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(71) Applicant: **RHEOLOGICS, INC.** [US/US]; 15 E. Uwchlan Avenue, Suite 414, Exton, PA 19341 (US).

(72) Inventors: **KENSEY, Kenneth**; 1494 Treeline Drive, Malvern, PA 19355 (US). **HOGENAUER, William, N.**; 220 Jordan Drive, Gilbertsville, PA 19525 (US). **CHO, Young, I.**; 132 Renaissance Drive, Cherry Hill, NJ 08003 (US). **SHIN, Sehyun**; Kyungpook National University, 1370 Sankyuk-Dong Buk-Gu, 702701 Daeku (KR). **KIM, Sangho**; 305 Cadwalder Circle, Exton, PA 19341 (US).

(74) Agent: **SLOMOWITZ, Scott, M.**; Caesar, Rivise, Bernstein, Cohen & Pokotilow, Ltd., Seven Penn Center, 1635 Market Street, 12th Floor, Philadelphia, PA 19103 (US).

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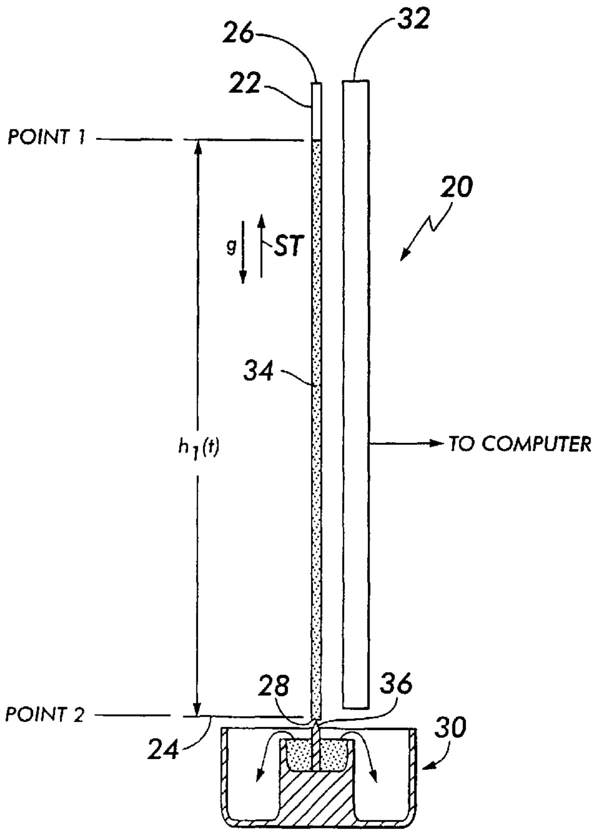

(57) Abstract: A method and apparatus for determining the viscosity of a non-Newtonian fluid over plural shear rates using a single capillary tube exposed to a continuously decreasing pressure differential and while minimizing the effects of surface tension of that fluid during the determination. A particular application of this method and apparatus is also provided for determining the viscosity of the blood of a living being whereby the single capillary tube initially forms a portion of a hand-held unit that obtains a portion of the circulating blood of the living being; the filled capillary tube is then ejected into an analyzer where the blood therein is exposed to the continuously decreasing pressure differential. Data is generated from the movement of the blood through the capillary tube, due to the decreasing pressure differential, and the blood viscosity is determined from that data.

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SINGLE CAPILLARY TUBE VISCOMETER

SPECIFICATION

FIELD OF INVENTION

This invention relates generally to the field of measuring the viscosity of liquids, and more particularly, to a method of isolating the surface tension and yield stress effects when determining the viscosity of a liquid using a single scanning capillary tube viscometer.

BACKGROUND OF THE INVENTION

As disclosed in A.S.N. 09/708,137, the effects of surface tension and yield stress can be isolated in the viscosity determination of a test fluid that is flowing through a scanning capillary tube viscometer. In particular, the scanning capillary tube viscometer disclosed therein basically comprises a U-shaped tube where one portion of the U-shaped tube is formed by a capillary tube. One leg of the U-shaped tube supports a falling column of fluid and the other leg supports a rising column of fluid Furthermore, movement of either one or both of these columns is monitored, hence the term "scanning." It should be understood that the term "scanning," as used in this Specification, also includes the detection of the change in mass (e.g., weight) in the column of fluid. Thus, all manners of detecting the change in the column mass, volume, height, etc. is covered by the term "scanning."

As also discussed in A.S.N. 09/708,137, in order to measure liquid viscosity using that U-shaped scanning capillary tube viscometer, the pressure drop across the capillary tube has to be precisely estimated from the height difference between the two fluid columns in the respective legs of the U-shaped tube. However, under normal circumstances, the height difference, $\Delta h(t)$, contains the effects of surface tension and yield stress. Therefore, the contributions of the surface tension (Δh_{st}) and yield stress (τ_y) to $\Delta h(t)$, have to be taken into account, or isolated; using a U-shaped scanning capillary tube viscometer, $\Delta h(t)$ is equal to $h_1(t) - h_2(t)$.

In addition, in the U-shaped scanning capillary tube viscometer of A.S.N. 09/708,137, the capillary tube remains completely filled with the test fluid during the test run such that the gas-liquid interface of the falling column never passes through the capillary tube. However, there remains a need for accounting for, or isolating, the surface tension and yield stress in viscosity measurements when using a scanning capillary tube viscometer wherein the viscometer comprises a single capillary tube and wherein the test fluid in the single capillary tube is continuously decreasing during the test run such that the gas-liquid interface of the falling column passes through the capillary tube.

SUMMARY OF THE INVENTION

An apparatus for detecting the movement of a fluid at plural shear rates using a decreasing pressure differential. The apparatus comprises: a capillary tube having a first end and a second end, wherein the capillary tube has a sample of the fluid therein and wherein the capillary tube is positioned at an angle greater than zero degrees with respect to a horizontal reference position; the second end is arranged to minimize surface tension effects thereat; a sensor for detecting the movement of the sample of fluid over time (e.g., a column level detector, a mass detector, etc.) while the sample of fluid moves through the capillary tube; the first end is exposed to atmospheric pressure creating a pressure differential between the first end and the second end, wherein the sample of fluid moves through the capillary tube at a first shear rate caused by the pressure differential, and wherein the movement of the sample of fluid causes the pressure differential to decrease from the first shear rate for generating the plural shear rates.

An apparatus for determining the viscosity of a non-Newtonian fluid over plural shear rates using a decreasing pressure differential. The apparatus comprises: a capillary tube having a first end and a second end, wherein the capillary tube has a sample of the fluid therein and wherein the capillary tube is positioned at an angle greater than zero degrees with respect to a horizontal reference position; the second end being arranged to minimize surface tension effects thereat; a sensor for detecting the movement of the sample of fluid over time (e.g., a column level detector, a mass detector, etc.) while the sample of fluid moves through the capillary tube; the first end being exposed to atmospheric pressure creating a pressure differential between the first end and the second end, wherein the sample of fluid moves through the capillary tube at a first shear rate caused by the pressure differential, wherein the movement of the sample of fluid causes the pressure differential to decrease from the first shear rate for generating the plural shear rates, and wherein the sensor generates data relating to the movement of the sample of fluid over time; a computer, coupled to the sensor, for calculating the viscosity of the sample of fluid based on the data relating to the movement of the sample of fluid over time; and wherein the sample of fluid comprises a trailing edge forming a gas-fluid interface and wherein any surface tension present at the gas-fluid interface is considered constant over time. A method for detecting the movement of a fluid at plural shear rates using a decreasing pressure differential. The method comprises: disposing a capillary tube having an upper first end and a lower second end, at angle greater than zero with respect to a horizontal reference position; arranging the lower second end of the capillary tube to minimize surface tension effects thereat; entering the fluid into the first end of the capillary tube to create a sample of fluid in the capillary tube and then closing the upper end of the capillary tube from atmospheric pressure to maintain the sample of fluid therein; exposing the first end to atmospheric pressure to create a pressure differential between the first end and the second end, wherein the sample of fluid moves through the capillary tube at a first shear rate caused by the pressure differential, wherein the movement of the sample of fluid causes the pressure differential to decrease from the first shear rate for generating the plural shear rates; and activating a sensor, positioned adjacent to the capillary tube, for detecting the movement of the sample of fluid through the capillary tube.

A method for determining the viscosity of a non-Newtonian fluid over plural shear rates using a decreasing pressure differential. The method comprises: disposing a capillary tube having an upper first end and a lower second end, at angle greater than zero with respect to a horizontal reference position; arranging the lower second end of the capillary tube to minimize surface tension effects thereat; entering the fluid into the first end of the capillary tube to create a sample of fluid in the capillary tube and then closing the upper end of the capillary tube from atmospheric pressure to maintain the sample of fluid therein; exposing the first end to atmospheric pressure to create a pressure differential between the first end and the second end, wherein the sample of fluid moves through the capillary tube at a first shear rate caused by the pressure differential, wherein the movement of the sample of fluid causes the pressure differential to decrease from the first shear rate for generating the plural shear rates; activating a sensor for detecting the movement of the sample of fluid through the capillary tube and generating data related to the movement of the sample of fluid over time; and calculating the viscosity of the sample of fluid based on the data relating to the movement of the sample of fluid over time while assuming that any surface tension present at a trailing edge of the sample of fluid, which forms a gas-fluid interface, is constant over time.

An apparatus for determining the viscosity of the circulating blood of a living being over plural shear rates using a decreasing pressure differential. The apparatus comprises: a portable unit comprising a capillary tube therein, wherein the capillary tube has an upper first end and a lower second end, and wherein the capillary tube is arranged to obtain a portion of the circulating blood of the living being through the second end; and an analyzer unit for immediately receiving the capillary tube containing the portion of the circulating blood; the analyzer comprises: a capillary tube support for positioning the capillary tube in the analyzer unit at an angle greater than zero degrees with respect to a horizontal reference position; means for exposing the upper first end to atmospheric pressure to create a pressure differential between the first end and the second end, wherein the blood in the capillary tube moves through the capillary tube at a first shear rate caused by the pressure differential, and wherein the movement of the blood causes the pressure differential to decrease from the first shear rate for generating the plural shear rates; a collector under which the second end is placed for receiving blood that flows out of the capillary tube, wherein the second end is arranged for minimizing surface tension effects thereat; a sensor for detecting the movement (e.g., a column level detector, a mass detector, etc.) of the blood in the capillary tube over time for generating data related to the movement over time; a computer, coupled to the sensor, for calculating the viscosity of the blood based on the data related to the movement over time; and wherein the portion of the circulating blood in the capillary tube comprises a trailing edge forming a gas-fluid interface and wherein any surface tension present at the gas-fluid interface is considered constant over time.

A method for determining the viscosity of the circulating blood of a living being over plural shear rates using a decreasing pressure differential. The method comprises: providing access to the blood of a living being; exposing a lower end of a capillary tube to the blood of the living being to allow the blood to substantially fill the capillary tube toward an upper end; closing off the upper end to atmospheric pressure to maintain the blood in the capillary tube; positioning the substantially-filled capillary tube at angle greater than zero with respect to a horizontal reference position; arranging the lower end of the capillary tube to minimize surface tension effects thereat; exposing the upper end to atmospheric pressure to create a pressure differential between the first end and the second end, wherein the blood moves through the capillary tube at a first shear rate caused by the pressure differential, wherein the movement of the blood causes the pressure differential to decrease from the first shear rate for generating the plural shear rates; activating a sensor for detecting the movement of the blood through the capillary tube and generating data related to the movement of the blood over time; and calculating the viscosity of the blood based on the data relating to the movement of the blood over time while assuming that any surface tension present at a trailing edge of blood, which forms a gas-fluid interface, is constant over time.

DESCRIPTION OF THE DRAWINGS

The invention of this present application will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

Fig. 1 is a functional diagram of a test fluid flowing in a single capillary tube viscometer (SCTV) having a capillary tube and with a column level detector for monitoring the movement of the test fluid;

Fig. 2 is an enlarged view of a prior art capillary tube that forms a meniscus under normal conditions;

Fig. 3 is an enlarged view of the portion identified in Fig. 1 showing the projection that prevents the meniscus from forming at the bottom of the capillary tube;

Fig. 4 is an isometric view of a preferred fluid collector used in the SCTV;

Fig. 5 is a graphical representation of the height of the column of test over time in the capillary tube;

Fig. 6 is a graphical representation of the height of the column of the test fluid in the capillary tube over time that exhibits yield stress;

Fig. 7 is a functional diagram of the SCTV of Fig. 1 but using a different method of minimizing surface tension effects by submerging the output of the capillary tube;

Fig. 8 is an isometric view, in partial cut-a-away, of a blood viscosity determining apparatus that uses the SCTV;

Fig. 9 is an enlarged side view of a hand-held portion of the blood viscosity determining apparatus using the SCTV;

Figs. 10A-10B depict the procedure for obtaining blood from a living being using the hand-held portion of the blood viscosity determining apparatus; and

Fig. 11 is an isometric view of the capillary tube used in the blood viscosity determining apparatus.

DESCRIPTION OF THE PREFERRED EMBODIMENT OF THE INVENTION

Referring now in detail to the various figures of the drawing wherein like reference characters refer to like parts, there is shown at 20 in Fig. 1, a single capillary tube viscometer (SCTV) that basically comprises a capillary tube 22 that is positioned at an angle greater than zero degrees with respect to a horizontal reference position 24 (e.g., the capillary tube 22 is oriented in a vertical or leaning position). The upper end 26 of the capillary tube 22 is exposed to atmospheric pressure and the second end 28 of the capillary tube 22 is positioned closely adjacent a receiving device 30 (a collector, cup, etc.). A detector 32 monitors the position over time of a column of fluid 34 that is formed in the capillary tube 22; although this detector can monitor either the rise of the column of fluid 34 in the capillary tube 22 or the fall of the column of fluid 34, the preferred method is to detect the column of fluid 34 as it falls.

The detector 32 may comprise a column level detector for detecting the movement (e.g., the height, $h_1(t)$) of the column of fluid 34 in the capillary tube 22, such as a charge-coupled device (CCD). The details of such types of detectors are disclosed in A.S.N. 09/439,745 and A.S.N. 09/573,267, both of which are assigned to the same Assignee as the present invention, namely Visco Technologies, Inc., and, therefore, the details of these detectors are not repeated here. Furthermore, although not shown in Fig. 1, but disclosed in these other applications, the detector 32 communicates with a computer for processing the data collected by the detector 32.

It should be understood that the column level detector is by way of example only and that a variety of sensors could be used for the detector 32. Another example of such a detector is a mass detector (e.g., a precision balance or load cell) upon which the receiving device 30 is placed. Thus, instead of having a level detector closely adjacent the capillary tube 22, the mass detector would detect the changing mass over time as the fluid flows out of the capillary tube 22 and into the receiving device 30. The mass detector generates data regarding the movement of the fluid through the capillary tube, e.g., the mass detector would transmit data related to the changing mass, m(t), to the computer. Thus, instead of a height vs. time curve (Figs. 5 and 6), a corresponding mass vs. time curve could be generated from such data; and from that mass vs. time data, the viscosity of the fluid can be determined.

In addition, the lower end 28 of the capillary tube 22 is juxtaposed to an upperwardly facing projection 36. This projection 36 may reside in the receiving device 30. The purpose of the projection 36 is to prevent the surface tension effect that normally would occur when the lumen containing the fluid is open (see Fig. 2). In particular, as shown in Fig. 3, the projection 36 separates the lower level of the falling column of fluid 34, thereby preventing this lower level from forming a meniscus 38 (Fig. 2) as would normally occur at the opening of the capillary tube 22.

The receiving device 30, as shown most clearly in Fig. 4, basically comprises an inner circular wall 35 that divides the collector into a central portion 31 and an annular portion 39. The central portion 31 comprises the projection 36 over which is positioned the lower end 28 of the capillary tube 22. As the fluid fills the collector 30, the fluid 34 can spill over the top of the inner circular wall 35 and into the annular portion 39.

Unlike the U-shaped scanning capillary viscometer of A.S.N. 09/708,137 where the test fluid completely fills the capillary tube 22 during the test run, the present invention comprises a capillary tube 22 that is initially filled but is increasingly evacuated during the test run such that the gas-liquid interface of the falling column 34 passes through most of the capillary tube 22. As a result, this effectively can be modeled as a capillary tube whose length is continuously decreasing with time, i.e., $L_c(t)$.

The operation of the invention 20 of the present application also begins with the conservation of energy equation, in terms of pressure, as set forth in A.S.N. 09/708,137, except that: it is assumed that the surface tension (ST) at point 1 (Fig. 1) is independent of time, t, through the capillary tube 22 and activated in the opposite direction of gravitational force, and that there is no effect of surface tension at point 2 since the point 2 is far from point 1 that is affected by surface tension:

$$P_1 + \frac{1}{2}\rho V_1^2 + \rho g h_1(t) = P_2 + \frac{1}{2}\rho V_2^2 + \rho g h_2(t) + \Delta P_c(t) + \rho g \Delta h_{st1} \quad (1)$$

where:

$P_1 = P_2$ = hydro-static pressures at points 1 and 2 respectively and which equal a constant;
ρ =density of the test fluid;
g = gravitational acceleration;
$V_1 = V_2$ = flow velocities at points 1 and 2 respectively, and which equal a constant;
$h_1(t)$ = the height of the column of fluid in the capillary tube 22;
$h_2(t)$ = the height of the column of fluid at point 2 = 0;
$\Delta P_c(t)$ = the pressure drop across the capillary tube 22; and
Δh_{st1} = the contribution of Δh_∞ resulting in the additional height difference due to surface
tension in the capillary tube 22.

As a result of the above assumptions and definitions, Equation (1) reduces to:

$$\Delta P_c(t) = \rho g\left(h_1(t) - \Delta h_{st1}\right), \quad (2)$$

where Δh_{st1} = constant.

Where no surface tension and no yield stress, τ_y, occurs, the falling column 34 of test fluid would have a height vs. time characteristic as shown in Fig. 5. However, in actuality, as shown in Fig. 6, where as time goes to infinity a constant separation between the level of the test fluid column and the reference level, h_2, occurs and is known as known as Δh_∞ which can be attributed to surface tension Δh_{st} and/or yield stress τ_y.

If the test fluid experiences yield stress, τ_y, there is a relationship between τ_y and the pressure drop across the capillary tube 22 that can be expressed using a model, e.g., a Casson model or a Herschel-Bulkley model, wherein this expression is defined as:

$$\tau_y = \frac{\Delta P_c(\infty)\cdot R_c}{2L_c(\infty)} \quad (3),$$

where,

$\Delta P_c(\infty)$ = the pressure drop across the capillary tube 22 at the end of the test run; and
R_c = capillary tube 22 radius; and
$L_c(\infty)$ = that portion of the capillary tube 22 length that contains the test fluid at the end of
the test run.

Depending on whether the test fluid experiences yield stress or not, $L_c(\infty)$ has a certain value due to the surface tension. If the test fluid does not experience yield stress, then $\Delta P_c(\infty) = 0$, i.e., $h_1(\infty) = \Delta h_{st}$; if, on the other hand, the test fluid does experience yield stress, then $h_1(\infty) > \Delta h_{st}$, i.e., $\Delta P_c(\infty)$ = non-zero value.

If the height of the column of fluid 34, $h_1(t)$ is defined in terms of the number of pixels of the detector 32, then the following pixel values can be assigned by way of example only:

The height of the column of fluid 34 at point 1 = pixel #4500;
The height of the reference level h_2 (at point 2)= pixel #500; and
The initial height of the column of fluid = pixel #5000.

It should be understood that using the detector 32, there can be at least 10,000 data points obtained for $h_1(t)$. With so many data points, the following equation for the velocity of the column of fluid in the capillary tube 22, namely, $\overline{V_c}$, using a Casson model, for example, can be solved for a number of unknowns:

$$\overline{V_c} = \frac{R_c^2}{8k}\left[\left(\frac{\Delta P_c(t)}{L_c(t)}\right) - \frac{16}{7}\left(\frac{2\tau_y}{R_c}\right)^{\frac{1}{2}}\cdot\left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{\frac{1}{2}} + \frac{4}{3}\left(\frac{2\tau_y}{R_c}\right) - \frac{1}{21}\left(\frac{2\tau_y}{R_c}\right)^4\left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{-3}\right] \quad (4)$$

where:

$$\Delta P_c(t) = \rho g\left(h_1(t) - \Delta h_{st1}\right); \quad (5)$$

$L_c(t) = h_1(t) - h_2$ (6); and

$$\tau_y = \frac{\Delta P_c(\infty)\cdot R_c}{2L_c(\infty)} = \frac{\rho g(h_1(\infty) - h_2 - \Delta h_{st})\cdot R_c}{2(h_1(\infty) - h_2)}$$

Using a curve-fitting method (e.g., the Microsoft Excel Solver), Equation (4) can then be solved for the 3 unknowns k, Δh_{st1}, and τ_y; in fact, Equation (4) can also be solved for R_c, the radius of the capillary tube 22; alternatively, it should be understood that the value of R_c could also be obtained directly from the manufacturer of the capillary tube 22 without the need to solve Equation (4) for that value. The k value is known as a consistency index and it is used in capillary viscometry.

With k, Δh_{st1}, τ_y, and R_c obtained, and since $h_1(\infty)$ is also determined by the detector 32, these values can be entered into the following equations for $\dot{\gamma}_w$, the shear rate at the wall of the capillary tube 22, and for τ_w, the shear stress at the wall of the capillary tube 22:

$$\dot{\gamma}_w = \frac{1}{k}\left(\sqrt{\frac{R_c \Delta P_c}{2L_c(t)}} - \sqrt{\frac{R_c \Delta P_c(\infty)}{2L_c(\infty)}}\right)^2 \qquad (7)$$

$$\tau_w = \frac{R_c \Delta P_c(t)}{2L_c(t)} \qquad (8)$$

Once the shear rate and the shear stress are known, the test fluid viscosity, η, can then be determined according to the following equation:

$$\eta = \frac{\tau_w}{\dot{\gamma}_w} \qquad (9).$$

One exemplary application of the SCTV 20 is in determining the viscosity of the blood of a living being.

In Fig. 8, there is shown a blood viscosity determining apparatus 120 that uses the SCTV 20. The apparatus 120 comprises a hand-held portion 122 and an analyzer portion 124. The hand-held portion 122 initially contains the capillary tube 22 and permits blood to be withdrawn from the living being and into the capillary tube 22. The hand-held portion 122 is then immediately interfaced with the analyzer portion 124 and the filled capillary tube 22 is released into the analyzer portion 124. With the filled capillary tube 22 inserted into the analyzer portion 124, the SCTV 20 is formed and the blood viscosity analysis begins immediately.

In particular, the hand-held portion (Fig. 9) comprises a body 126 that may be ergonomically contoured to facilitate handling by a technician. The body 126 includes an internal passageway 128 into which a substantial portion of the capillary tube 22 is inserted at the factory; only a small portion 129 of the capillary tube 22 projects out of the base 130 of the hand-held portion 124. To insert the capillary tube 22, a release button 132 at the top of the hand-held portion 124 is depressed. This action spreads a pair of clamp surfaces 134A and 134B that open the passageway 128 and permits insertion of the capillary tube 22. Upon releasing the release button 132, the capillary tube 22 is secured in the hand-held portion 124.

The hand-held portion 124 also includes a window 134 through which the technician can view the level of blood as it rises (as will be discussed later) towards the top end138 of the capillary tube 22. When the technician sees the blood level in the window 134, the technician depress a plug button 140 which inserts a plug (not shown) into the top end 138 which is open. This stops the entry of any more blood into the capillary tube 22 and the filled capillary tube 22 is now ready for insertion into the analyzer portion 124.

The analyzer portion 124 comprises a housing 142 that contains the column level detector 32, the receiving device 30 and a capillary tube support 144 (having an upper support arm 144A and a lower support arm 144B); the computer and any supporting electronics, power supplies for the detector 32 may also be contained within the housing 142 although it is not required. The housing also comprises a door 146 for providing access to the capillary tube 22 and receiving device 30 to allow these items to be discarded and a new receiving device 30 to be inserted in preparation for a new viscosity test run. The analyzer portion 124 also comprises a drop hole 148 through which the capillary tube 22 passes when released from the hand-held portion 122, as shown in Fig. 8.

A start button 150 is activated by the technician once the capillary tube 22 is installed in the analyzer portion 124. Depressing this start button 150 basically does two things: firstly, it removes the upper portion 152 (Fig. 11) of the capillary tube 22 that contains the plug (not shown); a score line 154 is created in the capillary tube 22 at the factory before it is inserted into the hand-held portion 122. When the start button 150 of the analyzer 124 is depressed, a force is applied to the upper portion 152 of the capillary tube 22, thereby causing the upper portion 152 to separate from the remainder of the capillary tube 22 containing the blood. This action exposes the new upper end of the capillary tube 22 to atmosphere and thereby allowing the column of blood 34 therein to fall towards the receiving device 30. Secondly, depressing the button 150 also initiates the column level detector 32 to monitor the falling column of blood 34 over time to begin the SCTV viscosity analysis described earlier. A read-out display 154 provides the technician with all of the viscosity-related data. Thus, the analysis used to determine the blood viscosity is in accordance with the previous discussion for the SCTV 20.

Although not shown, the removal of the upper portion 152 may be accomplished by having a support arm, similar to the support arms 144A/144B, that engages the upper portion 152 and applies slight pressure to separate it from the remainder of the capillary tube 22 at the score line 154. Once separated, this upper portion 152 is retained by the support arm and is removed at the end of the test by the technician when he/she is removing the capillary tube 22 and receiving device 30.

Once the test run is complete, the capillary tube 22 is removed, along with the receiving device 30 and properly and safely discarded. A new receiving device 30 is placed therein in preparation for the next viscosity test run.

Figs. 10A-10B depict the sequence for obtaining the blood from a living being. For example, a sufficient amount of blood from a human being can be obtained by first pricking the finger 10 of the individual with a lancet 12 (Fig. 10A) and then positioning the open, exposed end 129 of the capillary tube 22 onto the blood 14 that emanates from the blood vessel (Fig. 10B). The blood 14 wicks up into the capillary tube 22. As it does, the technician watches the window 134 and when he/she sees the blood level in the window 134, he/she depresses the plug button 140. The process continues as discussed earlier.

Without further elaboration, the foregoing will so fully illustrate our invention that others may, by applying current or future knowledge, readily adopt the same for use under various conditions of service.

CLAIMS

1. An apparatus for detecting the movement of a fluid at plural shear rates using a decreasing pressure differential, said apparatus comprising:

a capillary tube having a first end and a second end, said capillary tube having a sample of the fluid therein and wherein said capillary tube is positioned at an angle greater than zero degrees with respect to a horizontal reference position;

said second end being arranged to minimize surface tension effects thereat;

a sensor for detecting the movement of said sample of fluid over time while said sample of fluid moves through said capillary tube;

said first end being exposed to atmospheric pressure creating a pressure differential between said first end and said second end, said sample of fluid moving through said capillary tube at a first shear rate caused by said pressure differential, said movement of said sample of fluid causing said pressure differential to decrease from said first shear rate for generating said plural shear rates.

2. The apparatus of Claim 1 further comprising a fluid collector positioned under said second end and wherein said fluid collector comprises a projection that is closely positioned to said second end, said projection separating said sample of fluid as it passes through said second end to minimize surface tension effects.

3. The apparatus of Claim 1 wherein said capillary tube is positioned vertically with respect to said horizontal reference position.

4. The apparatus of Claim 1 wherein the fluid is a non-Newtonian fluid.

5. The apparatus of Claim 1 wherein said movement of fluid comprises a falling column of said sample of fluid and wherein said sensor monitors the changing height of said falling column of said sample of fluid over time, said height being defined as the distance between the top of said falling column of said sample of fluid and said horizontal reference position.

6. The apparatus of Claim 5 wherein said apparatus further comprises a computer, said computer being coupled to said sensor and wherein said computer

calculates the viscosity of the sample of fluid based on said changing height of said falling column of said sample of fluid over time.

7. The apparatus of Claim 1 further comprising a fluid collector positioned under said second end and wherein said second end is submerged in fluid accumulating in said fluid collector to minimize surface tension effects.

8. An apparatus for determining the viscosity of a non-Newtonian fluid over plural shear rates using a decreasing pressure differential, said apparatus comprising:

a capillary tube having a first end and a second end, said capillary tube having a sample of the fluid therein and wherein said capillary tube is positioned at an angle greater than zero degrees with respect to a horizontal reference position;

said second end being arranged to minimize surface tension effects thereat;

a sensor for detecting the movement of said sample of fluid over time while said sample of fluid moves through said capillary tube;

said first end being exposed to atmospheric pressure creating a pressure differential between said first end and said second end, said sample of fluid moving through said capillary tube at a first shear rate caused by said pressure differential, said movement of said sample of fluid causing said pressure differential to decrease from said first shear rate for generating said plural shear rates, said sensor generating data relating to the movement of said sample of fluid over time;

a computer, coupled to said sensor, for calculating the viscosity of the sample of fluid based on said data relating to the movement of the sample of fluid over time; and

wherein said sample of fluid comprises a trailing edge forming a gas-fluid interface and wherein any surface tension present at said gas-fluid interface is considered constant over time.

9. The apparatus of Claim 8 further comprising a fluid collector positioned under said second end and wherein said fluid collector comprises a projection that is closely positioned to said second end, said projection separating said sample of fluid as it passes through said second end to minimize surface tension effects.

10. The apparatus of Claim 9 wherein said collector comprises:

a container having an inner compartment over which said second end is disposed; and

an annular compartment surrounding said inner compartment for forming an overflow chamber.

11. The apparatus of Claim 10 further comprising a fluid collector positioned under said second end and wherein said second end is submerged in fluid accumulating in said fluid collector to minimize surface tension effects.

12. The apparatus of Claim 11 wherein said collector comprises:

a container having an inner compartment in which said second end is disposed; and

an annular compartment surrounding said inner compartment for forming an overflow chamber.

13. The apparatus of Claim 8 wherein said capillary tube is positioned vertically with respect to said horizontal reference position.

14. The apparatus of Claim 8 wherein said computer comprises an equation representing the velocity of said sample of fluid through said capillary tube over time, said computer using said data relating to the movement of said sample of fluid to solve said equation to determine shear rate at the wall of said capillary tube.

15. The apparatus of Claim 14 wherein said computer uses said data relating to the movement of the sample of fluid to determine shear stress at the wall of said capillary tube.

16. The apparatus of Claim 15 wherein said computer uses said determined shear rate and said determined shear stress to determine said viscosity the sample of fluid.

17. The apparatus of Claim 8 wherein said movement of fluid comprises a falling column of said sample of fluid and wherein said sensor monitors the changing height of said falling column of said sample of fluid over time, said height being defined as the distance between said trailing edge of said falling column of said sample of fluid and said horizontal reference position.

18. The apparatus of Claim 17 wherein said computer represents the pressure drop across said capillary tube, ΔP_c, as given by:

$$\Delta P_c(t) = \rho g\left(h_1(t) - \Delta h_{st1}\right),$$

where
ρ = the density of the fluid;
g = the gravitational constant;
$h_1(t)$ = the height of said falling column;
Δh_{st1} = said surface tension present at said gas-fluid interface.

19. The apparatus of Claim 18 wherein said capillary tube has a radius, R_c, and an effective length, $L_c(t)$, said effective length corresponding to said height of said falling column.

20. The apparatus of 19 wherein said computer represents the yield stress of said fluid, τ_y, as:

$$\tau_y = \frac{\Delta P_c(\infty) \cdot R_c}{2L_c(\infty)},$$

where
$\Delta P_c(\infty)$ = said pressure drop across said capillary tube after a long period of time; and
$L_c(\infty)$ = said effective length of said capillary tube after a long period of time.

21. The apparatus of Claim 20 wherein said computer utilizes an equation for the velocity of said sample of fluid through said capillary tube, $\overline{V_c}$, as:

$$\overline{V_c} = \frac{R_c^2}{8k}\left[\left(\frac{\Delta P_c(t)}{L_c(t)}\right) - \frac{16}{7}\left(\frac{2\tau_y}{R_c}\right)^{\frac{1}{2}} \cdot \left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{\frac{1}{2}} + \frac{4}{3}\left(\frac{2\tau_y}{R_c}\right) - \frac{1}{21}\left(\frac{2\tau_y}{R_c}\right)^4\left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{-3}\right]$$

where k is a consistency index.

22. The apparatus of Claim 21 wherein said computer uses a curve fitting method to solve said velocity equation for Δh_{st1}, k and τ_y.

23. The apparatus of Claim 22 wherein said computer calculates the viscosity of said fluid, η , as defined by:

$$\eta = \frac{\tau_w}{\dot{\gamma}_w},$$

where τ_w is the shear stress at the wall of said capillary tube and is defined as:

$$\tau_w = \frac{R_c \Delta P_c(t)}{2L_c(t)}, \text{ and}$$

where $\dot{\gamma}_w$ is the shear rate at the wall of said capillary tube and is defined as:

$$\dot{\gamma}_w = \frac{1}{k}\left(\sqrt{\frac{R_c \Delta P_c}{2L_c(t)}} - \sqrt{\frac{R_c \Delta P(\infty)}{2L_c(\infty)}}\right)^2.$$

24. A method for detecting the movement of a fluid at plural shear rates using a decreasing pressure differential, said method comprising:

disposing a capillary tube, having an upper first end and a lower second end, at angle greater than zero with respect to a horizontal reference position;

arranging said lower second end of said capillary tube to minimize surface tension effects thereat;

entering the fluid into said first end of said capillary tube to create a sample of fluid in said capillary tube and then closing said upper end of said capillary tube from atmospheric pressure to maintain said sample of fluid therein;

exposing said first end to atmospheric pressure to create a pressure differential between said first end and said second end, said sample of fluid moving through said capillary tube at a first shear rate caused by said pressure differential, said movement of said sample of fluid causing said pressure differential to decrease from said first shear rate for generating said plural shear rates; and

activating a sensor, positioned adjacent to said capillary tube, for detecting the movement of said sample of fluid through said capillary tube.

25. The method of Claim 24 wherein said arranging said lower second end of said capillary tube to minimize surface tension effects thereat comprises positioning a fluid collector under said second end and positioning an upwardly-directed projection closely adjacent said second end in said fluid collector.

26. The method of Claim 24 wherein said capillary tube is positioned vertically with respect to said horizontal reference position.

27. The method of Claim 24 wherein the fluid is a non-Newtonian fluid.

28. The method of Claim 24 wherein said movement of fluid comprises a falling column of said sample of fluid and wherein said sensor monitors the changing height of said falling column of said sample of fluid over time, said height being defined as the distance between the top of said falling column of said sample of fluid and said horizontal reference position.

29. The method of Claim 28 wherein said method further comprises calculating the viscosity of the sample of fluid based on said changing height of said falling column of said sample of fluid over time.

30. The method of Claim 24 wherein said arranging said lower second end of said capillary tube to minimize surface tension effects thereat comprises submerging said second end in fluid accumulating in said fluid collector.

31. A method for determining the viscosity of a non-Newtonian fluid over plural shear rates using a decreasing pressure differential, said method comprising:

disposing a capillary tube, having an upper first end and a lower second end, at angle greater than zero with respect to a horizontal reference position;

arranging said lower second end of said capillary tube to minimize surface tension effects thereat;

entering the fluid into said first end of said capillary tube to create a sample of fluid in said capillary tube and then closing said upper end of said capillary tube from atmospheric pressure to maintain said sample of fluid therein;

exposing said first end to atmospheric pressure to create a pressure differential between said first end and said second end, said sample of fluid moving through said capillary tube at a first shear rate caused by said pressure differential, said movement of said sample of fluid causing said pressure differential to decrease from said first shear rate for generating said plural shear rates;

activating a sensor for detecting the movement of said sample of fluid through said capillary tube and generating data related to the movement of said sample of fluid over time; and

calculating the viscosity of said sample of fluid based on said data relating to the movement of the sample of fluid over time while assuming that any surface tension present at a trailing edge of said sample of fluid, which forms a gas-fluid interface, is constant over time.

32. The method of Claim 31 wherein said arranging said lower second end of said capillary tube to minimize surface tension effects comprises positioning a fluid collector under said second end and positioning an upwardly-directed projection closely adjacent said second end in said fluid collector.

33. The method of Claim 31 wherein said arranging said lower second end of said capillary tube to minimize surface tension effects comprises positioning a fluid collector under said second end and wherein said lower second end is submerged in fluid accumulating in said fluid collector to minimize surface tension effects.

34. The method of Claim 31 wherein said step of disposing a capillary tube comprises vertically positioning said capillary tube with respect to said horizontal reference position.

35. The method of Claim 31 wherein said step of calculating the viscosity of said sample of fluid comprises the steps of:

(a) representing the velocity of said sample of fluid through said capillary tube as a velocity equation;

(b) using said data relating to said movement of said sample of fluid to solve said velocity equation to determine shear rate and the shear stress at the wall of said capillary tube; and

(c) calculating the viscosity of said sample of fluid from said shear rate and said shear stress.

36. The method of Claim 31 wherein said movement of fluid comprises a falling column of said sample of fluid and wherein said sensor monitors the changing height of said falling column of said sample of fluid over time, said height being defined as the distance between the top of said falling column of said sample of fluid and said horizontal reference position.

37. The method of Claim 36 wherein said capillary tube comprises a capillary tube and wherein said step of calculating the viscosity utilizes an expression for the pressure drop across said capillary tube, ΔP_c, as:

$$\Delta P_c(t) = \rho g\left(h_1(t) - \Delta h_{st1}\right)$$

where

ρ = the density of the fluid;
g = the gravitational constant;
$h_1(t)$ = the height of said falling column;
Δh_{st1} = said surface tension present at said gas-fluid interface.

38. The method of Claim 37 wherein said capillary tube has a radius, R_c, and an effective length, $L_c(t)$, said effective length corresponding to said height of said falling column.

39. The method of Claim 38 wherein said step of calculating the viscosity further comprises utilizing an expression for the yield stress of said sample of fluid, τ_y , as:

$$\tau_y = \frac{\Delta P_c(\infty) \cdot R_c}{2L_c(\infty)}$$

where
$\Delta P_c(\infty)$ = said pressure drop across said capillary tube after a long period of time; and
$L_c(\infty)$ = said effective length of said capillary tube after a long period of time.

40. The method of Claim 39 wherein said step of calculating the viscosity further comprises utilizing an expression for the velocity of said sample of fluid through said capillary tube, $\overline{V_c}$, as:

$$\overline{V_c} = \frac{R_c^2}{8k}\left[\left(\frac{\Delta P_c(t)}{L_c(t)}\right) - \frac{16}{7}\left(\frac{2\tau_y}{R_c}\right)^{\frac{1}{2}} \cdot \left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{\frac{1}{2}} + \frac{4}{3}\left(\frac{2\tau_y}{R_c}\right) - \frac{1}{21}\left(\frac{2\tau_y}{R_c}\right)^4\left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{-3}\right]$$

where k is a consistency index.

41. The method of Claim 40 wherein said step of calculating the viscosity further comprises solving said velocity expression for Δh_{st1}, k and τ_y.

42. The method of Claim 41 wherein said step of calculating the viscosity of said sample of fluid, η, is according to:

$$\eta = \frac{\tau_w}{\dot{\gamma}_w},$$

where τ_w is the shear stress at the wall of said capillary tube and is defined as:

$$\tau_w = \frac{R_c \Delta P_c(t)}{2L_c(t)}, \text{ and}$$

where $\dot{\gamma}_w$ is the shear rate at the wall of said capillary tube and is defined as:

$$\dot{\gamma}_w = \frac{1}{k}\left(\sqrt{\frac{R_c \Delta P_c}{2L_c(t)}} - \sqrt{\frac{R_c \Delta P(\infty)}{2L_c(\infty)}}\right)^2.$$

43. An apparatus for determining the viscosity of the circulating blood of a living being over plural shear rates using a decreasing pressure differential, said apparatus comprising:

a portable unit comprising a capillary tube therein, said capillary tube having an upper first end and a lower second end, said capillary tube being arranged to obtain a portion of the circulating blood of the living being through said second end; and

an analyzer unit for immediately receiving said capillary tube containing the portion of the circulating blood, said analyzer comprising:

a capillary tube support for positioning said capillary tube in said analyzer unit at an angle greater than zero degrees with respect to a horizontal reference position;

means for exposing said upper first end to atmospheric pressure to create a pressure differential between said first end and said second end, said blood in said capillary tube moving through said capillary tube at a first shear rate caused by said pressure differential, said movement of said blood causing said pressure differential to decrease from said first shear rate for generating said plural shear rates;

a collector under which said second end is placed for receiving blood that flows out of said capillary tube, said second end being arranged for minimizing surface tension effects thereat;

a sensor for detecting the movement of said blood in said capillary tube over time for generating data related to said movement over time;

a computer, coupled to said sensor, for calculating the viscosity of the blood based on said data related to said movement over time; and

wherein said portion of the circulating blood in said capillary tube comprises a trailing edge forming a gas-fluid interface and wherein any surface tension present at said gas-fluid interface is considered constant over time.

44. The apparatus of Claim 43 wherein said portable unit comprises:

a hand-held housing having a capillary tube passageway therein;

a releasable clamp for holding said capillary tube in said capillary tube passageway such that said second end projects out of said hand-held housing; and

a plug insertion means for inserting a plug into said first end of said capillary tube after a substantial portion of said capillary tube is filled with blood; and an ejector for opening said releaseable clamp to permit the transfer of said filled capillary tube into said capillary tube support.

45. The apparatus of Claim 44 wherein said capillary tube comprises a capillary tube and wherein said first end comprises a score line that permits said first end to be de-coupled from said capillary tube.

46. The apparatus of Claim 43 wherein said sensor comprises a column level detector for monitoring the changing level of said blood as it moves through said capillary tube.

47. The apparatus of Claim 43 further comprising a fluid collector positioned under said second end and wherein said fluid collector comprises a projection that is closely positioned to said second end, said projection separating said blood as it passes through said second end to minimize surface tension effects.

48. The apparatus of Claim 47 wherein said collector comprises:

a container having an inner compartment over which said second end is disposed; and

an annular compartment surrounding said inner compartment for forming an overflow chamber.

49. The apparatus of Claim 43 further comprising a fluid collector positioned under said second end and wherein said second end is submerged in blood accumulating in said fluid collector to minimize surface tension effects.

50. The apparatus of Claim 49 wherein said collector comprises:

a container having an inner compartment in which said second end is disposed; and

an annular compartment surrounding said inner compartment for forming an overflow chamber.

51. The apparatus of Claim 43 wherein said capillary tube support positions said capillary tube vertically with respect to said horizontal reference position.

52. The apparatus of Claim 43 wherein said computer comprises an equation representing the velocity of said blood through said capillary tube over time, said computer using said data relating to the movement of said blood to solve said equation to determine shear rate at the wall of said capillary tube.

53. The apparatus of Claim 52 wherein said computer uses said data relating to the movement of the blood to determine shear stress at the wall of said capillary tube.

54. The apparatus of Claim 53 wherein said computer uses said determined shear rate and said determined shear stress to determine said viscosity the blood.

55. The apparatus of Claim 43 wherein said movement of fluid comprises a falling column of said blood and wherein said sensor monitors the changing height of said falling column of blood fluid over time, said height being defined as the distance between said trailing edge of said falling column of said blood and said horizontal reference position.

56. The apparatus of Claim 55 wherein said capillary tube is a capillary tube and wherein said computer represents the pressure drop across said capillary tube, ΔP_c, as given by:

$$\Delta P_c(t) = \rho g\left(h_1(t) - \Delta h_{st1}\right),$$

where
ρ = the density of the blood;
g = the gravitational constant;
$h_1(t)$ = the height of said falling column of blood;
Δh_{st1} = said surface tension present at said gas-fluid interface.

57. The apparatus of Claim 56 wherein said capillary tube has a radius, R_c, and an effective length, $L_c(t)$, said effective length corresponding to said height of said falling column.

58. The apparatus of 57 wherein said computer represents the yield stress of said blood, τ_y, as:

$$\tau_y = \frac{\Delta P_c(\infty) \cdot R_c}{2L_c(\infty)},$$

where
$\Delta P_c(\infty)$ = said pressure drop across said capillary tube after a long period of time; and
$L_c(\infty)$ = said effective length of said capillary tube after a long period of time.

59. The apparatus of Claim 58 wherein said computer utilizes an equation for the velocity of said blood through said capillary tube, $\overline{V_c}$, as:

$$\overline{V}_c = \frac{R_c^2}{8k}\left[\left(\frac{\Delta P_c(t)}{L_c(t)}\right) - \frac{16}{7}\left(\frac{2\tau_y}{R_c}\right)^{\frac{1}{2}} \cdot \left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{\frac{1}{2}} + \frac{4}{3}\left(\frac{2\tau_y}{R_c}\right) - \frac{1}{21}\left(\frac{2\tau_y}{R_c}\right)^4 \left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{-3}\right]$$

where k is a consistency index.

60. The apparatus of Claim 59 wherein said computer uses a curve fitting method to solve said velocity equation for Δh_{st1}, k and τ_y.

61. The apparatus of Claim 60 wherein said computer calculates the viscosity of said blood, η , as defined by:

$$\eta = \frac{\tau_w}{\dot{\gamma}_w},$$

where τ_w is the shear stress at the wall of said capillary tube and is defined as:

$$\tau_w = \frac{R_c \Delta P_c(t)}{2L_c(t)}, \text{ and}$$

where $\dot{\gamma}_w$ is the shear rate at the wall of said capillary tube and is defined as:

$$\dot{\gamma}_w = \frac{1}{k}\left(\sqrt{\frac{R_c \Delta P_c}{2L_c(t)}} - \sqrt{\frac{R_c \Delta P(\infty)}{2L_c(\infty)}}\right)^2.$$

62. A method for determining the viscosity of the circulating blood of a living being over plural shear rates using a decreasing pressure differential, said method comprising:

providing access to the blood of a living being;

exposing a lower end of a capillary tube to the blood of the living being to allow said blood to substantially fill said capillary tube toward an upper end;

closing off said upper end to atmospheric pressure to maintain said blood in said capillary tube;

positioning said substantially-filled capillary tube at angle greater than zero with respect to a horizontal reference position;

arranging said lower end of said capillary tube to minimize surface tension effects thereat;

exposing said upper end to atmospheric pressure to create a pressure differential between said first end and said second end, said blood moving through said capillary tube at a first shear rate caused by said pressure differential, said movement of said blood causing said pressure differential to decrease from said first shear rate for generating said plural shear rates;

activating a sensor for detecting the movement of said blood through said capillary tube and generating data related to the movement of said blood over time; and

calculating the viscosity of said blood based on said data relating to the movement of said blood over time while assuming that any surface tension present at a trailing edge of blood, which forms a gas-fluid interface, is constant over time.

63. The method of Claim 62 wherein said step of arranging said lower end of said capillary tube to minimize surface tension effects thereat comprises positioning a blood collector under said lower end and positioning an upwardly-directed projection closely adjacent said lower end in said blood collector.

64. The method of Claim 62 wherein said step of arranging said lower end of said capillary tube to minimize surface tension effects thereat comprises positioning a blood collector under said lower end and wherein said lower end is submerged in blood accumulating in said blood collector to minimize surface tension effects.

65. The method of Claim 62 wherein said step of positioning said substantially-filled capillary tube at angle greater than zero comprises vertically positioning said capillary tube with respect to said horizontal reference position.

66. The method of Claim 62 wherein said step of calculating the viscosity of said sample of fluid comprises the steps of:

(a) representing the velocity of said blood through said capillary tube as a velocity equation;

(b) using said data relating to said movement of said blood to solve said velocity equation to determine shear rate and the shear stress at the wall of said capillary tube; and

(c) calculating the viscosity of said blood from said shear rate and said shear stress.

67. The method of Claim 62 wherein said movement of blood comprises a falling column of said blood and wherein said sensor monitors the changing height of said falling column of said blood over time, said height being defined as the distance between the top of said falling column of said blood and said horizontal reference position.

68. The method of Claim 67 wherein said step of calculating the viscosity utilizes an expression for the pressure drop across said capillary tube, ΔP_c, as:

$$\Delta P_c(t) = \rho g\left(h_1(t) - \Delta h_{st1}\right)$$

where
ρ = the density of the blood;
g = the gravitational constant;
$h_1(t)$ = the height of said falling column of blood;
Δh_{st1} = said surface tension present at said gas-fluid interface.

69. The method of Claim 68 wherein said capillary tube has a radius, R_c, and an effective length, $L_c(t)$, said effective length corresponding to said height of said falling column of blood.

70. The method of Claim 69 wherein said step of calculating the viscosity further comprises utilizing an expression for the yield stress of said blood, τ_y , as:

$$\tau_y = \frac{\Delta P_c(\infty) \cdot R_c}{2L_c(\infty)}$$

where
$\Delta P_c(\infty)$ = said pressure drop across said capillary tube after a long period of time; and
$L_c(\infty)$ = said effective length of said capillary tube after a long period of time.

71. The method of Claim 70 wherein said step of calculating the viscosity further comprises utilizing an expression for the velocity of said blood through said capillary tube, $\overline{V_c}$, as:

$$\overline{V_c} = \frac{R_c^2}{8k}\left[\left(\frac{\Delta P_c(t)}{L_c(t)}\right) - \frac{16}{7}\left(\frac{2\tau_y}{R_c}\right)^{\frac{1}{2}} \cdot \left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{\frac{1}{2}} + \frac{4}{3}\left(\frac{2\tau_y}{R_c}\right) - \frac{1}{21}\left(\frac{2\tau_y}{R_c}\right)^4\left(\frac{\Delta P_c(t)}{L_c(t)}\right)^{-3}\right]$$

where k is a consistency index.

72. The method of Claim 71 wherein said step of calculating the viscosity further comprises solving said velocity expression for Δh_{st1}, k and τ_y.

73. The method of Claim 72 wherein said step of calculating the viscosity of said blood, η, is according to:

$$\eta = \frac{\tau_w}{\dot{\gamma}_w},$$

where τ_w is the shear stress at the wall of said capillary tube and is defined as:

$$\tau_w = \frac{R_c \Delta P_c(t)}{2L_c(t)}, \text{ and}$$

where $\dot{\gamma}_w$ is the shear rate at the wall of said capillary tube and is defined as:

$$\dot{\gamma}_w = \frac{1}{k}\left(\sqrt{\frac{R_c \Delta P_c}{2L_c(t)}} - \sqrt{\frac{R_c \Delta P(\infty)}{2L_c(\infty)}}\right)^2.$$

FIG. 1

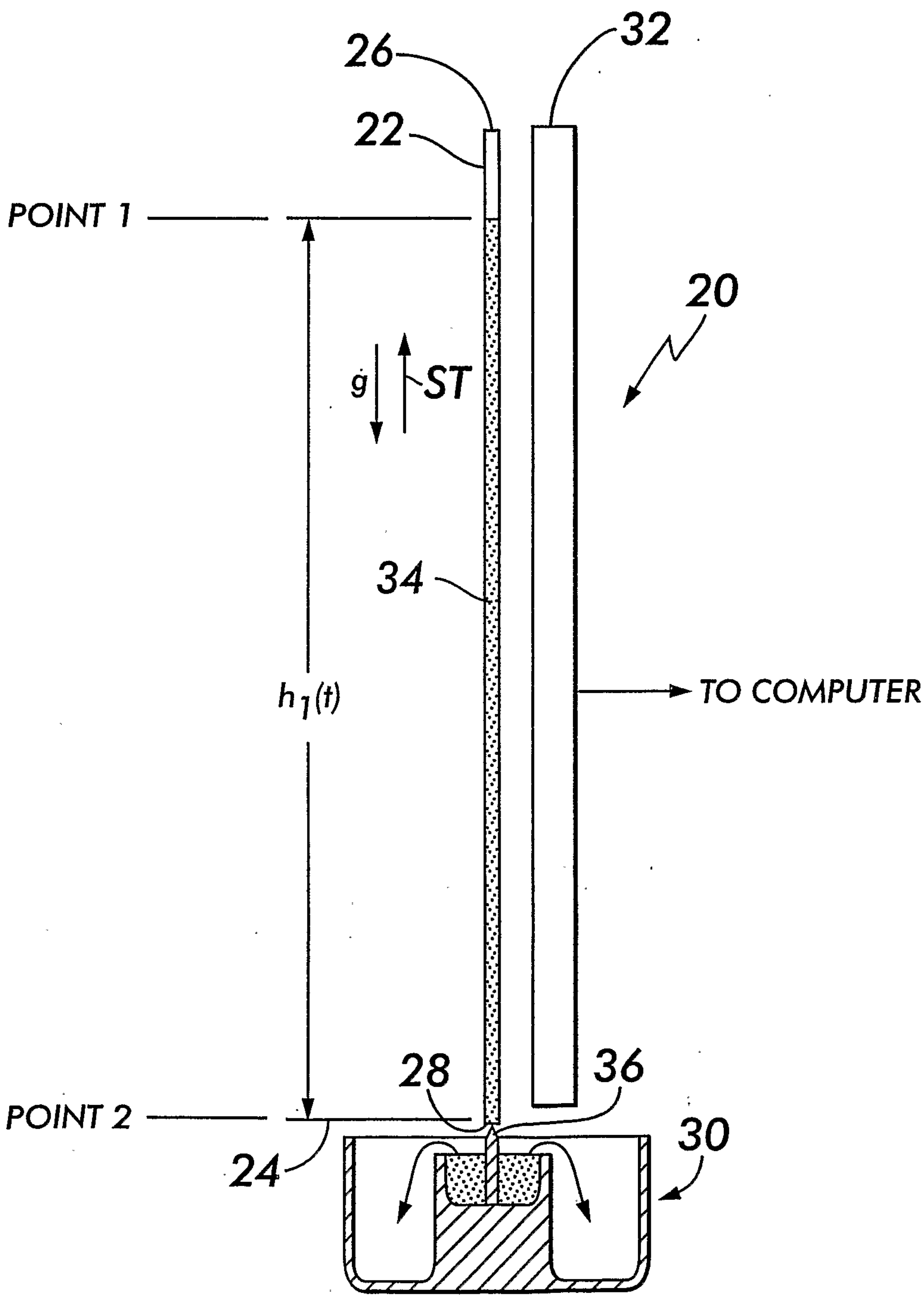


FIG.2
PRIOR ART

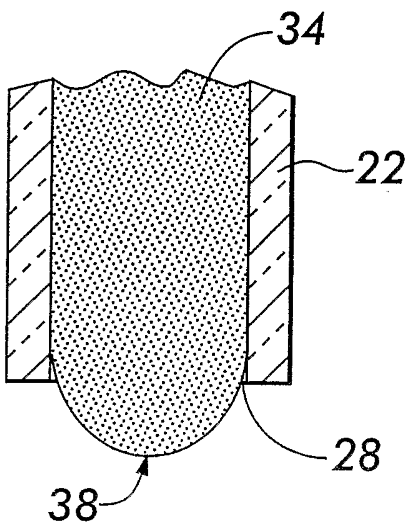
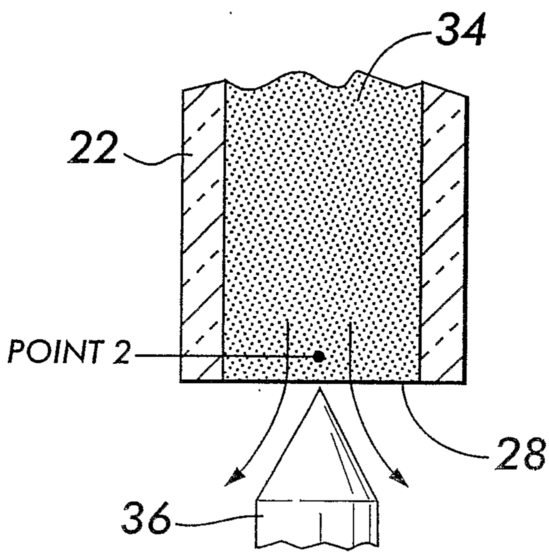


FIG.3



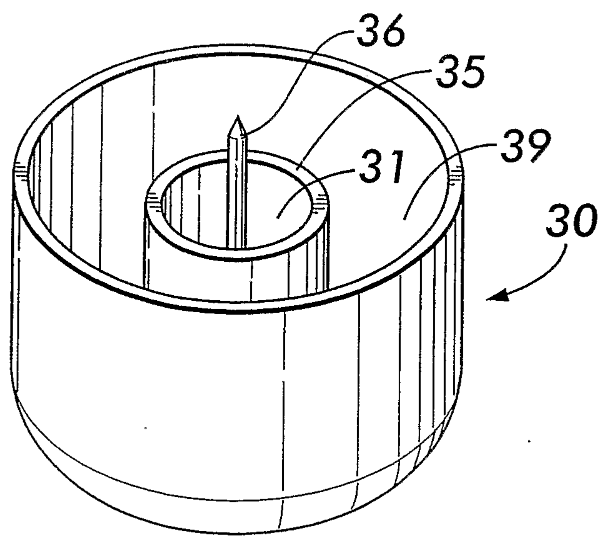


FIG.4

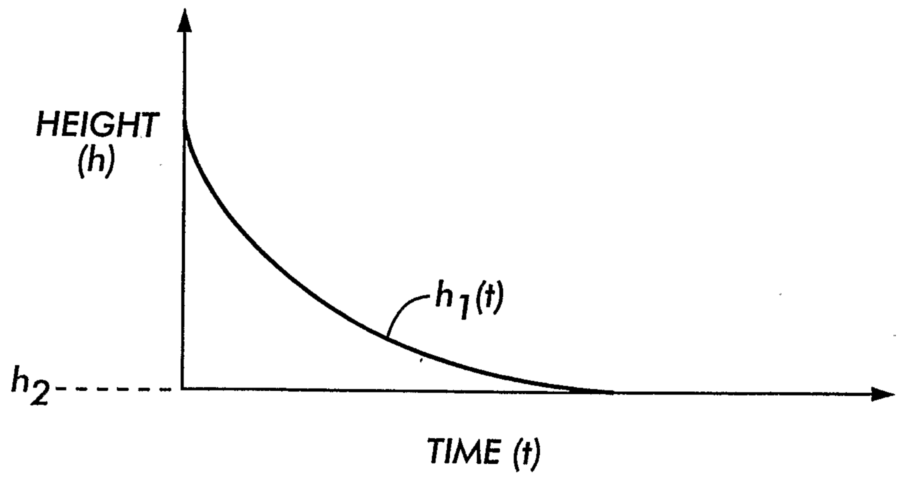


FIG.5

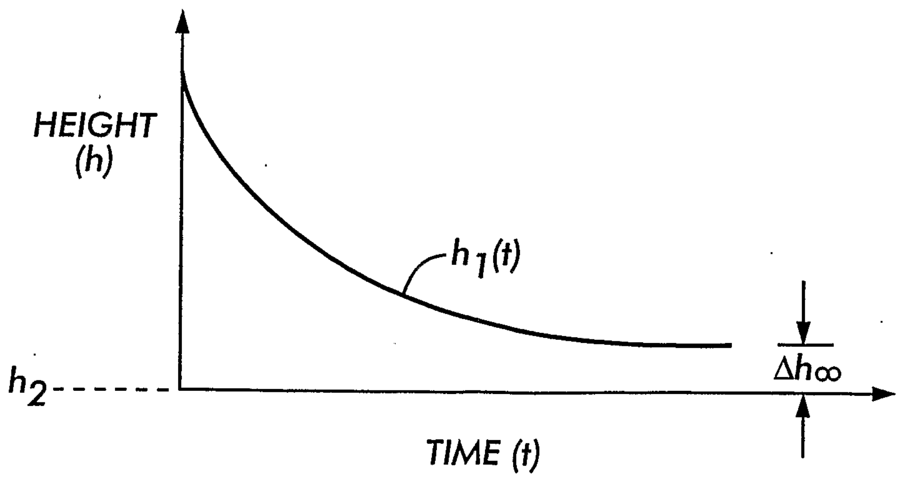


FIG.6

FIG. 7

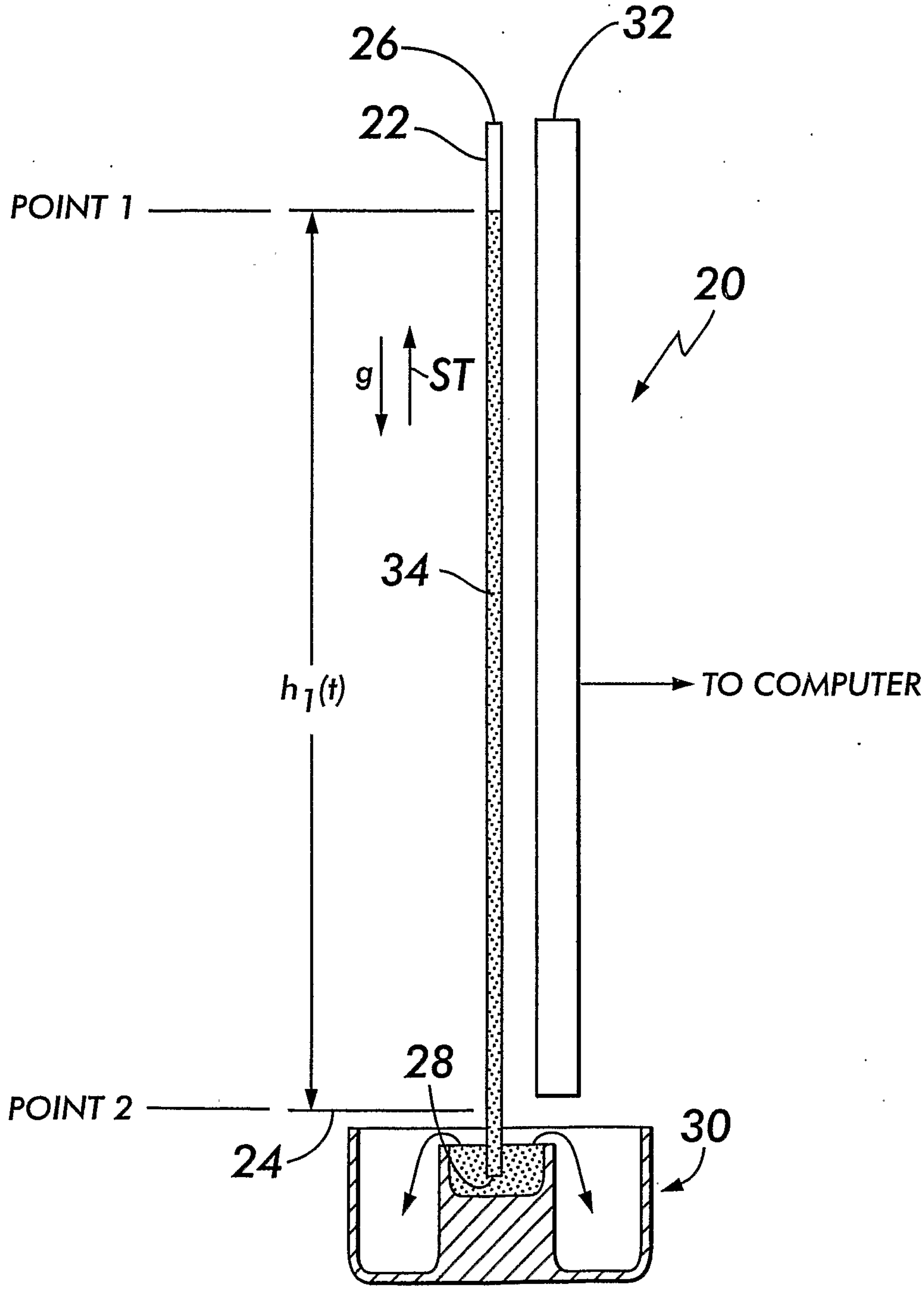
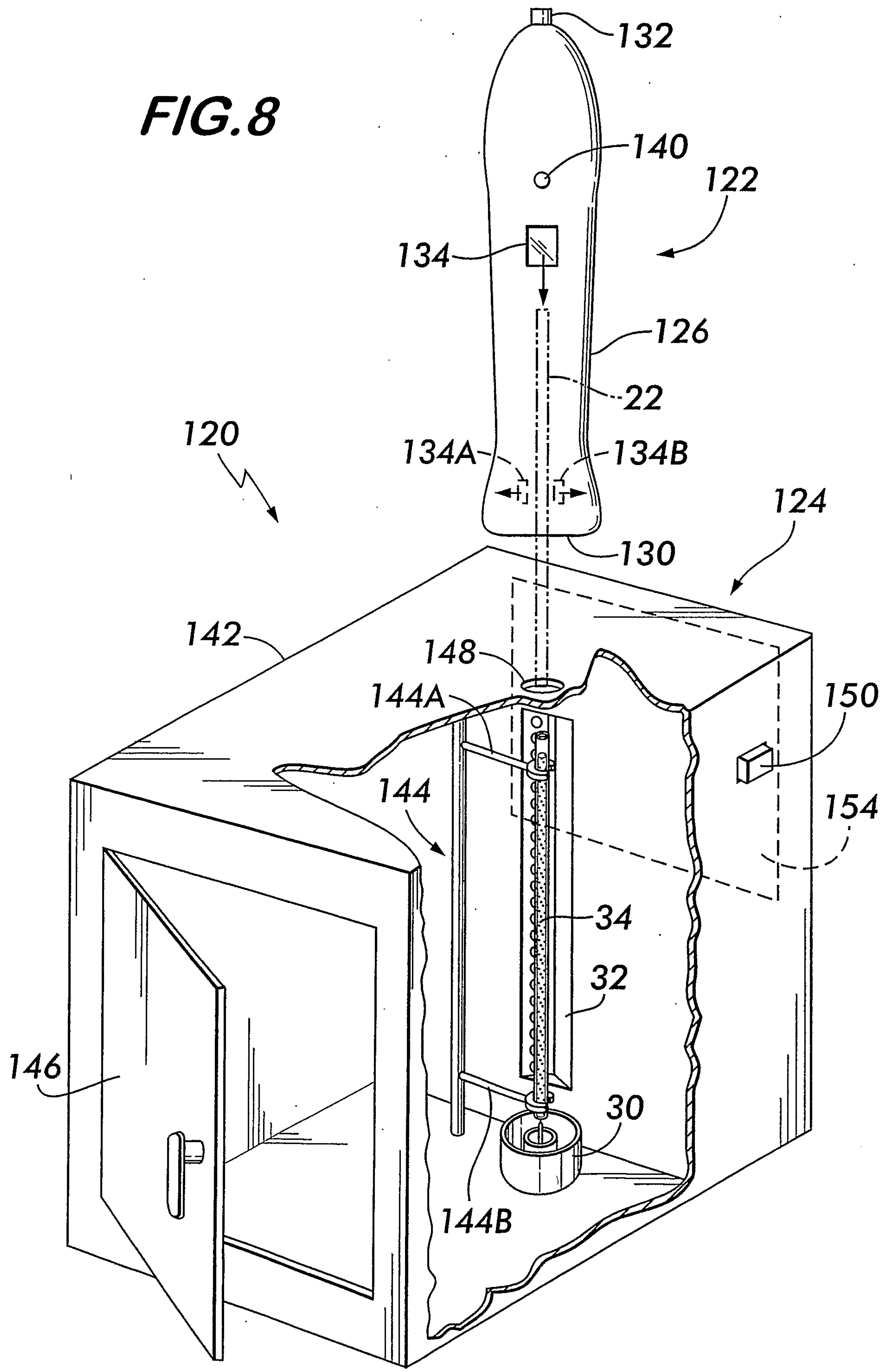


FIG.8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144B

FIG.9

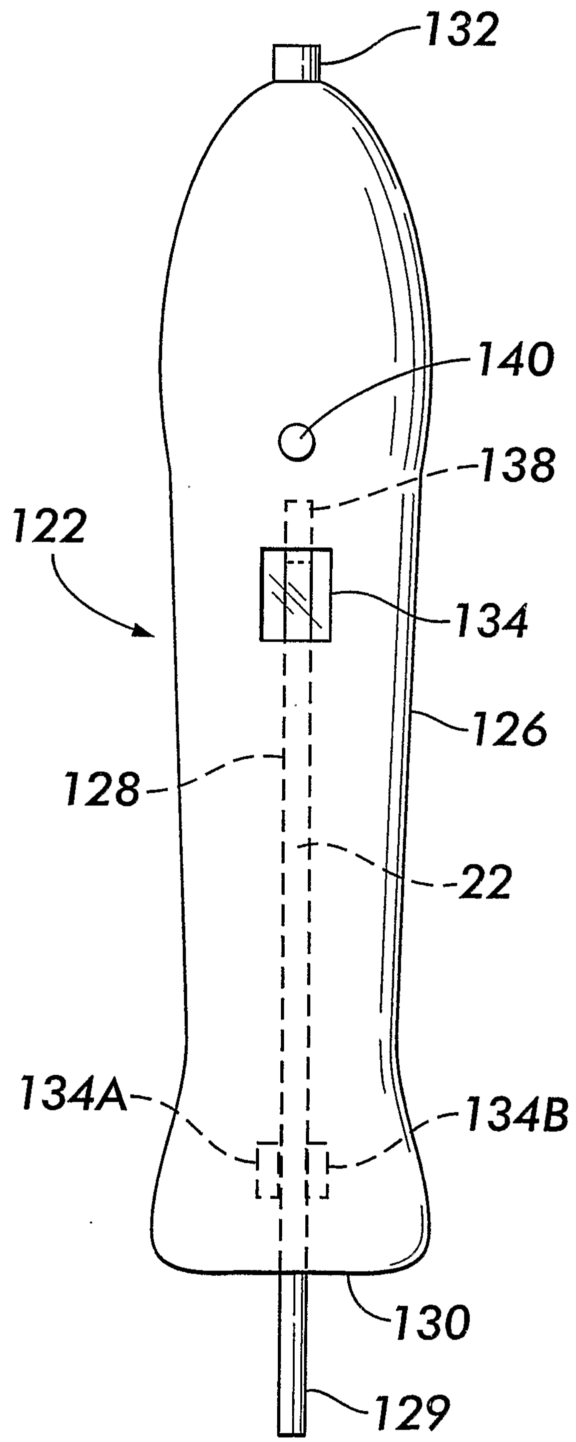
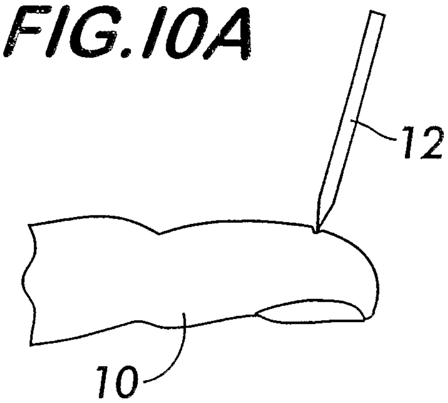


FIG.10A



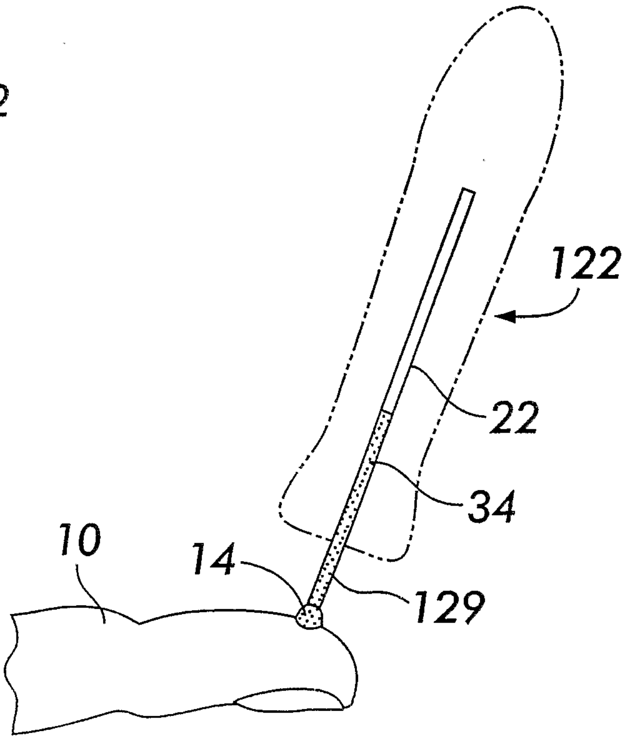


FIG.10B

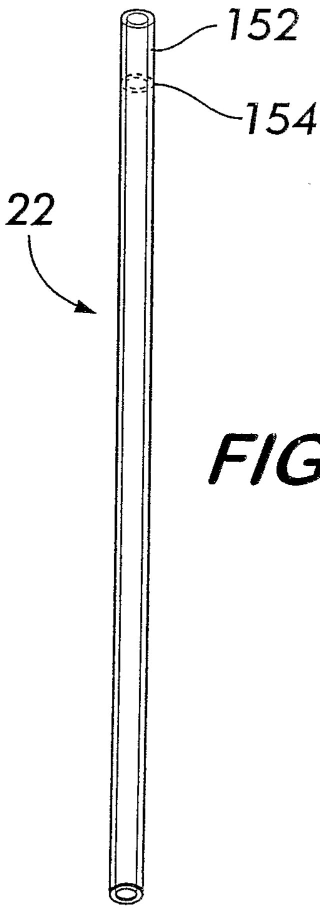


FIG.11