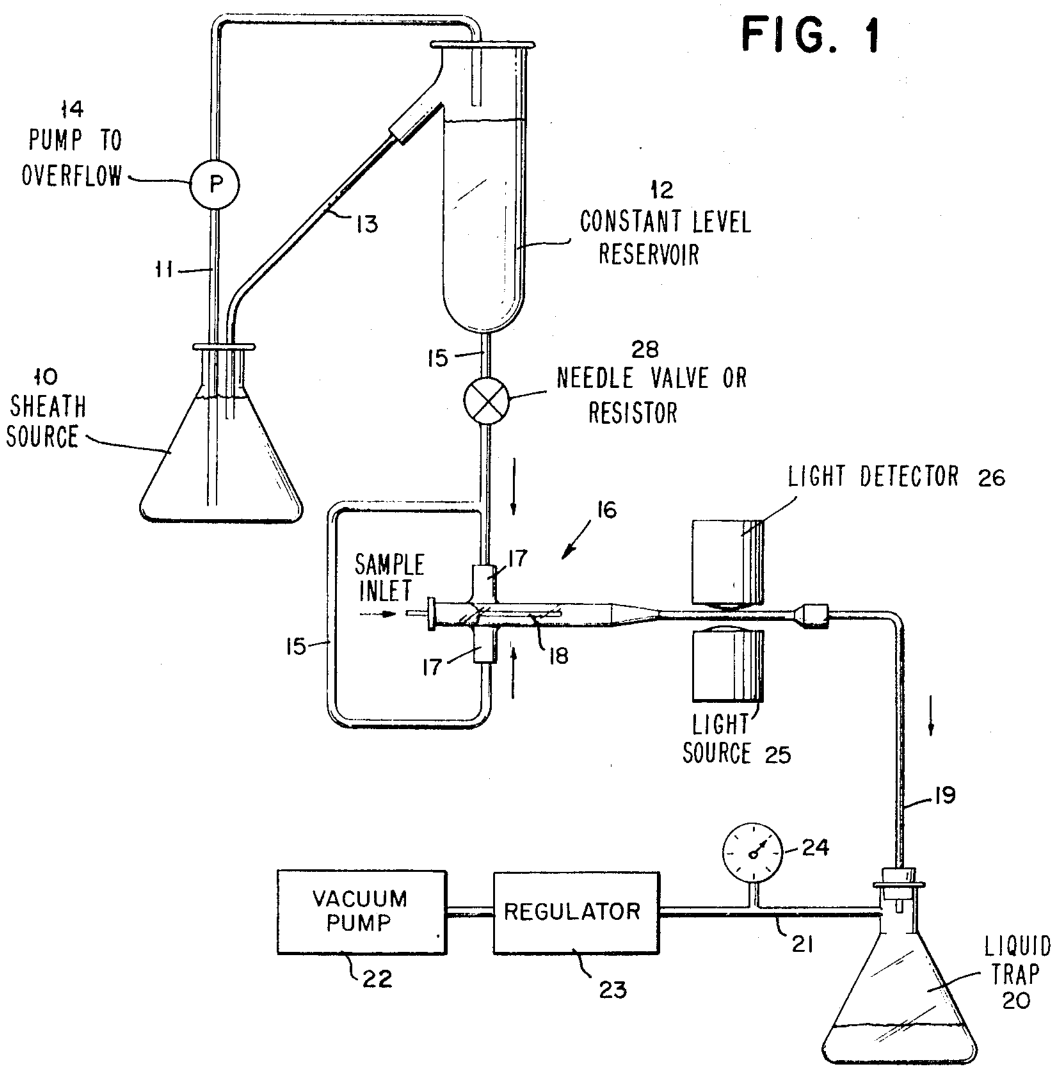


FIG. 1

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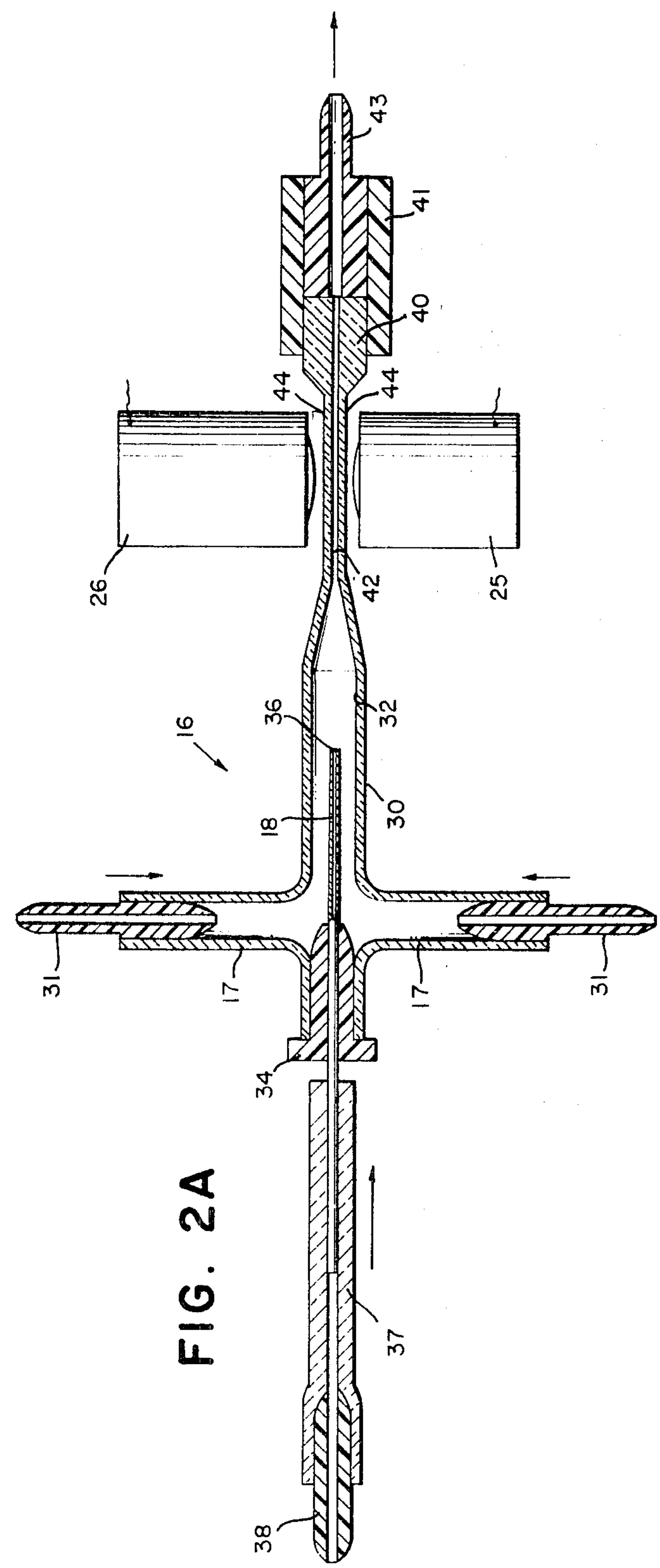
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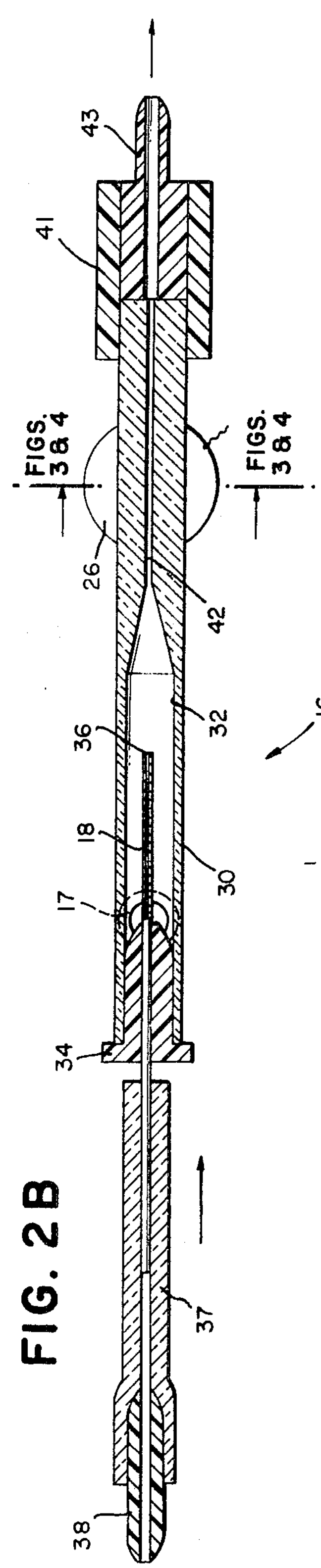
FIG. 2A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FIGS. 3 & 4
FIGS. 3 & 4
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FIG. 2B

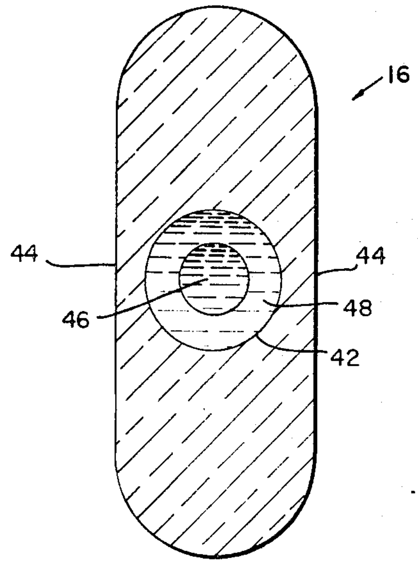

FIG. 3

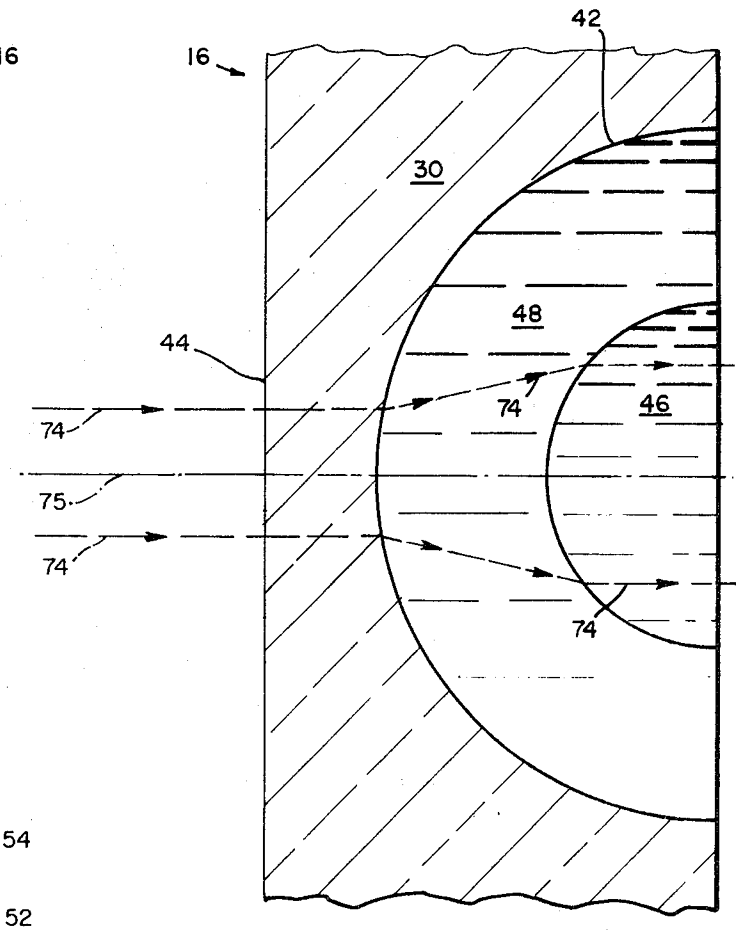

FIG. 4

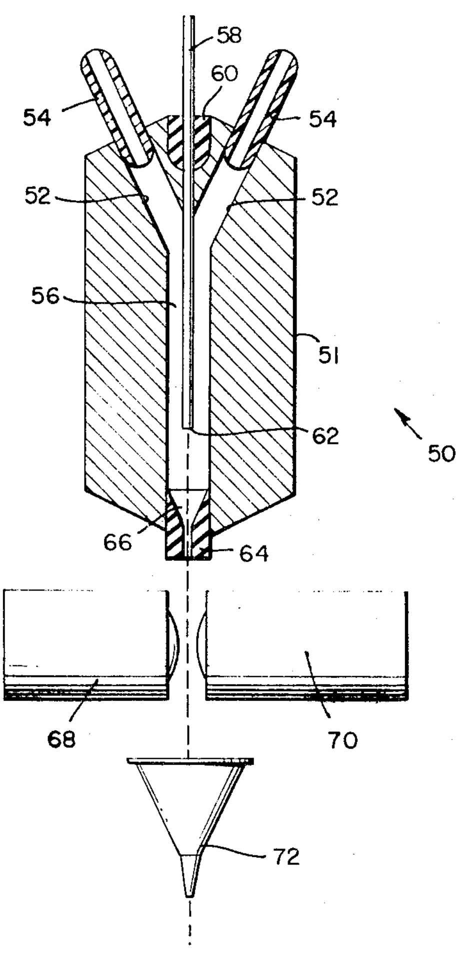

FIG. 5

METHOD AND APPARATUS FOR OPTICAL ANALYSIS OF THE CONTENTS OF A SHEATHED STREAM

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a method and apparatus for optical analysis by photometry of a substance flowing in a liquid stream within a coaxial sheath stream of a transparent confining liquid in which it is entrained.

2. Prior Art

Fine streams utilized for optical examination of their content frequently clog in small diameter transparent tubing as is well known, especially in circumstances where the stream contains, intentionally or otherwise, particulate matter. Also, it has long been recognized that in the use of such fine tubing there is an undesirable pressure drop.

At least certain of these difficulties were recognized by P. J. Crosland-Taylor who proposed, in an article entitled "A Device for Counting Small Particles Suspended in a Fluid through a Tube", which appeared in the Jan. 3, 1953 issue of the publication NATURE, page 37, injecting a suspension of particles to be counted into a stream of liquid flowing in the same direction. Under conditions in which very little turbulence existed, the relatively wide column of particles was accelerated by the faster flowing stream to form a narrow column surrounded by the sheath liquid previously selected to match the index of refraction of the suspension.

The sheathed stream was enclosed in a block-like device for observation, and the author made no mention of any light refraction problem existing with reference to the outer interface of the sheath, probably, because in that device the viewing parts did not permit close observation of the sample. It presently appears that no thought was then given to the problem of refraction of light at both interfaces of a cylindrical sheath stream which encloses a cylindrical inner stream.

Subsequently, further experimental work was reported along the same general lines by P. F. Mullaney, M. A. Van Dilla, J. R. Coulter, and P. N. Dean, in an article entitled "Cell Sizing: A Light-Scattering Photometer for Rapid Volume Determination" which appeared in the publication THE REVIEW OF SCIENTIFIC INSTRUMENTS, Vol. 48, No. 8, Aug. 1969. A flow chamber was described in which the sheathed stream was injected into an ambient body of liquid confined by the chamber in the windowed observation area upstream of a restrictive orifice and carried therebeyond through the orifice. This work was based on the earlier work of P. J. Crosland-Taylor.

The later use by others of the last-mentioned flow chamber was fraught with optical problems among which was the preclusion of optics with close working distances, say, in the order of 2 mm, and multiple difficulties, same caused by entrapment of air bubbles, involving undesirable refraction of light in the observation area including but not limited to refraction of light at the interfaces of the sheath stream. Also, observation was restricted to a small area, upstream of the aforementioned restrictive orifice.

The present invention effectively tends to obviate the aforementioned difficulties, particularly in dark field light-scattering photometric techniques.

SUMMARY OF THE INVENTION

It is an object of the invention to provide an improved method and apparatus for optical analysis by photometry of a substance flowing in a liquid stream within a coaxial sheath stream of a transparent liquid which sheath stream flows in the same direction and entrains the inner stream so as to confine it in concentric relationship.

Another object includes the narrowing of the sheathed stream to a very small diameter in which it may be confined by a wall structure in the area of examination, and the avoidance in this area of any more volume of the sheathed stream than necessary to carry the sample. This tends effectively to reduce any ambient fluid which might obscure the sample.

A further object is to provide equal and opposite refraction of light in photometric analysis of a cylindrical sheathed stream by varying the radius of the inner stream within limited but practical ranges through the control of the relative flow of the inner and outer streams.

According to the invention, there may be provided in such apparatus a flow chamber having an elongated passageway portion provided with an outlet end and at the other end a tube inlet of substantially smaller diameter extending concentrically a distance into the passageway portion and terminating forwardly in a free tube end. The flow chamber further comprises a second inlet in the passageway portion at a location a distance rearwardly from the free tube end. The flow cell further comprises a restriction in the aforementioned passageway portion intermediate the aforementioned outlet end thereof and the free tube end, which defines a round opening, the internal surfaces of the passageway portion of the tube being circular.

Provision is made for flowing a sample stream through the tube inlet into the passageway portion and for flowing a sheath stream into the aforementioned second passageway inlet at a greater velocity than the sample to entrain the latter so as to increase the velocity of the sample stream and narrow it as the streams flow toward the aforementioned restriction of the passageway portion wherein they are narrowed proportionately, thereby both being accelerated.

A photometer is provided downstream from the upstream extremity of the restriction of the passageway portion and includes a light source, on one side of the sheathed stream in a position to direct light onto the sample stream, and a light detector externally of the sheathed stream in an angular position to detect the photometric results of impingement of light on the contents of the sample stream. A further provision is made for controlling the relative flow of the streams which controls the radius of the sample stream, so that the last named radius may be varied and thereby compensate for refraction of light at the interfaces of the sheath stream.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 is a diagramatic view of apparatus for optical analysis by photometry including a flow chamber, embodying the invention;

FIG. 2A is a view of the flow chamber of FIG. 1 illustrating it in longitudinal horizontal section;

FIG. 2B is a longitudinal elevational sectional view of the flow chamber;

FIG. 3 is an enlarged sectional view taken on line 3—3 of FIG. 2B, illustrating the sheathed stream within the flow chamber;

FIG. 4 is a further enlarged, fragmentary view in section taken on line 4—4 of FIG. 2B, illustrating the sheathed stream within the flow chamber and indicating how refraction of light at the interfaces of the sheath stream is compensated; and

FIG. 5 is a view similar to FIG. 2A illustrating in vertical section a modified form of the flow chamber.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In FIG. 1 there is shown the principal elements of apparatus for optical analysis by photometry of a substance flowing in a liquid stream within a coaxial sheath stream of a transparent liquid, the illustration being by way of example only. There is indicated at **10** a supply of transparent liquid for the sheath stream, the source being illustrated as a flask from which passes tube **11** emptying into an elevated vessel **12** for the sheath stream. The vessel **12** has an overflow outlet including a tube **13** to carry off excess liquid and return it to the source **10** by gravity.

A pump **14** is provided to convey liquid from the source **10** to the vessel **12** which forms a constant-level reservoir for the sheath stream liquid. The bottom of the vessel is provided with a liquid outlet connected to a gravity feed tube **15** connecting the vessel 12 with a lower flow chamber indicated generally at 16. The flow chamber is generally of elongated tubular shape and, in the illustrated form, the tube 15 is branched so that the flow chamber has a pair of liquid inlets 17 for the sheath stream which are arranged opposite one another in the sidewall structure of the flow chamber.

A sample inlet tube, extending through a closed end of the flow chamber and indicated generally at 18 is arranged axially of the flow chamber intermediate the inlets 17, the tube terminating forwardly a distance within the longitudinal passageway of the chamber 16 in a free end. The tube 18 is arranged concentrically with reference to the longitudinal passageway of the flow chamber, the tube 18 being of substantially smaller outer diameter than the passageway portion into which it extends.

The other end of the flow chamber 16 is a discharge end connected to a tube 19 discharging into a suitable receptacle which is here shown as a stoppered flask 20. Vacuum tube 21 is connected to the upper portion of the flask 20 to create a vacuum for the purpose of withdrawing the sheathed stream from the flow chamber 16, and to this end the tube 21 is connected to a vacuum pump 22 through a regulator 23, and the tube 21 is provided with a suitable pressure guage 24.

The flow chamber 16, details of which will be discussed hereinafter with reference to other views of the drawings, is structured largely of a transparent material such as a suitable glass, and has associated with a transparent region thereof a photometer including a light source 25 at one side of the flow chamber and at the opposite side a light detector 26 so that light from the source passes through the contents of the flow chamber to the light detector in the illustrated form.

This arrangement, however, is not a limitation. In this connection it may be noted that while the light source and light detector are indicated to be in opposing relationship, the light detector might be arranged at right angles to the path of light impinged on the sheathed stream to detect fluoresence, for example, in the contents of the flow chamber 16. In a certain photometric technique, the light emitted from the light source and impinged on the stream to be analyzed may be reflected back in the direction of the light source for a distance before being diverted to the light detector conveniently located to receive such diverted light rays, and such a technique is also possible according to the invention. The illustrated arrangement of the light source and light detector permits analysis of a sample by its light transmitting characteristics or its light absorbing characteristics, and also by light-scattering techniques.

For illustrative purposes it may be considered that the sample contains particles in suspension to be counted by a forward scattering of light by the particles, that is, toward the light detector in the position shown, as they pass substantially one after another in a stream intermediate the light source and the light detector. Avoidance of light refraction for accuracy of analysis is particularly important in the use of light-scattering techniques.

The sample stream may be fed to the inlet tube 18 intermittently or continuously and be pulled or pushed for introduction into the flow chamber. U.S. Pat. No. 2,879,141 issued Mar. 24, 1959 discloses (the disclosure of which is incorporated herein by reference) a suitable automated sample supply apparatus, not shown, which has provision for holding a plurality of samples, which may be used. The samples of a series in tubing may be separated from one another by a segmenting fluid which maintains the integrity of the samples and tends to cleanse the tubing wall as the sample stream passes toward the examination area as described in the last-mentioned patent. Usually any segmenting fluid is removed prior to entry of a smple into the flow chamber as by a device, not shown, such as that illustrated and described in U.S. Pat. No. 3,109,714 issued Nov. 5, 1963. It has been found that samples may be conveniently transmitted to and through the last-named device by a peristaltic pump, not shown, such as that illustrated and described in U.S. Pat. No. 2,935,028 issued May

3, 1960 without causing undue pulsations of the sample within the flow chamber. The disclosure of U.S. Pat. No. 2,935,028, supra, is incorporated herein by reference.

Pulsations within the flow chamber of both the sample and sheath streams is considered disadvantageous. For this reason the sheath stream may be fed to the flow chamber 16 by gravity from an elevated constant-level reservoir such as the vessel 12 establishing a head of liquid. It should be noted that the sample and sheath streams should have similar viscosities, at least when they meet and are present in the flow chamber. If desired the sheath stream, like the sample stream, may be pushed or pulled by a pump for introduction into the flow chamber inlets 17, which may be considered together as an inlet for the sheath stream.

It will be apparent that the flow chamber may have a single inlet for the sheath stream, such as one concentric with the tube 18. It is necessary, here, that the sheath stream have a sufficient distance of travel from its point of entry to the free forward end of the sample tube 18 to completely fill the passageway portion and establish steady state laminar flow surrounding the tube in order to properly entrain the sample stream injected thereinto from the tube 18 on its passage toward the discharge end of the flow chamber connected to the tube 19, as will be more readily apparent from the discussion hereinafter of other views of the drawings.

As will appear more fully hereinafter, the entrained sample stream is reduced in diameter after leaving the tube 18, and the radius of the sample stream may be varied by controlling the relative flow of the sample and sheath streams as previously indicated. As it is usually deemed undesirable to place a restrictive device such as a valve or the like in the sample stream inlet line due to the risk of clogging of the sample stream, a needle valve 28 may be interposed in the sheath stream tube 15 intermediate the vessel 12 and the chamber inlet 17 to control the inlet flow of the sheath stream to the flow chamber. A resistor may be used in place of the valve 28, if desired. It will be evident that if the flow of the sheath stream is reduced, the radius of the sample stream is enlarged. Also, if the sheath stream flow is increased, the radius of the sample stream diminishes. Refraction of light impinged on the sample stream by the light source 25 is a function, at least in part, of the radius of the sample stream.

Referring now to the details of the flow chamber 16 shown in FIGS. 2A though 4, the chamber includes an elongated tubular body 30 of transparent glass material having diametrically opposite side arms in alignment with one another providing the inlets 17 for the sheath stream, in which arms nipple fittings may be received, respectively, for connection to the respective branches of the tube 15 shown in FIG. 1. These inlet arms are located intermediate the ends of the body of the flow chamber and are of approximately the same internal diameter as the longitudinal portion 32 of the flow chamber passageway with which they communicate, which may be approximately .125 inch.

The longitudinal passageway portion 32 continues to the rear end of the flow chamber and is closed by a plug 34 through the center of which extends the mid-portion of the sample stream inlet tube 18, so that the tube 18 is concentrically supported in fluid-tight relation thereby in the passageway portion 32. The forward free end 36 of the tube 18 extends beyond the inlet arms 17 and terminates in the passageway portion 32 which is circular in cross section. The cylindrical tube 18 which has an outer diameter substantially smaller than that of the passageway portion 32 may have an inner diameter of approximately 0.0195 inch and be constituted by hypodermic tubing or of a small-diameter tube structure of a non-corrosive metal. Its fluid passageway is circular in cross section.

As shown in FIGS. 2A and 2B, the rear end portion of the tube 18 is received in one end of a sleeve 37 the other end of which sleeve may receive a nipple fitting 38 for connection to a suitable sample tube not shown. A distance forwardly of the free end 36 of the tube 18, the inner wall surface of the longitudinal passageway in the tubular body **30** slopingly narrows creating a restriction, indicated at **42**, of circular cross section defining an orifice and extending forwardly in the area of and beyond the light path between the light source **25** and the light detector **26** as shown in FIGS. **2**A and **2**B.

In the region of the light path, outer wall surfaces of the tubular body are thinned and flattened, as at **44**, on opposite sides thereof in opposing relation to the light source and the light detector to minimize light refraction at the outer surface of the tubular body **30** and to permit the aforementioned optical elements **25**, **26** to closely approach the fluid contents of the restricted passageway portion **42**, as indicated in FIGS. **2**A and **3**. This close working distance of the optical elements from the fluids contents may be approximately 0.010 inch, and permits use of a high numerical aperature condenser and objective. If desired, the portion of the tubular body **30** of the flow chamber in the light path may be immersed in optical oil for a refractive index match.

The restriction **42** in the tubular body **30**, which may be 0.010 inch, is illustrated as extending through the thickened discharge end **40** (FIG. **2**A) of the body **30** received in one end of a sleeve **41** the other end of which receives a nipple fitting **43** for connection to the discharge tube **19** (FIG. **1**) for discharge of the composite liquid stream from the flow chamber into the waste receptacle or trap **20** shown in FIG. **1**. The illustrated vacuum pump **22** connected through tube **21** to the receptacle **20** effectively discharges the flow chamber, and it has been found that the pump **22** may be run at varying vacuums without changing the radial dimension of the sample stream within the sheath stream in the examination area provided by the restricted passageway portion **42** of the flow chamber.

It will be understood from the foregoing that when the sample stream is injected through the tube **18** into the passageway portion **32** of the flow chamber it is entrained and accelerated by the faster flowing laminar sheath stream, and the streams are proportionately narrowed and accelerated as they are influenced by the restriction **42** of the passageway prior to reaching the examination area. Hence, small particles in diluted suspension forming the sample stream tend to follow one another through the passageway portion **42** rather than pass abreast of one another, which enables the particles to be counted by the action of the photometer which operates a suitable recorder not shown. In FIGS. **3** and **4** the sample stream is indicated at **46** and the sheath stream at **48**.

The diameter of the sample stream may be, in a particular instance, depending on the relative flow of the sample and sheath streams, approximately 0.003 inch. Also, by way of example, the sample stream may equal **9** per cent of the total flow. In such circumstances a total flow of the combined streams through the flow chamber of 5 ml per minute, or 3 millionths of a cubic foot per second, equal a Reynolds number of 510.

In the modified form of the invention illustrated in FIG. **5**, the flow chamber, indicated generally at **50**, has an elongated block-like body **51** vertically arranged provided through its upper end with a pair of converging bores or sheath stream inlets **52** respectively receiving nipple fittings **54** for connection to the respective branches of a sheath stream supply tube similar to the tube **15** previously described with reference to FIG. **1**. These inlets **52** converge, as shown, in a central, longitudinal bore or passageway portion **56** of the body **51**, extending through the lower end thereof. Through the upper end portion of the body **51**, there is provided a central longitudinal bore intermediate the sheath stream inlets **52** which bore, communicating with the passageway portion **56**, receives a sample stream inlet tube **58**, similar to the sample stream inlet tube **18**, previously described. The tube **58** extends through a supporting plug **60**, provided in an enlargement of the last-mentioned bore, and the tube **58** is concentrically arranged in the passageway portion **56**, with its lower free end **62** terminating a distance upwardly from the lower end of the passageway portion **56**, as illustrated in FIG. **5**.

As shown in the last-mentioned view, a restriction is formed in the lower discharge end of the passageway portion **56**, the restriction in this instance being formed by a plug **64** inserted for support in the lower end of the passageway portion **56**, the plug **64** having a central opening **66** defined by a funnel-like surface. From the opening **66** in the plug **64**, the sheathed stream is injected downwardly into the ambient atmosphere for examination by a photometer, illustrated as comprising a light source **68**, closely located at one side of the stream, and the light detector **70**, located closely to the stream on the diametrically opposite side thereof, for a light path therebetween. Also, as shown in FIG. **5**, there may be provided a funnel **72** to catch the streams shortly after they cross the last mentioned light path and collect them for drainage into a suitable receptacle therebelow, not shown.

In the operation of the flow chamber **50**, the sheath liquid supplied to the inlets **52** of the flow chamber **50** picks up, in the passageway portion **56**, the sample stream injected into the passageway portion **56** through the tube **58**, in a manner to entrain it and accelerate the sample stream, narrowing it as the streams flow toward the restriction formed in the passageway portion **56** by the plug **64**, wherein they are narrowed proportionately, thereby both being accelerated, all in a manner similar to the operation of the flow chamber **16** previously described. As previously indicated, the sheathed stream is unconfined after it exits from the flow chamber **50** through the plug **64** and passes across the light path between the light source **68** and the light detector **70**. This makes possible extremely short working distances from the sheathed stream to the optical elements **68**, **70**, with attendant apparent advantages.

To compensate for the refraction of light at the interfaces of the sheath stream in the area in which the stream is examined, the radius of the inner or sample stream may be varied, as in the use of the previously described flow chamber **16**, by adjusting the relative flow of the sheath and sample streams. This control of the relative flow of the streams may be accomplished in the previously described manner. Another advantage of the form of the invention shown in FIG. **5** over that shown in FIG. **1**, is that by injecting the sheathed stream into the ambient atmosphere for examination, a significant pressure drop may be avoided in the area of examination.

However, one of the advantages of the form of the invention shown in FIG. **1**, is that the flow chamber **16** may be oriented in any position so that the optical elements associated with the flow chamber may accordingly be positioned, that is, vertically or horizontally. If the flow chamber **16** is arranged vertically with the flow directed upward, it is obvious that any air bubbles which might be caught in the chamber will be swept to the upper end thereof and out of the viewing area. Still another advantage of the form of FIG. **1**, is that the sheathed stream is confined in the examination area so as to prevent splattering of the optical elements associated with the flow chamber as by an aberration in the sheathed stream.

Referring now to the optical problems, specifically refraction of light, overcome by the invention, it is known that the external surface of a cylinder such as the sheath stream will refract light if the substance with which it is in contact has a different index of refraction, such as air or glass. This refraction may be compensated within workable limits including the indexes of refraction of the outer substance such as air or glass, the sheath stream and the sample stream.

Compensation is achieved if rays **74** (FIG. **4**) parallel to the optical axis **75** reach the center line of the sample stream in parallel relation to the axis **75** of light from the aforementioned light source **25**. This compensation may be obtained by determining and establishing the correct radius of the sample stream with reference to the particular operating conditions prevailing at the time including the last-mentioned indexes of refraction. The radial dimension of the sample stream must be such as to bring about equal and opposite refraction at the two interfaces of the sheath stream.

In the form illustrated in FIG. 4 in which the sheathed stream is enclosed within a hollow cylindrical wall surface, the index of refraction N_3 of the sample stream must be greater than the index of refraction N_2 of the sheath stream to obtain compensation of refraction at the interfaces of the sheath stream. The converse is true in the situation of FIG. 5 in which the sheath stream in the area of examination is unconfined, that is, it is exposed to a gas such as air.

The refracting power of a cylindrical interface is directly proportional to the cylinder radius. Compensation of refraction of light may be effected through control of the sample stream radius within the sheath stream provided that the absolute difference in refraction indexes of the inner and outer streams is less than the absolute difference in refraction indexes of the outer stream and that (here, glass) to which it is externally exposed.

Thus, in the following an example, where N_1 is 1.51; N_2 is 1.36; N_3 is approximately 1.38; and r_o, the radius of the sheath stream, is 0.005 inch: in solving for r, the radius of the sample stream, the following equation is used:

$$rx\left[1+\frac{1}{N_3-N_2}\right]=r_0x\left[\frac{1}{N_1-N_2}+1\right]$$

$$r=r_0x\left[\frac{1+\frac{1}{N_1-N_2}}{1+\frac{1}{N_3-N_2}}\right]$$

r=approximately .00076 inch

from elementary optics wherein:

$$\frac{r}{N_3-N_2}=\frac{r_0}{N_1-N_2}+[r_0-r]$$

In the foregoing example, the sample stream is constituted by human blood diluted with propylene glycol and in which the red cells are hemolyzed. The red cell ghosts have the same index of refraction as the diluent so that the red cells are rendered invisible, for the counting by photometric means, as aforesaid, of the white cells. One obvious advantage of the invention is that there is no requirement in the use of the flow chamber that the index of refraction of the sheath stream match the index of refraction of the sample stream.

The photometer has a conventional ocular, not shown, to observe, with the human eye, the flow of the stream in the flow chamber so that it may be determined whether or not refractive errors have been compensated. In this connection a conventional target, not shown, of the optical elements, projected through the flow chamber is brought into sharp focus at the particular sample stream radius which achieves compensation of light refraction as indicated above. The photometric viewing area should be larger than the diameter of the sample stream.

It is believed the many advantages of this invention will now be apparent to those skilled in the art. The foregoing description is illustrative, rather than limiting, as a number of variations and modifications may be made without departing from the true spirit and scope of the invention. The invention is limited only to the scope of the following claims.

What is claimed is:

1. Apparatus for optical analysis of a sample stream including a liquid in a coaxial sheath stream liquid comprising: means defining a flow chamber having an elongated passageway portion having a forward outlet end and at a rear end of said portion a tube inlet of substantially smaller diameter than said passageway portion extending concentrically a distance forwardly into said passageway portion and terminating forwardly in a free tube end, the last-named means defining a second inlet in said passageway portion at a location a distance rearwardly from said free tube end, and the last-named means also defining a restriction with a narrow sloping approach in said passageway portion intermediate said outlet end thereof and said free tube end, the internal and external surfaces of said free tube end and the internal surface of said passageway portion being circular in cross section, means for flowing a sample stream through said tube inlet into said passageway portion, means for flowing a sheath stream into said second passageway inlet at a greater flow rate than the sample stream to entrain the latter so as to increase the velocity of the sample stream and narrow it as the streams flow toward said restriction of the passageway portion, photometric means downstream from the upstream extremity of said restriction of the passageway portion in proximity to the sheathed stream and including a light source on one side of the sheathed stream in a position to direct light onto the contents of the sample stream and a light detector externally of the sheathed stream in angular position to detect the photometric results of impingement of light on the sample stream, and means controlling the relative flow rates of said streams into said flow chamber, which controls the radius of the sample stream, so that in the area where said light is directed on the sample stream the last-named radius may be varied proportionately to the radius of the inner surface of the sheath stream for equal and opposite refraction of light at the interfaces of said sheath stream.

2. Apparatus as defined in claim 1, wherein: said means controlling the relative flow rates of said streams comprises a device operative to restrict the flow of the sheath stream into the flow chamber.

3. Apparatus as defined in claim 1, wherein: said means for flowing the sheath stream into said flow chamber comprises a constant-level reservoir establishing a head of sheath stream liquid.

4. Apparatus as defined in claim 1, wherein: said means for flowing the sample stream into said tube inlet of the flow chamber comprises a pump upstream of the tube inlet.

5. Apparatus as defined in claim 1, wherein: said outlet end of the flow chamber is connected to a pump.

6. Apparatus as defined in claim 1, wherein: said means controlling the relative flow rates of the streams comprises a valve operative to vary the flow of the sheath stream into the flow chamber.

7. Apparatus as defined in claim 1, wherein: said means for flowing the sample stream into said sample tube inlet of the flow chamber comprises a pump upstream of the tube inlet, said outlet end of the flow chamber being connected to a liquid trap through an outlet conduit, and further comprising a vacuum pump operatively connected to the last-named outlet conduit.

8. Apparatus as defined in claim 1, wherein: the flow chamber is vertically arranged.

9. Apparatus as defined in claim 1, wherein: the sheathed stream is directed from said outlet end of the flow chamber into a gas, and said photometric means examines the sheathed sample stream in said gas.

10. Apparatus as defined in claim 1, wherein: the sheathed stream is directed into ambient air from said outlet end of the flow chamber, and said photometric means examines the sheathed sample stream in said ambient air.

11. Apparatus as defined in claim 1, wherein: the flow chamber is horizontally arranged.

12. Apparatus as defined in claim 1, wherein: said means defining a flow chamber comprises a tubular body having said restriction of the passageway portion therein.

13. Apparatus as defined in claim 1, wherein: said means defining a flow chamber comprises a tubular body having said restriction of the passageway portion therein, said restriction enclosing the sheathed stream where light from said source is impinged on the sample stream.

14. A method for optical analysis of a sample stream including a liquid in a coaxial sheath stream liquid comprising: providing means defining an elongated passageway portion of circular cross section in a flow chamber which portion has at one end thereof a circular restriction; flowing a first laminar liquid stream into said passageway portion in a direction

toward said restriction; concurrently flowing in the same direction a slower moving liquid stream of cylindrical cross section and of a substantially smaller diameter than said first stream, containing a sample, into the first stream concentrically so that the latter sheaths and entrains the second stream, accelerating and narrowing it as the streams approach said restriction in a concentric relation to one another; directing an impinging light beam of a photometer, in a direction transversely of the aforementioned direction of flow, onto the sample-containing stream for photometric analysis of the sample by a light detector of the photometer, downstream from the upstream extremity of said restriction; and controlling the relative flow rates of the streams into said passageway portion, which controls the radius of the second or sample stream, so that in the area where said light beam impinges said sample stream the last-named radius may be varied proportionately to the radius of the inner surface of the sheath stream for equal and opposite refraction of light at the interfaces of the sheath stream.

15. The method as defined in claim 14, wherein: the step of controlling the relative flow of the streams into said flow chamber comprises controlling said sheath stream.

16. The method as defined in claim 14, wherein: the step of flowing the sheath stream into the flow chamber comprises flowing the sheath stream from a constant-pressure source.

17. The method as defined in claim 14, further comprising introducing the sheath and sample streams into the flow chamber under positive pressure, and withstanding the sheath stream from the flow chamber under negative pressure through an outlet of the flow chamber downstream from said restriction.

18. The method as defined in claim 14, further comprising narrowly confining the sheath stream where said light beam is impinged on the sample stream.

19. The method as defined in claim 14, further comprising directing the sheathed stream into a gas from the flow chamber in a downward direction and examining the sheathed stream by the photometer in said gas.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,661,460 Dated May 9, 1972

Inventor(s) Alan H. Elkind et al

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

On the cover sheet [72] the inventor's name "Alan H. Elking" should read -- Alan H. Elkind --.

Signed and sealed this 7th day of November 1972.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents