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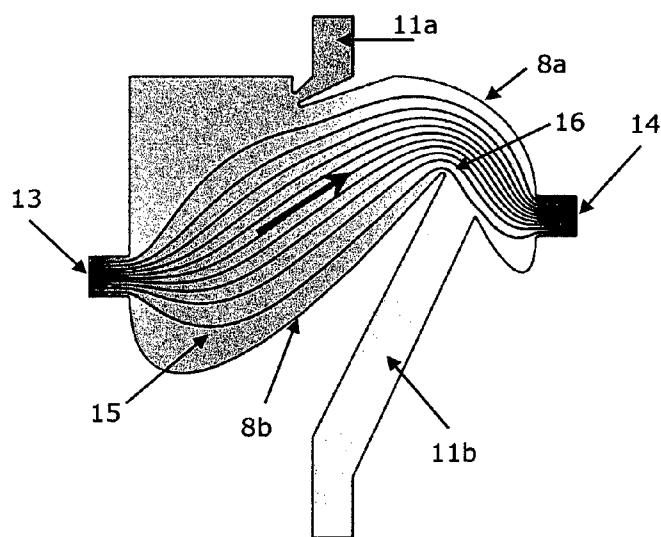


Fig. 2

(57) Abstract: The present invention relates to a fluid device comprising a capillary device and a non-linear response device. The capillary device typically having a flow channel comprising a contraction and the geometry of the flow channel of the capillary device being adapted to provide a flow response by the linear effects in the fluid, with the least response from the non-linear effects in the fluid. The non-linear response device typically having a flow channel connected to the flow channel of the capillary device, and the geometry of the flow channel of the non-linear response device being adapted to provide a flow response primarily driven by the non-linear effects in the fluid.

A FLOW MEASUREMENT DEVICE AND METHOD

FIELD OF THE INVENTION

The present invention relates to a method of determining a property of a fluid, the
5 method utilising a fluid device comprising a capillary device and a non-linear
response device, wherein the capillary device is configured to provide, preferably,
a developed flow and the non-linear response device being configured to provide,
preferably, a non-developed flow. The method comprising feeding a non-
Newtonian fluid at different volume flows through the fluid device and recording
10 simultaneously the first and the second flow response (e.g. ΔP_Q , ΔP_C); the infeed
of fluid includes at least one period with increase of volume flow and/or at least
one period with decrease of volume flow.

15 The invention also relates to method of utilising devices according to the present
invention.

BACKGROUND OF THE INVENTION

Reference is made to WO 2009/061943 A9, Publication 14 May 2009 Entitled:
20 Micro Rheometer for measuring flow viscosity and elasticity for micro sample
volumes, and Helen L. Bandey et al. (Helen et al), Blood rheological
characterization using the thickness-shear mode resonator, Biosensors and
Bioelectronics 19, 1657 (2004).

25 *Choice of materials*

The device described in WO 2009/061943 A9 involves electrodes of Au (gold), and
it is therefore very sensitive to high temperatures. The devices disclosed in WO
2009/061943 A9 are explicitly described as being fabricated using clean-room
techniques, which involve less corrosion and heat-resistive metals.

30

Mobility and robustness against varying working conditions

Even though the fluid characterization in both WO 2009/061943 A9 and Helen et
al involves small microchannel, these two devices, as described in WO
2009/061943 A9 and Helen et al., cannot be realized in a mobile handheld device
35 of the same dimensions and weight as for the invention (described above),

because they both depend on a pump producing a fixed precise volume-flowrate. With present prior art technology, such pumps must be syringe-pumps, which exceeds more than 10 fold the volume and weight of the invention, as described above.

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Further drawback

The devices and methods disclosed in WO 2009/061943 A9 and Helen et al also suffer the drawback of being less efficient, difficult to produce and sensitive to external influences.

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WO 2012/175093 suggest to use a capillary device and a downstream non-linear response device in order to quantify e.g. a sugar concentration in a non-Newtonian fluid by use of a stationary measuring technique in which pressure determinations are used to estimate the desired quantity. According to

15 WO2012/175093 a mapping between volume flow and a characteristic fluid property (e.g. sugar concentration) at different volume flows is provided. The method disclosed in WO2012/175093 resides inter alia in that for a pre-determined mapping between volume flow and response for a fluid with known properties, a fluid with unknown properties may be characterised by this mapping
20 by use of the device utilised to provide the mapping for the fluid with known properties.

Thus, although the documents considered above present leaps forward towards
25 characterising non-Newtonian fluid, it has been found in connection with the present invention that an improved method for characterising non-Newtonian fluids may be beneficial and in particular beneficial for characterising and/or quantifying thixotropic nature of non-Newtonian fluids.

30 OBJECT OF THE INVENTION

Hence, improved devices and methods for determining one or more properties of fluids would be advantageous, and in particular a more efficient and/or reliable device and method would be advantageous.

It is a further object of the present invention to provide an alternative to the prior art.

In particular, it may be seen as an object of the present invention to provide a
5 device and a method that solves the above mentioned problems of the prior art.

SUMMARY OF THE INVENTION

Thus, the above described object and several other objects are intended to be obtained in a first aspect of the invention by a method of determining the dynamic
10 flow response for a non-Newtonian fluid. The non-Newtonian fluids considered herein are in particular visco-elastic and/or thixotropic fluids, i.e. typically non-Newtonian fluids that show a time dependent change in viscosity. The method preferably comprises providing a fluid device comprising a capillary flow device and a non-linear response device immediately downstream or upstream of the
15 capillary flow device.

Although the present invention as disclosed herein is disclosed with focus on embodiments wherein the capillary flow device is upstream of the non-linear response device, it has been found that if, e.g. the non-linear response is to be
20 obtained with a minor influence prior to obtaining the non-linear response, it is advantageously to place the non-linear response device upstream of the capillary flow device.

The capillary flow device comprises a longitudinal extending channel having two
25 longitudinal distanced measuring positions at which a flow parameter is measured so as to determine a first flow response (e.g. ΔP_Q) over at least a part of the longitudinal extending channel, the channel being preferably configured to provide a developed flow in a region in between the two measuring positions.

30 Preferably, the channel of the capillary device comprises a straight section in between the two longitudinal distanced measuring positions, and the straight section having a longitudinal extension being larger than the hydraulic diameter of the cross section of the straight section.

The non-linear response device comprises a curved channel configured to provide, preferably, a non-developed flow and having two measuring positions at which a flow parameter is measured so as to determine a second flow response (e.g. ΔP_c) over at least a part of the non-linear response device.

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Preferably, the non-linear response device comprises a transition channel reaching from an inlet to an outlet, and the transition channel comprises two walls on opposite sides of the channel. At least one of these walls being a curved wall and at least one of the at least one curved walls proceed to define a bump. As disclosed
10 below, a bump is preferably considered to be a wall geometry which first tends to increase the boundary layer momentum thickness and subsequently (such as downstream) tends to decrease the boundary layer momentum thickness.

The method further comprising feeding a non-Newtonian fluid at different volume
15 flows through the fluid device and recording simultaneously, preferably the timewise progression of, the first and the second flow response; the infeed of fluid includes at least one period with increase of volume flow and/or at least one period with decrease of volume flow, preferably during which the time wise progression of the first and the second responses are recorded.

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By recording the time wise progression of the first and second responses a measure or at least an indication of the time scale at which e.g. a relaxation or transient takes place can be determined by a method according to the present invention. As will become clear at least from the description considered herein, it
25 may be highly relevant to have at least an indication on such a time scale for instance when initiating a pumping process or valuating a fluid is within a given specification for e.g. lubrication purposes.

Preferred but non limiting values for the increase respectively decrease of volume
30 flow are in the range of $10^{-6} \text{m}^3/\text{s}^2$, preferably in the range of $10^{-1} \text{m}^3/\text{s}^2$, such as in the range of $10^{-2} \text{m}^3/\text{s}^2$, preferably in the range of $10^{-3} \text{m}^3/\text{s}^2$, such as in the range of $10^{-3} \text{m}^3/\text{s}^2$, preferably in the range of $10^{-4} \text{m}^3/\text{s}^2$, and even in the range of $10^{-5} \text{m}^3/\text{s}^2$.

As presented herein, the straight section of the capillary flow device may preferably have a longitudinal extension being larger than the hydraulic diameter of the cross section of the straight section. By hydraulic diameter is preferably meant a diameter calculated as:

5
$$D = 4 * A/P$$

where A is the cross sectional area and P is the wetted perimeter. It is noted that in case of an open channel configuration or the fluid not filling the full cross sectional area of the channel, the parameters considered are those defined by the fluid as conventionally used.

10

As also presented herein, the transition channel comprising two curved walls on opposite sides of the channel. The term "curved wall" should preferably be understood broadly to include a wall which proceed in a longitudinal direction (direction from inlet to outlet) with a curvature, piecewise straight sections or
15 combinations thereof. Preferably, the walls are curved in the sense of providing a convex and/or concave geometry.

It has been found in connection with the present invention, that although a measure may be obtained for a property of the non-Newtonian fluid, such
20 property is often obtained in a quasi-stationary manner (obtained for a constant flow condition being different from rest), in the sense that the dynamic behaviour of the fluid is not taken into account. However, for non-Newtonian fluids, hysteresis as an example often occur in the sense that depending of the route for reaching e.g. a particular volume flow, e.g. the pressure difference experienced in
25 the fluid depends on whether the particular volume flow is reached in an increasing or decreasing volume flow manner. In addition, the actual level reached in this manner may shift during use of the fluid e.g. due to decomposition of the fluid. As discussed above, many characterisations of non-Newtonian fluid are determined in a stationary or quasistationary manner (in the sense that the
30 condition at which the characterisation is performed is kept constant) thereby neglecting the dynamic effects of the fluid. This may have the consequence that depending of the working condition of e.g. a machinery utilising the fluid, the fluid may or may not be acceptable for the particular use.

The present invention has solved this problem by use of the fluid device, comprising a capillary device and a non-linear response device, into which a fluid is fed at varying volume flows, such as at increasing and/or decreasing volume flow. As the flow in the capillary device compared to the flow in the non-linear
 5 response device substantially provides a flow without triggering the non-Newtonian effects (non-linear effects) it is possible to obtain measures for the shear rate and shear stress substantially independent of each other for the same fluid which has the advantageous that the fluid may be characterised e.g. through a hysteresis.

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As an example, considering e.g. a lubricating oil for an engine, the non-Newtonian properties during use of the oil may be of vital importance for the lubricating performance of the oil (and thereby also the lifetime of the engine). Often such oil is exposed to varying load and flow rate through the engine and if the non-
 15 Newtonian properties of the fluid is determined at e.g. a constant flow rate (a single load), the properties determined may not be illustrative for the performance of the oil. The present invention remedies this issue in certain embodiments by using a typically standardised way of providing a measure (e.g. a hysteresis curve or a time scale) for the non-Newtonian properties of the fluid in a
 20 dynamic flow regime.

As presented herein, the present invention provides a parameter substantially independent of the non-Newtonian nature (the response from the capillary device) and a crux of the present invention may therefore be seen as shear rate and
 25 shear stress for a fluid being determined in a substantially decoupled manner, by:

$$\gamma \approx \Delta P_Q \text{ and } \tau \approx \Delta P_c$$

This difference is preferably referenced herein by "capillary" and "transition"
 30 respectively. It is noted, that although the pressure differences are mentioned, other parameters may be used.

In preferred embodiments of a method according to the present invention, the feeding of non-Newtonian fluid at different volume flows may preferably include at
 35 least one period with constant volume flow. In addition or in combination

therefore, a method according to the invention may comprise feeding the fluid through the device in a step wise manner, wherein the fluid is alternatingly fed to through the fluid device at at least two different volume flows. Preferably, the stepwise feeding of fluid comprises keeping the flow between two consecutive
5 alterations constant, preferably until the flow has relaxed.

In preferred embodiments of a method according to the present invention, the method may comprise feeding the fluid through the device in manner where the volume flow is alternatingly ramped-up and ramped-down between two extremes
10 $Q_{\max}$ and $Q_{\min.}$, Preferably the ramping-up and ramping-down are carried out with a constant increment/decrement of the volume flow with respect to time.

In preferred embodiments of a method according to the present invention, the recorded corresponding flow responses may be compared with reference flow
15 responses. Preferably, the comparison with the reference flow responses may further comprise determining deviations between the reference flow responses and the recorded flow responses and determining if the deviation(s) is(are) within selected boundaries.

20 In preferred embodiments of a method according to the present invention, the measuring positions for the capillary device and the non-linear response device are pressure measuring positions and the flow responses determined are pressure differences in the capillary device and in the non-linear response device.

25 In preferred embodiments of a method according to the present invention, the measuring positions of the capillary device comprises two sidelets each comprising a pressure sensor arranged at a distal end of the sidelet.

In preferred embodiments of a method according to the present invention, the
30 non-linear response device may comprise a flow channel directly connected to the flow channel of the capillary device. Preferably, the flow channel of the non-linear response device comprising sidelets each comprising a pressure sensor arranged at distal end of the sidelet, the sidelets being arranged to determine a pressure difference over at least a part of the flow channel.

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In preferred embodiments of a method according to the present invention, the curved channel of the non-linear response device comprising

- two opposite curved wall sections extending asymmetrically to each other at least through out a part of the flow channel, wherein one of the opposing curved wall sections defines a bump in the flow channel, so as to provide a fluid deflection into a flow pattern with curved stream lines from an inlet and to an outlet of the flow channel with increased shear in flow regions at the bump.

10 In preferred embodiments of a method according to the present invention, the curved wall section opposing the curved wall section defining a bump extends in a manner increasing or decreasing the cross sectional area of the flow channel downstream of the bump.

15 In preferred embodiments of a method according to the present invention, the flow channel of the capillary flow device comprising a straight channel in a region between the two measuring points.

In preferred embodiments of a method according to the present invention, the flow channel of the capillary device comprising a narrowing section upstream and an expanding section downstream of a contraction, preferably being a straight channel section, with the sidelets being arranged upstream and downstream of the contraction.

25 In preferred embodiments of a method according to the present invention, the geometrical dimension of the flow channel of the capillary device, the flow channel of the non-linear response device and of the sidelets may be in the micrometer range size.

30 In preferred embodiments of a method according to the present invention, the flow channel of the non-linear response device may comprise a constriction at an inlet of the flow channel. In addition, the flow channel downstream of the constriction may have a diffuser geometry with diverging sides, and, preferably, the diffuser geometry is terminated by a wall having an outlet. Preferably, a sidelet is arranged at the constriction and a sidelet is arranged at the wall.

In preferred embodiments of a method according to the present invention, the non-Newtonian fluid may be selected from the group consisting of visco-elastic fluids.

- 5 In preferred embodiments of a method according to the present invention, the fluid may be selected from the group consisting of sugar dissolved in water, soft-drink concentrate, paint, enamel, engine oil, engine fuel.

Preferably, the capillary device has a flow channel comprising a contraction.

- 10 Preferably, the capillary device is configured with a sidelet upstream and sidelet downstream of the contraction, the sidelets each comprises a pressure sensor arranged to determine the pressure difference over the contraction, the geometry of the flow channel of the capillary device being adapted to provide a flow response by the linear effects in the fluid, with the least response from the non-
15 linear effects in the fluid. Alternatively to a sidelet, a pressure sensor – or a sensor in general – may be arranged (preferably seamless) in the wall of the channel upstream and/or downstream of the contraction.

Preferably, the non-linear response device has a flow channel connected,

- 20 preferably directly, to the flow channel of the capillary device, the flow channel of the non-linear response device comprising sidelets arranged to determine a pressure difference over at least a part of the flow channel, wherein the geometry of the flow channel of the non-linear response device being adapted to provide a flow response primarily driven by the non-linear effects in the fluid.

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- Preferably, a fluid device according to the present invention may comprise a capillary device and a non-linear response device wherein the capillary device comprising a flow channel with two sidelets each comprising a pressure sensor arranged at a distal end of the sidelet, the sidelets being arranged in the capillary
30 device to determine the pressure difference over at least a part of flow channel.

- The non-linear response device may preferably comprise a flow channel directly connected to the flow channel of the capillary device, the flow channel of the non-linear response device being a curved channel and comprising sidelets each
35 comprising a pressure sensor arranged at distal end of the sidelet, the sidelets

being arranged to determine a pressure difference over at least a part of the flow channel, the curved channel comprising two opposite curved wall sections extending asymmetrically to each other at least through out a part of the flow channel, wherein one of the opposing curved wall sections defines a bump in the flow channel, and an opening of one of the sidelets is arranged immediately downstream of maximum height of the bump.

Preferably, the geometry of the flow channel of the capillary device being adapted to provide a flow response by the linear effects in a fluid, with the least response from the non-linear effects in the fluid.

Preferably, two opposite curved wall sections of the non-linear response device extends asymmetrically to each other at least through out a part of the flow channel so as to provide a fluid deflection into a flow pattern with curved stream lines from an inlet and to an outlet of the flow channel with increased shear in flow regions at the bump.

The physical dimensions of the invention can be reduced dramatically, compared to common cup-rheometers, without compromising the functionality. This is partly because the invention does not involve any moving parts, except of the fluid, and also because the physical phenomena, utilized in the functionality of the invention, does not require large volumes of the fluid. This, combined with the fact that the energy consumption required for operating the invention is small enough to be supplied by a small battery, makes it possible for one realization of the invention to be a handheld device.

Preferably, the curved wall section opposing the curved wall section defining a bump extends in a manner increasing or decreasing the cross sectional area of the flow channel downstream of the bump.

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In preferred embodiments of the fluid device according to the invention, the flow channel of the capillary device is a straight channel.

Preferably, the curved wall section defining a bump extends from the inlet of the non-linear response device and to the top of the bump in a convex manner and in

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a convex manner from the top of the bump and to the outlet of the non-linear response device, and the opposing wall section extend from the inlet and to the outlet of the non-linear response device in a concave manner.

- 5 Furthermore, the sidelets of the non-linear response device are preferably arranged on opposite sides of the flow channel.

In many preferred embodiments of the invention, the capillary device is adapted to produce a symmetric flow inside the flow channel.

10

In some preferred embodiments, the flow channels and the sidelets of the fluid device are square-shaped.

- According to many preferred embodiments of the invention, the flow channels and sidelets of the fluid device are provided in a single block of material, preferably by cutting, milling, moulding, or electric discharge machining. Furthermore, the flow channels and sidelets of the fluid device are preferably defined by wall elements made of plastic or metal.

- 15 In certain preferred embodiments of the invention, the flow channel of the capillary device comprising a narrowing section upstream and an expanding section downstream of a contraction preferably being a straight section, preferably with the sidelets being arranged upstream and downstream of the contraction.

25

Preferably, the geometrical dimensions of the flow channel of the capillary device, the flow channel of the non-linear response device and of the sidelets is in the micrometer or millimeter range size.

- 30 In many preferred embodiments of the invention, the flow channel of the non-linear response device comprising a constriction at an inlet of the flow channel, and wherein the flow channel downstream of the constriction has a diffuser geometry with diverging sides, the diffuser geometry is terminated by a wall having an outlet, a sidelet is arranged at the constriction and a sidelet is arranged
35 at the wall.

In further preferred embodiments, the flow channel of the non-linear response device comprises a single transition channel reaching from an inlet to an outlet, and one of the sidelets is connected to the part of transition channel in vicinity of the inlet, and the other of the sidelets is connected to the transition channel in vicinity of outlet, but not in direct connection with the outlet. A substantial geometrical feature, preferably being the parts defining the flow, of the transition channel may preferably consists of two curved walls on opposite sides of the channel, which acts to deflect the fluid flow into a curved path.

Preferred embodiments of the invention may further comprise a pump for pumping fluid through the capillary device and the non-linear response device. Preferably, the pump is a manually actuated pump, such as a piston pump. Furthermore, the fluid device and the pump may advantageously be formed as a handheld device in the form of a pipette, such as a micro-pipette.

In preferred embodiments of the invention, the fluid device is integrated in a lab equipment or a production facility.

A particular embodiment, a mobile handheld device, will be small enough to fit within a common micro-pipette, complete with batteries and a small display for showing quantitatively the results from the fluid characterization measurements. There will be no time-delay in processing the measurements into these quantitative results.

For the handheld device the combined dimensions of the following parts: the invention, measurement-processing electronics, battery, and display, is estimated to fit within: 3 x 1,5 x 1,5 cm, with an estimated weight below 40 gram.

The non-Newtonian fluids considered herein are preferably selected from the group consisting of visco-elastic fluids. Preferably, the fluid is sugar dissolved in water and the property being determined is the sugar concentration, the fluid is paints and the property being determined is the rate of shear-thinning, the fluid is concentrates of soft-drinks and the property being determined is the rate of shear-thinning, the fluid is enamel and the property being determined is the rate of shear-thinning, the fluid is engine oil and the property being determined is the

degradation of the oil, or the fluid is engine fuel and the property being determined is the type of engine fuel.

In the present context, a number of terms are used in an ordinary manner.

5 However, for the sake of completeness some of the terms are explained below.

Dynamic flow response is used to mean the response (e.g. pressure difference) obtained by varying the flow through a fluid device as presented herein. It is noted that within the scope of *dynamic flow response* is not only the immediate
10 response observed or recorded when the flow through the device is increased/decreased ($dQ/dt \neq 0$) but also the response observed when the flow is relaxed and $dQ/dt = 0$ after a time period with varying volume flow.

Pressure difference over a channel is preferably used to mean a pressure change
15 being positive or negative in the streamwise direction of the channel

Directly connected is preferably use to mean that all the fluid flowing through the capillary device flows through the non-linear response device, or vice versa.

20 *Immediately downstream* as used in "a non-linear response device immediately downstream or upstream of the capillary device" is preferably used to mean that the fluid flows from outlet of one device to inlet of the downstream device without delay so that the volume flow in the two devices are equal at same time instant considered. Within the scope of this use is considered the situation where the two
25 devices are connected to each other with a channel (as disclosed in e.g. fig. 1)

Immediately downstream of the maximum height of the bump is preferably used to mean that the upstream edge of the opening of the sidelet being arranged in a position downstream of the maximum height of the bump being less than 5%
30 such as less than 1% of the distance measured by a straight line extending from the inlet and to the outlet of the non-linear response device.

A bump is preferably used to mean a wall geometry which first tends to increase the boundary layer momentum thickness and subsequently tends to decrease the
35 boundary layer momentum thickness. The maximum height of the bump is

preferably used to mean the point (in two dimension) or the line (in three dimension) where the increase in boundary layer momentum thickness changes into a decrease in boundary layer momentum thickness. In many preferred embodiments the maximum height coincides with a geometrical maximum height
5 where the horizontal is direction is defined as the flow direction of the fluid into the device. A bump may be embodied as a corner in a flow channel around which the flow turns.

A constriction is preferably used to mean that the cross sectional area of a flow
10 channel is locally reduced. A constriction is typically provided by a bump or narrowing cross section in the flow channel. *Contraction* is preferably used interchangeably with *constriction*.

Straight channel means preferably a channel extending symmetrically along a
15 straight line; the straight channel may accordingly comprise variations in cross sectional areas.

Developed flow as used herein is preferably used to characterise a flow region in which the derivatives of the velocities in streamwise direction are zero.
20

Non-developed flow as used herein is preferably used to characterise a flow region in which the derivatives of the velocities in the streamwise direction are different from zero.

25 *Flow response* is used to designate a measurable quantity in the flow. Typically and preferably the flow response type is a measured pressure difference over a distance of either the capillary flow device or the non-linear response device. However, other quantities may be measured such as a mean velocity, a friction force (typically determined on a surface) or other fluid mechanic/dynamic
30 variables. In case, the response type is pressure, ordinary pressure sensors may be applied. In case the response type is velocity (which correlates to momentum, which also may be used as response), a hot-wire may be applied. In case the response type is friction, strain-gauge may be used. It is further noted that the response obtained by the capillary device and the non-linear response device may
35 be different types of responses. In addition, a flow response may be determined

by use of Laser Doppler Anemometry or Light diffraction methods. A flow response may preferably be seen as a measure for/of the instantaneous flow of the fluid flow through a channel as disclosed herein, e.g. a measure for/or the flow's response to flowing through the channel in question.

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Recording simultaneous the two flow responses is used to mean that the two flow responses should be obtained at the same time (i.e. the same volume flow). It is noted that the "degree of simultaneous" may be dictated by the equipment used in the sense that some sensor may lack timewise behind the other. However,

10 simultaneous preferably means that the difference in time between the two recordings of flow responses is smaller than 1 sec, such as smaller than 1/10 sec. and even smaller than 1/100 sec.

Herein two realizations of the non-linear response device are introduced with the
15 following names: High shear viscosity device, and Low shear viscosity device.

High shear viscosity device, in short HSV device, means preferably a device in which a flow is established resulting in at least locally shear thinning. *Low shear viscosity device*, in short LSV device, means preferably a device in which a flow is
20 established in which inertia effects influences the flow. The HSV and LSV devices are members of the generic class of devices named Shear viscosity devices which preferably means a device designed to operate either as a HSV or a LSV device.

The 2 dimensional flow presented is a representation of a real physical 3D flow
25 The following embodiments of the invention are presented by flows restricted to two dimensions (2D flow), and this generally corresponds to full three dimensional fluid flows and device structures, where the variation along the third dimension (perpendicular to the presented two dimensions) is insignificant related to the variations along the two presented dimensions. In practice, this can be
30 accomplished by having the height (along the third dimension) of the fluid confinement being at least twice the maximal channel width (along the two presented dimensions).

Sensor and *transducer* are used interchangeably herein to reference a device determining a measure for e.g. pressure and signaling the measure e.g. by an electrical signal.

- 5 It is noted that although the present invention as disclosed herein may appear to reside in a 2-dimensional flow regime, the invention is not limited to such 2-dimensional flow regimes. In practice, the invention may operate equally well in a full 3-dimensional flow regime and such regimes are also considered within the scope of the invention.

10

The devices realizing the invention are preferably based on extruding a planar design into the height dimension, and thereby having a fixed height all over the fluid region. This type of device realization is used since it simplifies the numerical process in obtaining the presented devices, but the invention should not be

- 15 limited to this planar-based approach, but rather capture any three dimensional channel structure.

- Capillary device* which preferably is used as an identifying name for a flow device means preferably a device used to determine a linear flow response (or a flow
20 response by the linear effects). It is noted, that the linear flow response often is correlated to the volume flow through capillary flow device, so that the response from the capillary device, e.g. the pressure difference, may be transformed (by a calibration e.g.) into the volume flow through either the HSV device or the LSV device. As indicated by the wording capillary, the device comprises restricted flow
25 passage(s) but is not restricted to a device producing capillary flow or effects. In general, a capillary is a flow device in which no shear thinning or thickening occur while shear thinning or thickening occur in the non-linear response device.

- Non-linear response device* is preferably used as an identifying name for a flow
30 device in which shear thinning or shear thickening occur at the same flow situation which does not create shear thinning or thickening in the capillary device.

- Sidelet* means preferably channel branch extending from the flow channel of the
35 flow device and to a pressure sensor constituting a closed end wall of the sidelet.

The length of the sidelet is selected so as to be sufficient to assure that substantially no shear is generated by the flow at the closed end wall of the sidelets. In many practical preferred embodiments of the invention, the ratio between the length, L , and the width, W , of the sidelet is typical $W/L < 0.5$ such as
 5 $W/L < 0.25$ preferably $W/L < 0.125$ where W is defined as the square root of [cross sectional area of the opening of the sidelet into the flow channel multiplied by 4 and divided by π] and the length is defined as the volume of the sidelet divided by the cross sectional area of the opening of the sidelet into the flow channel.

10 As presented herein, the non-linear response device is in accordance with many preferred embodiments shaped with curved wall sections. The curvature of these wall sections are selected so that the effects of curved wall section is to accelerate the fluid to increase the shear in the fluid typically up to a geometrical maximum typically being the maximum height of a bump and subsequently an additional
 15 acceleration of fluid. It is noted that "accelerate" is used in the general meaning as a change of local velocity, including situations such as: acceleration, deceleration, and transverse acceleration, where the latter results in a curved flow path. The curvature of the wall sections are preferably designed so that the dot-product between the gradient of the pressure and the velocity inside the channel
 20 is close to zero except at a region close to the geometrical maximum.

Shear is used as an abbreviation for shear-rate which in a two dimensional form can be written as (having velocity components u, v in a coordinate system with axis x, y):

25

$$\dot{\gamma} = \sqrt{2 \left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2}$$

It is noted, again, that the invention is not limited to 2 dimensional flow regimes.

30 *Rheometry* generically refers to the experimental techniques used to determine the rheological properties of materials, that is the quantitative and qualitative relationships between deformations and stresses and their derivatives.

A flow response by the linear effects means preferably that there exists a significant linear relation between variations in the action (which in this particular case is variations of the flow-rate Q) and the response being measured (which in this particular case is variations of the pressure difference, measured by the
5 pressure sensors at two sidelets).

A flow response by the non-linear effects means preferably that there exists a significant non-linear relation between variations in the action (which in a particular case is variations of the flow-rate Q) and the response being measured
10 (which in this particular case is variations of the pressure difference, measured by the pressure sensors at two sidelets).

A linear relation $f(x)$ is described by a first-order polynomial $f(x) = A + B \cdot x$, where A , B are real numbers.
15

A non-linear relation $g(x)$ is a relation which cannot significantly be described by a linear relation. In most cases, a non-linear relation further involves second-order or higher-order polynomials: $g(x) = A + B \cdot x + C \cdot x^2 + D \cdot x^3 + \dots$, where A , B , C , D , ... are real numbers.
20

Measuring position is preferably used to reference the position of e.g. a sidelet in the wall of a channel, or where sensor used to measure a response is arranged in the wall of a channel. Preferably, one measuring position of the non-linear response device is positioned at the wall defining a bump and downstream of the
25 bump and one measuring position is arranged upstream of the bump, preferably at the opposite wall.

Further details of the invention are presented in the accompanying claims and in the following detailed description of the invention.
30

The invention relates in a second aspect to a device for obtaining responses, such as hysteresis responses, for a non-Newtonian fluid, the device comprising a fluid device having a capillary flow device and a non-linear response device immediately downstream or upstream of the capillary flow device, wherein

- the capillary flow device comprising a longitudinal extending channel having two longitudinal distanced measuring positions (5a, 5b) at which a flow parameter is measured so as to determine a first flow response (ΔP_Q) over at least a part of the longitudinal extending channel, the channel being configured to provide a developed flow in a region in between the two measuring positions (5a, 5b);
- the non-linear response device comprising a curved channel configured to provide a non-developed flow and having two measuring positions (11a, 11b) at which a flow parameter is measured so as to determine a second flow response (ΔP_C) over at least a part of the non-linear response device.

The device preferably further comprising means, such as a metering pump, a syringe, adapted to feed a non-Newtonian fluid at different volume flows through the fluid device; the infeed of fluid includes at least one period with increase of volume flow and/or at least one period with decrease of volume flow.

Alternatively, the device may receive the fluid at different volume flows, from e.g. a production line or machinery, and in such cases, the means adapted to feed the fluid may be omitted from the device.

The device typically and preferably comprises means adapted to record simultaneously the first and the second flow response (ΔP_Q , ΔP_C). Such means are often sensors, such as pressure sensors, connected to an electronic device, such as a computer for receiving and storing the signal produced by the sensors. The first, and second aspects of the present invention may each be combined with any of the other aspects. These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

BRIEF DESCRIPTION OF THE FIGURES

The various aspects and embodiments according to the invention will now be described in more details with regard to the accompanying figures. The figures show ways of implementing the present invention and are not to be construed as being limiting to other possible embodiments falling within the scope of the invention.

Fig. 1 is a schematic illustration of a preferred embodiment of a fluid device according to the present invention; the embodiment is an example of a non-linear response device with an upstream arranged capillary device.

5 Fig. 2 is a schematic illustration of an embodiment of an HSV device according to the present invention, where the fluid flows through the device from left to right, both indicated by the arrow and by the black streamlines. The pressure is showed throughout the device in grey shading, ranging from high pressure in darkest shade to low pressure in lightest shade. One type of fluid property is characterized
10 by measuring the pressure difference between the two sidelets, which are the two (closed) channel branches at the top and bottom of the device. The device of fig. 2 is typically used with a capillary device of fig. 1 or 9. For the results presented herein with device of fig. 2, the device of fig. 2 is combined with the capillary device of fig. 1 to form a fluid device.

15

Fig. 3 is a graph showing

- top: pressure difference over the capillary device (Labelled "pressure drop over Q-device"),
- middle: pressure difference over non-linear response device (Labelled
20 "pressure drop over C-device")
- bottom: a hysteresis loop obtained by plotting pressure difference values for same volume flow against each other.

Fig. 4 is a graph showing the hysteresis curve being the result of cyclic
25 measurements for a fluid containing 0.6 % locust bean gum and by use of the device comprising the capillary flow device of fig. 1 and the non-linear response device of fig. 2,

Fig. 5 shows a further embodiment of a capillary device according to preferred
30 embodiments of the present invention,

Fig. 6 shows a further embodiment of an HSV device according to the present invention,

Fig. 7 shows a further embodiment of an HSV device according to the present invention, and

Fig. 8 shows a further embodiment of an HSV device according to the present
5 invention.

DETAILED DESCRIPTION OF THE INVENTION

As presented herein, the method of determining characteristics of a non-Newtonian fluid comprises use of a fluid device comprising a capillary device and a
10 non-linear response device. As presented above, two realizations of the non-linear response device are disclosed with the following names: High shear viscosity device, and Low shear viscosity device. In use, the capillary device may be the same for both the high shear viscosity device and the low shear viscosity device.

15 *On the Low shear viscosity device*

Reference is made to fig. 1 being a schematic drawing of a preferred embodiment of a fluid device used in connection with the to the present invention. In fig. 1 the flow measurement device 1 comprises a capillary device 2 and a non-linear response device 3. The capillary device 2 is a device designed inter alia to
20 measure the volume flow going through the downstream non-linear response device by determining the volume flow through the channel of the capillary device (due to fulfillment of the continuity, the volume flow going through the capillary device equals the flow going through the non-linear response device). This also implies that the pressure difference (ΔP_Q) over the capillary device and the volume
25 flow through capillary device are interchangeable parameters.

The capillary device 2 has an flow channel 4 having a narrowing section 4a – in the form of a funnel - upstream of a contraction 4b, being a straight section, and an expanding section 4c downstream of the straight section 4b. Two sidelets 5a
30 and 5b are connected to the narrowing respectively the expanding section 4a, 4c. The openings of the sidelets 5a, 5b into the flow channel 4 form measuring positions of the capillary device. The sidelets 5a and 5b are channels communicating the pressure in the fluid in the channel 4 to pressure transducers 6a and 6b respectively.

35

A further embodiment of a capillary device 2 is shown schematically in fig. 5. In this embodiment, the flow channel 4 has a uniform cross sectional area and comprising a number of bends 17 connecting straight sections of the channel 4. The flow channel 4 can be characterized as a meandering channel. Similarly to the capillary device of fig. 1, the capillary device of fig. 5 comprises sidelets 5a, 5b with pressure transducers 6a, 6b arranged at a distal end of a sidelet to determine the pressure difference over the channel 4. Again, the openings of the sidelets 5a, 5b into the flow channel 4 form measuring positions of the capillary device.

10

The non-linear response device 3 is located downstream of the capillary device 2 and receives the same amount of fluid as has passed through the capillary device 2. In the embodiment shown in fig. 1, the non-linear response device is designed as a low shear viscosity device and comprises a constriction 7 followed by a diffuser geometry with diverging sides. The constriction 7 formed by a bump (16) in the lower wall of the flow channel. The bump comprising a step with a flat surface facing normal to the incoming flow and a top surface sloping downwardly continuing into the diverging side of the channel. The constriction creates a jet of fluid which spreads out downstream in the diffuser. The diffuser geometry is terminated by a wall 9 having an outlet 10. A sidelet 11a is arranged at the constriction 7 immediately downstream of the maximum height of the bump (16) and a sidelet 11b is arranged at the wall opposite to the wall comprising to bump. Also in this device, the openings of the sidelets 11a, 11b into the flow channel form measuring position of the device. This arrangement of sidelets provided a pressure measurement on two opposite sides of the flow through the channel. The sidelets 11a and 11b communicate the pressure in the fluid to pressure transducers 12a and 12b to detect the pressure difference labeled ΔP_c in fig. 1. As shown in fig. 1, the channel, labelled transition channel, reaches from the inlet 13 to the outlet 10 and comprising two curved walls (8a, 8b, 9) on opposite of the channel, wherein the wall section 8b proceed to defined a bump 16. It is noted that the curved walls in this embodiment is at least partially defined by straight sections by the sections 8a and straight section of wall 9 above the outlet 10 and by the sections 8b and the section of wall 9 below the outlet.

Fig. 1 also includes a close-up view of the area around the bump 18 shown in the dotted circle to the right and below the main fig. 1.

The device 1 may preferably also comprise a pump to pump (or suck) fluid through device. It is further noted that the channels of the device are closed channels in the sense that they constitute tubes. Furthermore, the capillary device 2 and the non-linear response device 3 are connected without any further elements than the channel leading fluid from the outlet of the capillary device 2 to the inlet of the non-linear response device 3. Often the capillary device 2 and the non-linear response device are formed in a single block of material.

On the High shear viscosity device

Reference is made to fig. 2. The channel structure of the non-linear response device is characterized by having a single transition channel 15 reaching from the inlet 13 to the outlet 14. The transition channel is preferably at its inlet 13 or at its outlet 14 connected to a capillary device as disclosed herein. The upper sidelet 11a is connected to the part of transition channel 15 close to the inlet 13, and the lower sidelet 11b is connected to the transition channel closer to the outlet 14, but not in direct connection to the outlet 14. The main geometrical feature of the transition channel consists of two curved walls 8a, 8b on opposite sides of the channel 15, which acts to deflect the fluid flow into a curved path. The curved wall 8b is shaped so as to define a bump 16. Again, the openings of the sidelets 11a, 11b into the flow channel form measuring positions of the device.

As shown in fig. 2, the channel, labelled transition channel 15, reaches from the inlet 13 to the outlet 14 and comprising two curved walls on opposite of the channel, wherein the curved wall 8b proceeds to define the bump 16. It is noted that the curved walls in this embodiment are at least partially defined by straight sections in the upper left part of the fig. 2 which goes into the section of wall 8a having a curvature.

As illustrated in fig. 2, the curved wall section 8b defines a bump 16 extends from the inlet 13 of the non-linear response device and to the top of the bump in a convex manner and in a convex manner from the top of the bump 14 and to the outlet 14 of the non-linear response device. The opposing wall section 8a extends

from the inlet 13 and to the outlet 14 of the non-linear response device in a concave manner. The opening of one of the sidelets 11b is arranged immediately downstream of maximum height of the bump and the opening of the other sidelet 11a is arranged in a downstream region as depicted in fig. 2. A result of the two
5 opposite curved wall sections 8a, 8b extending asymmetrically to each other at least through out a part of the flow channel, wherein one of the opposing curved wall sections 8b defines a bump 16 in the flow channel, is a deflection of fluid into a flow pattern with curved stream lines from an inlet and to an outlet of the flow channel with increased shear in flow regions at the bump. In use, the device of
10 fig. 2 is typically used with a capillary device of fig. 1 or fig. 5.

Reference is made to fig. 6 which is a schematic illustration of a further embodiment of an HSV device according to the present invention, and in which the fluid flows through the device from left to right. The fluid flows into the device
15 through the inlet 13 and out of the device through outlet 14. As indicated in fig. 6 and by comparison with fig. 2, the device shown in fig. 6 does not comprise the sidelets 11a and 11b of fig. 2 although the remaining geometry of the device illustrated in fig. 2 is maintained in the device shown in fig. 6. Thus, the geometry of the HSV device in fig. 6 is as described in connection with fig. 2 except that the
20 sidelets 11a, 11b are no longer present and where each of the openings of the sidelets into the channel of the device are replaced by surface of a pressure sensor or – as disclosed below – a membrane.

Thus, instead of the sidelets 11a and 11b, pressure sensors 18, 19 are arranged
25 where the openings of the sidelets 11a and 11b are arranged in the embodiment illustrated in fig. 2. It is noted that although fig. 6 illustrates that the pressure sensors 18, 19 extend into the interior of the device, this illustration is only made to render the position of the pressure sensors 18, 19 visible in the figure. In a practical implementation, the surface of the pressure sensors 18, 19 are
30 preferably seamless integrated in the device so that sensor surfaces are arranged flush with the surface of the device surrounding the sensor. However, as indicated in fig. 6, for sensor 18, the surface of the sensor may form its own surface and be integrated in a manner providing corners in the wall surface of the HSV device.

The actual implementation of the pressure sensors 18, 19 may be carried out e.g. by letting the surface of the sensor form a part of the surface of the HSV device preferably in a seamless manner. Alternatively, the pressure sensors 18, 19 may be arranged in a cavity covered preferably in a seamless manner by a membrane
5 made from a material being suitable for communicating pressure to the cavity below the membrane and thereby to the pressure sensor arranged below the membrane. The void in between pressure sensor and the membrane may be filled with a substantial incompressible fluid to avoid faulty pressure readings arising from a compression of the fluid in the void.

10

The geometrical size of the pressure sensors may vary from the disclosure in fig. 6. Further the position of the pressure sensor in the device may also vary from the disclosure in fig. 6. Preferably, the geometrical size of the pressure sensor could be sufficient to provide a geometrical averaging of the pressure
15 determined in order to avoid average out pressure spikes due to e.g. local geometrical surface imperfections in the device. While it is preferred to arrange the pressure sensor 19 immediately downstream the bump 16 defined as a sharp corner in the device, the pressure sensor may be arranged in another position in the device, such as at a distant downstream from the bump 16. The pressure
20 sensor 18 may also be arranged at another position in the device although it is preferred to arrange the pressure sensor 18 in a position where the shear is substantially smaller than the shear at the position of the sensor 19. These contemplations are also valid for positions of the sidelets 11a and 11b as well.

25 Reference is made to fig. 7 illustrating a further embodiment of a HSV device according to the present invention. The device is similar to the device shown in fig. 2 except that the sidelet 11b has been made shorter (relatively to the device in fig. 2) and that the upper wall part 20 instead of proceeding as a 90° bend (as in the embodiment of fig. 2 and 6) proceeds in a smooth and curved manner. As
30 indicated in fig. 7, pressure sensor 18, 19 are arranged at a distal end of the sidelets 11a, 11b.

The HSV devices shown in fig. 6 and 7 are typically used as disclosed in connection with fig. 2 and a fluid property is characterized by measuring the
35 pressure difference between the two pressure sensor 18, 19 (in the embodiment

of fig. 2 the pressure sensor are not illustrated but are arranged at the distal ends of the sidelets 11a, 11b as shown e.g. in fig. 7). Thus, the device of fig. 6 and that of fig. 7 is typically used with a capillary device of fig. 1 or 5.

- 5 It noted that the various features of the embodiments of fig. 2, 6 and 7 are interchangeable so that for instance a HSV may have one sidelet e.g. 11a with a pressure sensor at the distal end, and a pressure sensor 19 seamlessly integrated (no sidelet 11b) or vice versa. Also the smooth curved upper wall of fig. 7 may be applied to the embodiment of fig. 6 and 2.

10

Reference is made to fig. 8 illustrating schematically an embodiment of an HSV device according to the present invention. As illustrated, the non-linear response device (HSV device) comprising a transition channel 15 reaching from the inlet 13 to the outlet 14. The transition channel comprising two walls 8a, 8b on opposite
15 sides of the channel 15, and one of said walls being a curved wall 8b and the other wall 8a is a straight wall. The curved wall 8b proceeds to define a bump 16.

At two measuring positions, one of which is arranged at the wall defining the bump 16 and downstream of the bump 16 and one of which is arranged upstream
20 of the bump 16, preferably at the opposite wall, pressure sensors 18, 19 are arranged.

Thus, the walls 8a, 8b thereby define curved channel 15 configured to provide a non-developed flow and having two measuring positions 18, 19 at which a flow
25 parameter is measured so as to determine a second flow response (ΔPC) over at least a part of the non-linear response device. Also in this case, a capillary device is used to provide the first flow response. Instead of the pressure sensor – or sensor in general – sidelets as disclosed in connection with fig. 2 e.g. may be applied at the position of the sensors 18, 19.

30

On determining flow responses

With reference to fig. 3, it has been found that by utilizing a capillary device 2 and a non-linear response device, e.g. as depicted in fig. 1, 2, 6, 7 or 8, a hysteresis curve defining the non-Newtonian characteristics of the fluid may be obtained by
35 plotting corresponding values of the pressure differences over the capillary device

2 and the non-linear response device 3. By corresponding values is meant that they are recorded at the same time instant, implying due to mass conservation at the same volume flow.

- 5 On an overall level, and as depicted in fig. 3, the timewise progression of the first and the second flow responses are recorded – in fig. 3 this is ΔP_Q and ΔP_c at the same time instances. This recorded timewise progression may be plotted against each other to provide the hysteresis curve.
- 10 It is mentioned that although the wording hysteresis curve may suggest a closed loop, this is not necessarily considered the case in connection with the present invention. On the contrary, depending on the strategy according to which the volume flow is altered, the plot of corresponding pressure values may show a curve, different levels etc.

15

- From the three curves presented, it can be seen that due to the non-Newtonian nature of the fluid – which is water comprising 0.6 % by volume locust bean gum – the plot of corresponding pressure differences represents a hysteresis curve (labelled “Thixotropic Loop”). The upper part of fig. 3 may translate into volume
- 20 flow as the capillary device is designed so that there exists a calibrateable relation between ΔP_Q and the volume flow Q . The hysteresis curve progress in a clockwise orientation and the lower left region corresponds to low volume flow.

- With reference to the middle part of fig. 3 (labelled Pressure drop from c-Device),
- 25 the transient flow and a time scale characteristic, relaxation time, thereto can be identified. Initiating a steep increasing in volume flow at $t=750$ sec (see fig. 3, upper part) gives rise to a steep increase ΔP_c at $t=750$ sec (see fig. 3, middle part). The flow between $t=750$ sec and $t=1600$ sec is kept constant and the flow relaxes due to its thixotropic nature which is identified as the pressure
- 30 asymptotically ΔP_c goes towards a constant value. At $t=1600$ sec a further steep increase in volume flow is initiated and the response ΔP_c increases steeply. Again, the response ΔP_c decreases while the volume flow is kept constant.

From the figures, it may be seen that the relaxation time is within the range of 1000 sec. However, it is noted that the relaxations times may be in ranges of 1000 such as 100 even in the range 10 such as 1 or even the range of 0.1 sec.

5 *On Cyclic measurements*

Fig. 4 is a graph showing the hysteresis curve being the result of cyclic measurements for a fluid (water) containing 0.6 % locust bean gum and by use of the device comprising the capillary flow device of fig. 1 and the non-linear response device of fig. 2.

10

The measuring method disclosed in X2 is suggested to be a way to standardize measurements of thixotropy and involves measuring the pressure differences ΔP_Q , ΔP_C and alter the volume flow after a certain time period – e.g. sufficiently long to allow the flow to relax (may be observed by observing when the pressure

15 differences have stabilised). As indicated in fig. 4, the volume flow has a step wise evolution alternating between a high flow rate and a low flow rate (in fig. 4, high flow rate is about 1500 μ L/min and low flow rate is 0 μ L/min). As it appears from fig. 4, the hysteresis curve proceed in a clockwise direction. The steps is in the scale of the figure shown to be square-shaped, however, in practise a vertical
20 increment of the volume flow is not possible and

$$\frac{dQ}{dt} < \text{limit}$$

is in general preferred. The magnitude of the limit often depends inter alia on the
25 magnitude of the volume flow (as larger volume flow includes e.g. larger inertia forces practically limiting the rate of change of the volume flow). In the example considered herein, where the volume flow is in the pico-litre range, *limit* is chosen the order of $10^{-6} \text{m}^3/\text{s}^2$. Other preferred limits are $10^{-1} \text{m}^3/\text{s}^2$, such as $10^{-2} \text{m}^3/\text{s}^2$, preferably $10^{-3} \text{m}^3/\text{s}^2$, such as $10^{-3} \text{m}^3/\text{s}^2$, preferably $10^{-4} \text{m}^3/\text{s}^2$, and even $10^{-5} \text{m}^3/\text{s}^2$.

30

In another embodiment, the measurement involves an alternating ramp-up and ramp-down of the volume flow between two extremes $Q_{\max}$ and $Q_{\min}$. The ramp-up

and ramp-down are preferably carried out with a constant increment/decrement of the volume flow with respect to time that is

$$\frac{dQ}{dt} = \text{constant}$$

5

Again, the “constancy” of *constant* may depend on the actual equipment used and it is generally accepted, within the scope of the present invention, that *constant* is within certain limits, such as varies with respect to a timely average volume flow less to +/- 2% such as less than 5%.

10

However, although the disclosure of the method presented herein, details preferred ways of altering the volume flow, methods according to the invention are not limited to those preferred method only. As a general measure, it has been found in connection with the present invention, that the actual strategy for

15 varying the volume flow could be set out in relation to how the obtained hysteresis results are used.

On the use of the hysteresis results

As presented in the introduction, the invention has the potential to provide a
20 measure for the non-Newtonian effects in a dynamic manner. This can be utilised e.g. in order to monitor the quality of fluid and used to indicate that the fluid no longer satisfy e.g. a dynamic quality parameter.

In engines, for instance, the lubricating fluid can be monitored in a dynamic
25 manner by e.g. diverting a small amount of oil from the lubricating system in the engine into fluid device as disclosed herein. The flow of oil may be delivered at varying pressures thereby providing a varying volume flow through the flow device. In that case, the method according to present invention may provide a hysteresis curve, which may be compared to a reference hysteresis curve. If the
30 deviations from the reference hysteresis curve is(are) within selected boundaries, the oil may be qualified as falling within the specification and if not, the oil may be qualified as falling outside the specification and needs to be replaced. It is noted that in case the oil is delivered at constant pressure, the volume flow through the device may be set to mimic the dynamic flow regimes in the engine.

Similarly, the method according to the present invention finds use in connection with e.g. production methods involving non-Newtonian fluid. In such case, the a portion of the fluid used in the production may be diverted into a fluid device as disclosed herein at a varying volume flow mimicking the flow in the production (or
5 varying according to a pre-set schedule). Again, the result obtained by the method according to the present invention may be compared to reference hysteresis curve(s).

A different use of the hysteresis results, as presented above, is a use where a
10 particular property of the fluid is determined. If, for instance, the concentration of sugar in water is to be determined, the method according to the present invention may be applied to obtain responses for a plurality of water solutions with known sugar concentrations so to provide a calibration between hysteresis results and known properties. Once such a calibration has been established, hysteresis data
15 for a fluid for which the property is to be determined may be obtained and an interpolation in the calibration may be used to estimate the property in question. It is noted, that the variation in volume flow should preferably be the same for all calibration data and the hysteresis data for the fluid to be determined.

20 *On the Fluid dynamic principle employed by the HSV device*

Contrary to the LSV device (fig. 1), which utilized the inertia effect for characterizing the fluid, regardless of the properties at the shear thinning region, the HSV device is designed to enforce strong shear rates in the fluid, and it does so by deflecting the fluid path by two curved walls 8a and 8b placed at opposite
25 positions of the main transition channel 15 (see fig. 2).

On the implementation of the invention

A particular preferred embodiment of a device according to the present invention relates to a small handheld device. The device comprises a capillary device 2 and
30 a non-linear response device 3 as outlined above. The device is formed as a pipette with the capillary and the non-linear response device integrated in the pipette. The pressure sensors are connected to the a processor either being an integrated part of the pipette or through wires to e.g. a computer. The integrated processor or the computer being equipped with software and a characterisation
35 thereby enabling the processor or the computer to determine the fluid property

aimed at. Once activated, the pipette will such fluid through the device and the processor or the computer will provide the magnitude of the fluid property in question. This embodiment furthermore illustrates the advantageous feature of the invention that the flow through the device needs not to be stationary; the flow
5 through the pipette device varies over time but the device is able to provide the desired magnitude of the fluid property in question.

In a further embodiment, the device is integrated in fluid connection of either a lab equipment, such as a test facility, or a production facility in which a certain
10 fluid property is to be monitored. Again, the pressure sensors are connected to processor means, such as a computer, with software.

As disclosed herein, handling of fluids with thixotropic flow characteristics may often cause serious issues due to the fluids inherent delayed adaptation of the
15 fluid (liquid) viscosity. For fluid, such as liquids, with very profound thixotropic flow-characteristics, the resulting delayed adaption of the liquid viscosity to the applied shear-rate causes great difficulties when initiating a pumping of the liquid. The inherent characteristic time-scale for this delayed adaptation is crucial and is denoted the "relaxation time". In the following an example will be disclosed with
20 reference to start-up of a pump pumping a fluid with thixotropic characteristics.

Before the pump starts pumping, the liquid is at rest and has in the described example a high viscosity (zero shear viscosity).

25 After pumping initiation, specifically after several times the relaxation times, the pump gives a prescribed flowrate, and the viscosity is significantly reduced compared to the zero shear case due to the shear-thinning characteristics of the liquid. This causes the pump to work on a significantly reduced power consumption compared to the power consumption if the liquid had still been at the
30 zero shear viscosity.

During pumping initiation, if the flowrate is increased to the prescribed flowrate at a time-scale shorter than the relaxation time, the liquid still has a viscosity comparable to the zero shear viscosity. The increased power consumption of the
35 pump during such initiation may overload the pump and cause its breakdown.

Contrary if the flowrate is increased slowly to the prescribed flowrate, at a time-scale longer than the relaxation time, the viscosity of the liquid can adapt to the increasing flowrate and thereby keeping the power-consumption of the pump within a manageable level.

5

It is noted that the time scales involved in characterising a non-Newtonian fluid may be seen as having a contribution defined by the device used and a contribution from the inherent time scale of the fluid. For instance, if a device having channel with a relatively broad cross section, the time it takes for the shear along the wall to penetrate into the flow is relatively larger than compared to a channel with a relatively narrow cross section. If it is desired to remove the contribution in time scale from the measurement, two devices with different geometry could be applied and the difference between measurements obtained can be separated out to provide the inherent time scale of the fluid.

15

This illustrates that thixotropic flow-characteristics of liquids influence the time-scales at which they have to be handled. The invention will be very useful in monitoring the thixotropy of a liquid and using this information in adapting the operation of a pump.

20

On an approximate theoretical disclosure of the flow in the two flow devices according to the present invention

As presented herein, the fluid flows through two fluid devices (a capillary device and a non-linear response device) being arranged in series (meaning that the fluid flow directly from the first flow device and into the second flow device). In the following, the co-ordinate system is orientated with its x-axis in a main flow direction of the first device, y-axis perpendicular thereto.

While shear rate is in general quantified by:

30

$$\gamma_{ij} = \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}$$

Shear stresses can only for very simple fluids be determined on the basis of a dynamic viscosity and the shear rate. In general shear stress, τ , is quantified as:

$$\tau_{(n)} = \lim_{\Delta S \rightarrow 0} \frac{\Delta F}{\Delta S}$$

5

where $\mathbf{F}$ is a force vector and S is a surface of differential surface. For non-Newtonian fluids, the force is not linear scalable with the dynamic viscosity and is therefore difficult to estimate.

- 10 In connection with the following, theoretical, description of the present invention, body forces are ignored and the governing equations (assuming substantive derivatives equal zero and two-dimensional flow) may be written as:

$$\frac{1}{\rho} \frac{Du}{Dt} = 0 = \frac{\partial p_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y}$$

15

$$\frac{1}{\rho} \frac{Dv}{Dt} = 0 = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial p_{yy}}{\partial y}$$

(tensor notation is used for p and τ).

- 20 As follows from the below, the governing equations are considered for stationary flow condition (the substantive derivatives are set to zero), and information obtained therefrom may be expanded to such quasi stationary and even non-stationary flow situations.

25 Flow in the capillary device:

The first flow device – herein called capillary device – is configured so that it during use contains a region in which the flow is developed. Inside this regions, the flow is considered to be two-dimensional in the sense that any velocity in the z-direction (w), the velocity v in the y-direction and any derivative of flow related

30

variables with respect to the co-ordinate z is zero. This means:

$$v = w = 0$$

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = 0$$

5

$$\frac{\partial u}{\partial y} \neq 0 \text{ and } \frac{\partial v}{\partial y} = 0$$

Thereby the shear rate is reduced to:

$$\gamma = \frac{du}{dy}$$

10

which shows that the shear rate along a streamline in the capillary device is constant. Further, the governing equations reduces to

$$\frac{\partial p_{xx}}{\partial x} = -\frac{\partial \tau_{yx}}{\partial y}$$

15

While $\tau \neq \text{const} \cdot \gamma$ the assumption that the flow is fully developed implies

$$\frac{d\gamma}{dx} = 0$$

and assuming

20

$$\tau_{xy} \approx f(u) \cdot \gamma = f(u) \cdot \frac{du}{dy}$$

Where $f(u)$ is a unknown function, the governing equation is reduced to

25

$$\frac{\partial p_{xx}}{\partial x} \approx -f(u) \frac{d\gamma}{dy}$$

As the velocity, u , varies with the co-ordinate y only (and not x)

$$f(u) = f(g(y))$$

in the capillary device, the governing equation for the flow in the capillary device along a stream line at position y_{sl} is reduced to:

$$\frac{\partial p_{xx}}{\partial x} \approx -a \cdot \frac{d\gamma}{dy} \quad \text{where } a \text{ is constant along a streamline} = (g(y_{sl}))$$

5

Showing that the for the flow in the capillary flow device, the shear rate is substantially in equilibrium with the pressure along the region considered. This is used to determine the shear rate in the capillary device.

10 Flow in the non-linear response device:

In the non-linear response device, the flow is characterised as

$$\frac{\partial u}{\partial x} \neq 0, \quad \frac{\partial u}{\partial y} \neq 0, \quad \frac{\partial v}{\partial x} \neq 0, \quad \frac{\partial v}{\partial y} \neq 0,$$

15

$$\gamma_{ij} = \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \neq 0.$$

Contrary to the equations adapted to the flow the capillary device, the governing equations for the flow in the non-linear flow device may be written as (assuming substantive derivatives equal zero and two-dimensional flow):

20

$$\frac{1}{\rho} \frac{Du}{Dt} = 0 = \frac{\partial p_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y}$$

$$\frac{1}{\rho} \frac{Dv}{Dt} = 0 = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial p_{yy}}{\partial y}$$

25

Assuming, that

$$\tau_{yx} = f(u, v) \cdot \gamma_{yx} + o(u, v) \quad \text{and} \quad \frac{Du}{Dt} = \frac{Dv}{Dt} = 0$$

It may be shown that e.g.

$$\frac{\partial p_{xx}}{\partial x} \cong -\frac{\partial}{\partial y}(f(u, v) \cdot \gamma_{yx})$$

$$\frac{\partial p_{yy}}{\partial y} \cong -\frac{\partial}{\partial x}(f(u, v) \cdot \gamma_{xy})$$

- 5 Showing that as the velocities varies throughout the x,y domain, no simple correlation between the pressure and the shear rate exist.

Thus, by the proper design of the non-linear response device as presented herein, the non-Newtonian effects of a fluid is set into effect and the magnitude of the
10 non-Newtonian effects is quantified by measuring the pressure difference over the non-linear response device.

To summarise, let ΔP_c denote the pressure difference over the non-linear response device and let ΔP_Q denote the pressure difference over the capillary device, then it
15 follows from the above that:

$$\gamma \approx \Delta P_Q \text{ and } \tau \approx \Delta P_c$$

On the response measured

- 20 As disclosed herein, it is preferred to measure the pressure differences as the response from the capillary device and non-linear response device respectively. However, as the pressure is considered a parameter dependent on the velocities (which may be considered the independent parameters), other parameters may be used as response.

25

- Although the present invention has been described in connection with the specified embodiments, it should not be construed as being in any way limited to the presented examples. The scope of the present invention is set out by the accompanying claim set. In the context of the claims, the terms "comprising" or
30 "comprises" do not exclude other possible elements or steps. Also, the mentioning of references such as "a" or "an" etc. should not be construed as excluding a plurality. The use of reference signs in the claims with respect to elements indicated in the figures shall also not be construed as limiting the scope of the

invention. Furthermore, individual features mentioned in different claims, may possibly be advantageously combined, and the mentioning of these features in different claims does not exclude that a combination of features is not possible and advantageous.

CLAIMS

1. A method of determining the dynamic flow response for a non-Newtonian fluid, the method comprising
- 5 - providing fluid device comprising a capillary flow device and a non-linear response device immediately downstream or upstream of the capillary flow device, wherein
- the capillary flow device comprising a longitudinal extending channel having two longitudinal distanced measuring positions (5a, 5b) at which a
10 flow parameter is measured so as to determine a first flow response (ΔP_Q) over at least a part of the longitudinal extending channel, the channel comprising a straight section (4b) in between the two longitudinal distanced measuring positions (5a, 5b), the straight section having a longitudinal extension being larger than the hydraulic diameter of cross
15 section of the straight section, thereby the channel being configured to provide a developed flow in a region in between the two measuring positions (5a, 5b);
 - the non-linear response device comprising a
 - transition channel (15) reaching from an inlet (13) to an outlet (14),
20 the transition channel comprising two walls (8a, 8b), at least one of said walls being a curved wall, on opposite sides of the channel (15), wherein at least one of the at least one curved wall (8b) proceed to define a bump (16),thereby defining a curved channel (15) configured to provide a non-
25 developed flow and having two measuring positions (11a, 11b) at which a flow parameter is measured so as to determine a second flow response (ΔP_C) over at least a part of the non-linear response device;
- feeding a non-Newtonian fluid at different volume flows through the fluid device and recording simultaneously the time wise progression of the first and
30 the second flow response (ΔP_Q , ΔP_C); the infeed of fluid includes at least one period with increase of volume flow and/or at least one period with decrease of volume flow during which the time wise progression of the first and the second responses are recorded.

2. A method according to claim 1, wherein the feeding of non-Newtonian fluid at different volume flows includes at least one period with constant volume flow.
3. A method according to claim 1 or 2, wherein the method comprising feeding
5 the fluid through the device in a step wise manner, wherein the fluid is alternatingly fed to through the fluid device at at least two different volume flows.
4. A method according to claim 3, wherein the stepwise feeding of fluid comprising keeping the flow between two consecutive alterations constant,
10 preferably until the flow has relaxed.
5. A method according to any of the preceding claims, wherein the method comprising feeding the fluid through the device in manner where the volume flow is alternatingly ramped-up and ramped-down between two extremes $Q_{\max}$ and
15 $Q_{\min}$.
6. A method according to clam 5, wherein the ramping-up and ramping-down are carried out with a constant increment/decrement of the volume flow with respect to time.
20
7. A method according to any of the preceding claims, wherein the recorded corresponding flow responses are compared with reference flow responses.
8. A method according to claim 7, wherein the comparison with the reference flow
25 responses further comprising determining deviations between the reference flow responses and the recorded flow responses and determining if the deviation(s) is(are) within selected boundaries.
9. A method according to any of the preceding claims, wherein the measuring
30 positions for the capillary device and the non-linear response device are pressure measuring positions and the flow responses determined are pressure differences in the capillary device and in the non-linear response device.

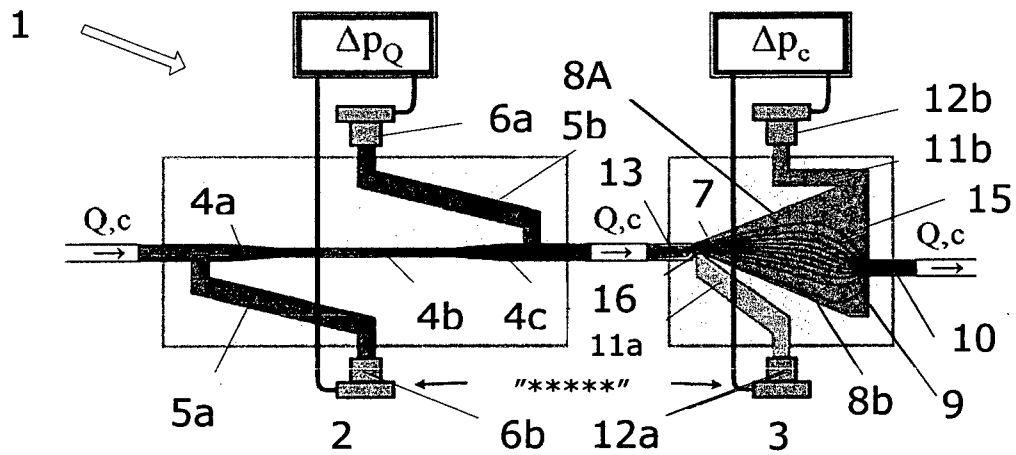
10. A method according to any of the preceding claims, wherein the measuring positions of the capillary device (2) comprising two sidelets (5a, 5b) each comprising a pressure sensor arranged at a distal end of the sidelet.
- 5 11. A method according to any of the preceding claims, wherein the the non-linear response device (3) comprising a flow channel directly connected to the flow channel of the capillary device, the flow channel of the non-linear response device comprising sidelets each comprising a pressure sensor arranged at distal end of the sidelet, the sidelets being arranged to determine a pressure difference over at
- 10 least a part of the flow channel.
12. A method according to any of the preceding claims, wherein the curved channel of the non-linear response device comprising
- two opposite curved wall sections (8a, 8b) extending asymmetrically to
- 15 each other at least through out a part of the flow channel, wherein one of the opposing curved wall sections (8b) defines a bump (16) in the flow channel, so as to provide a fluid deflection into a flow pattern with curved stream lines from an inlet and to an outlet of the flow channel with increased shear in flow regions at the bump.
- 20
13. A method according to claim 12, wherein the curved wall section (8a) opposing the curved wall section defining a bump extends in a manner increasing or decreasing the cross sectional area of the flow channel downstream of the bump.
- 25
- 14 A method according to any of the preceding claims, wherein the flow channel of the capillary flow device comprising a straight channel in a region between the two measuring points.
- 30 15. A method according to any of the preceding claims, wherein the flow channel of the capillary device comprising a narrowing section (4a) upstream and an expanding section (4c) downstream of a contraction (4b), preferably being a straight channel section, with the sidelets (5a, 5b) being arranged upstream and downstream of the contraction.
- 35

16. A method according to any of the preceding claims, the geometrical dimension of the flow channel of the capillary device, the flow channel of the non-linear response device and of the sidelets is in the micrometer range size.
- 5 17. A method according to any of the preceding claims, wherein the flow channel of the non-linear response device comprising a constriction (7) at an inlet of the flow channel, and wherein flow channel downstream of the constriction (7) has a diffuser geometry with diverging sides, the diffuser geometry is terminated by a wall (9) having an outlet (10), a sidelet (11a) is arranged at the constriction (7)
10 and a sidelet (11b) is arranged at the wall (9).
18. A method according to any of the preceding claims, wherein the non-Newtonian fluid is selected from the group consisting of visco-elastic fluids.
- 15 19. A method according to any of the preceding claims, wherein the fluid is selected from the group consisting of sugar dissolved in water, soft-drink concentrate, paint, enamel, engine oil, engine fuel.
20. A device for obtaining responses for a non-Newtonian fluid, the device
20 comprising a fluid device having a capillary flow device and a non-linear response device immediately downstream or upstream of the capillary flow device, wherein
- the capillary flow device comprising a longitudinal extending channel having two longitudinal distanced measuring positions (5a, 5b) at which a flow parameter is measured so as to determine a first flow response
25 (ΔP_Q) over at least a part of the longitudinal extending channel, the channel being configured to provide a developed flow in a region in between the two measuring positions (5a, 5b);
 - the non-linear response device comprising a curved channel configured to provide a non-developed flow and having two measuring positions (11a,
30 11b) at which a flow parameter is measured so as to determine a second flow response (ΔP_c) over at least a part of the non-linear response device;
- wherein the device further comprising
- means adapted to feed a non-Newtonian fluid at different volume flows through the fluid device; the infeed of fluid includes at least one period with

increase of volume flow and/or at least one period with decrease of volume flow, and

- means adapted to recording simultaneously the first and the second flow response (ΔP_Q , ΔP_C).

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*****:Pressure transducers

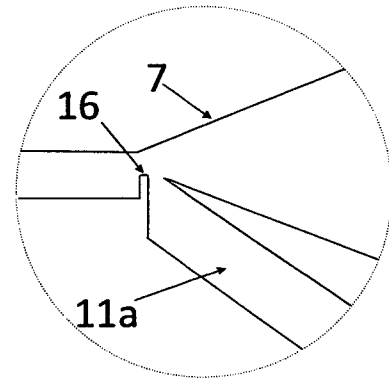


Fig. 1

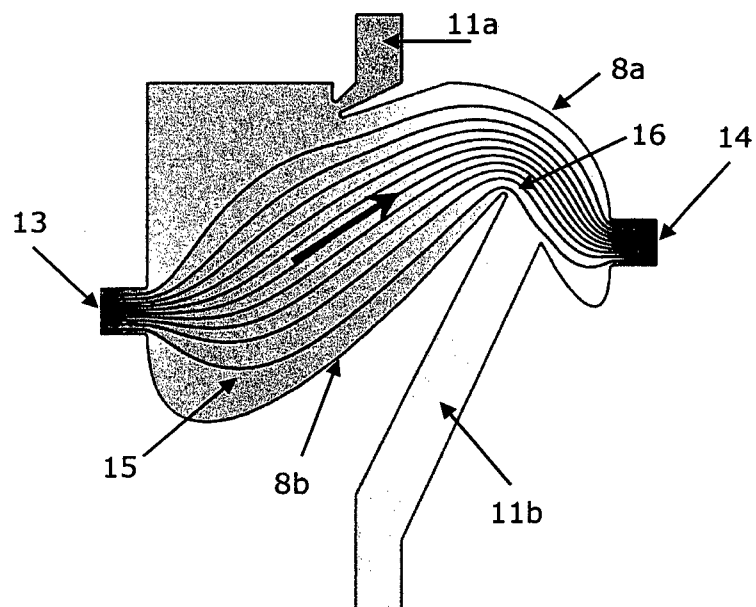


Fig. 2

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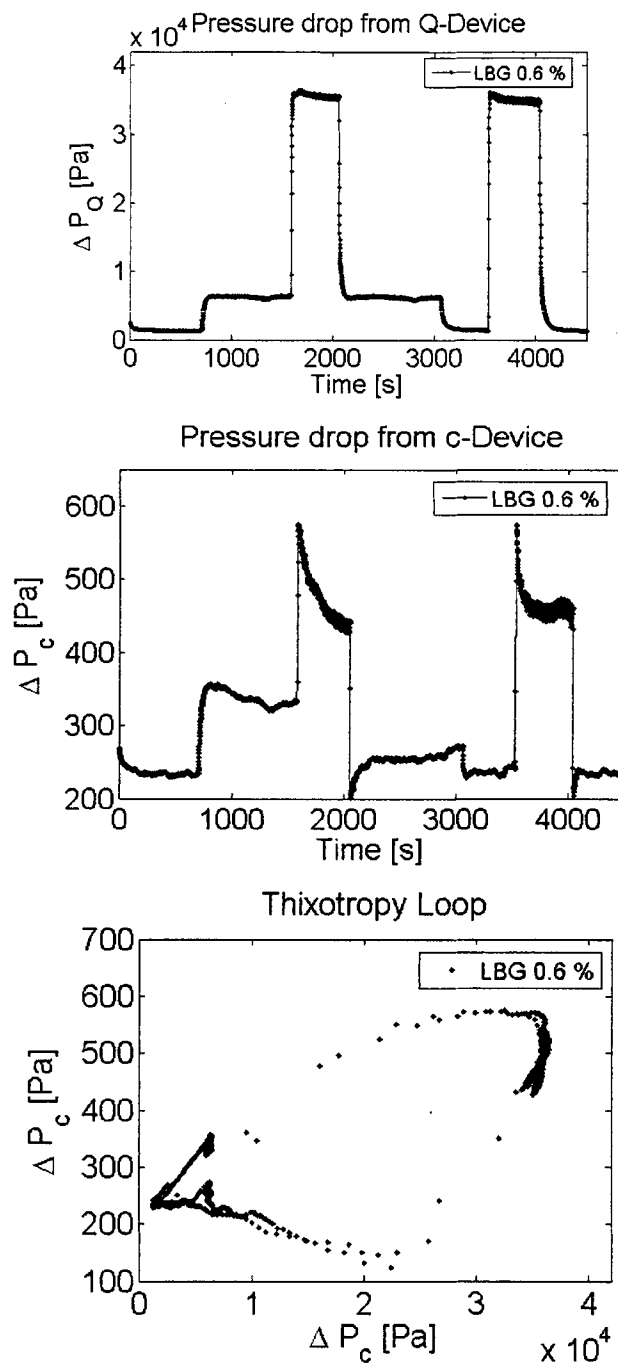


Fig. 3

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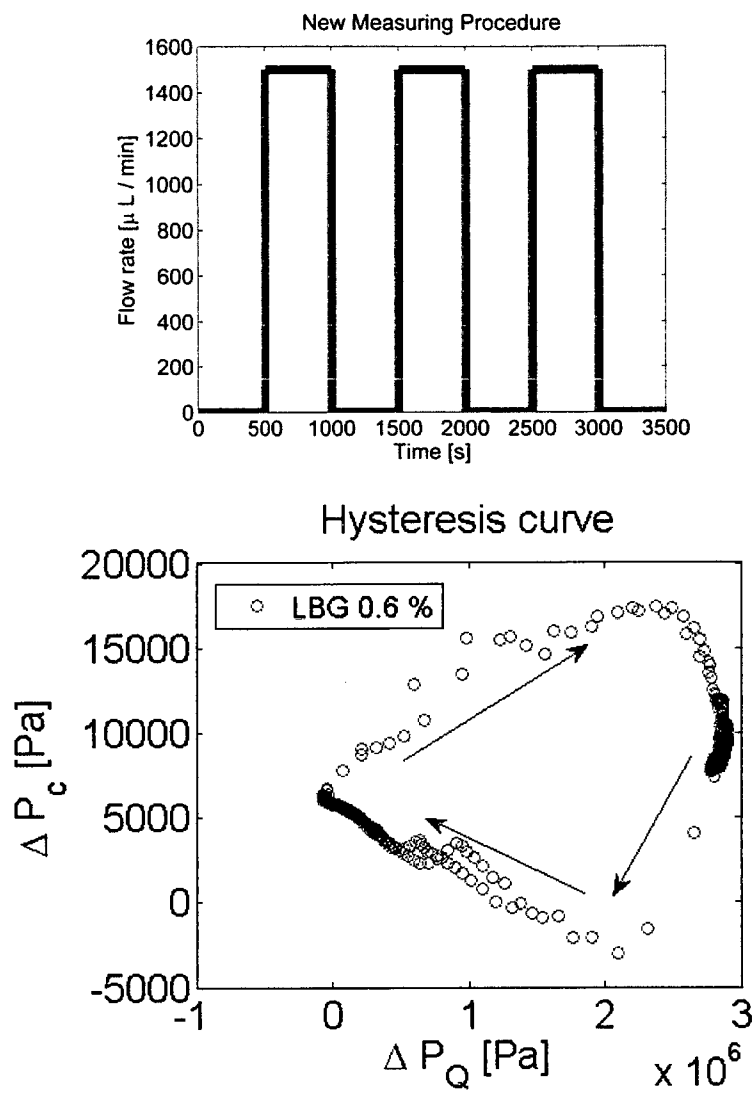


Fig. 4

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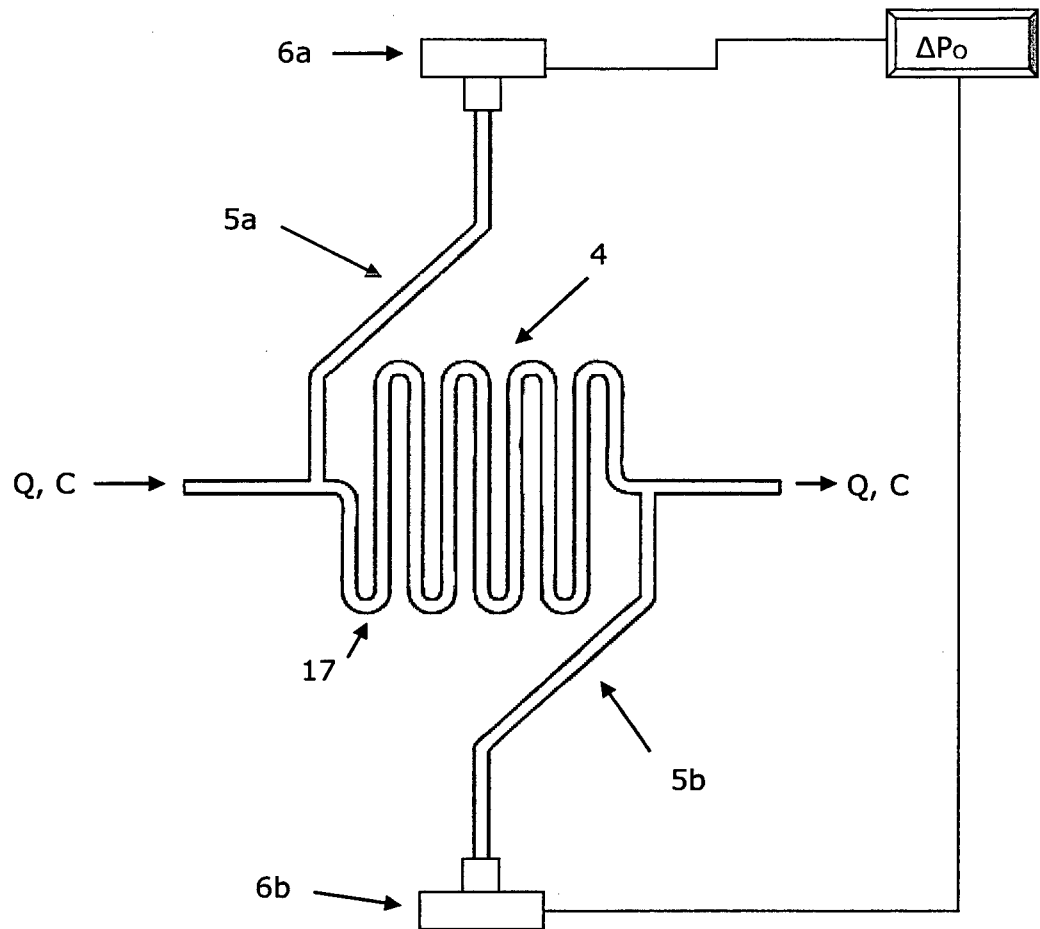


Fig. 5

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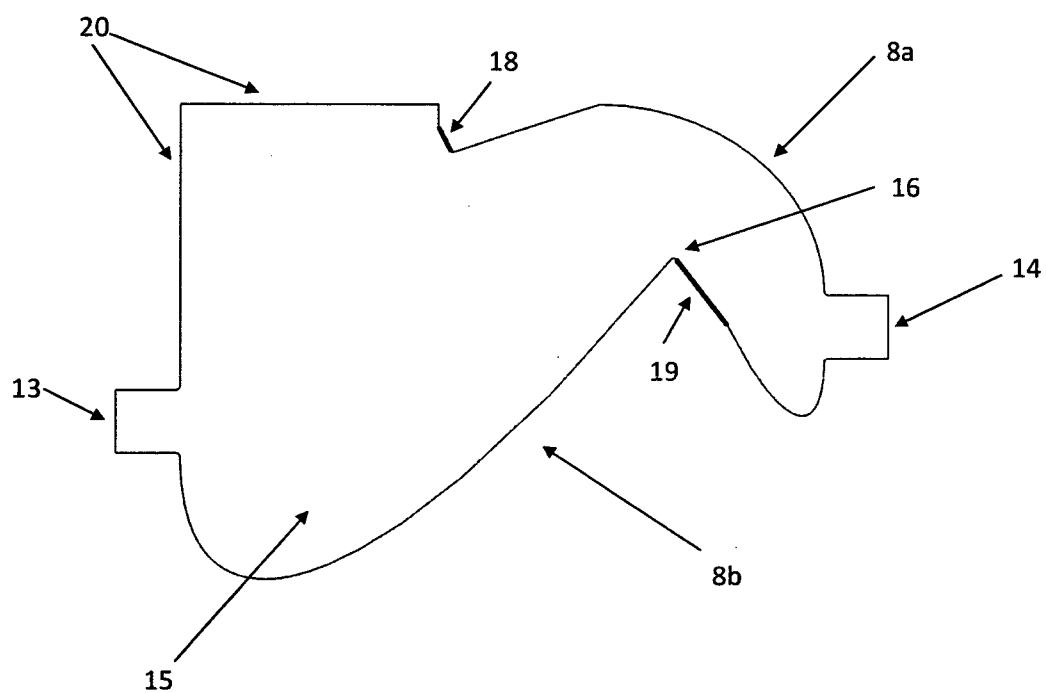


Fig. 6

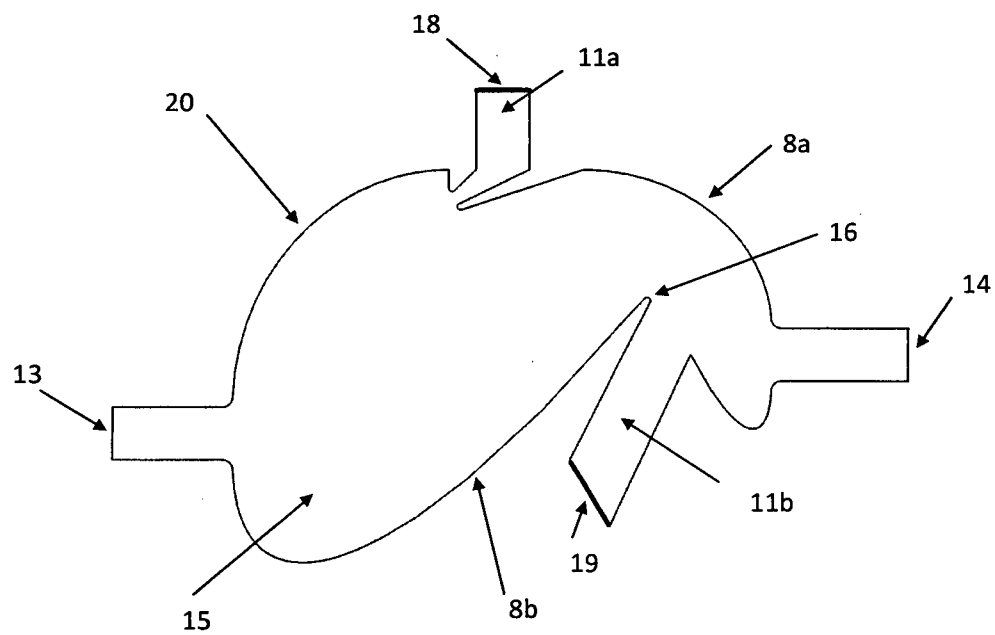


Fig. 7

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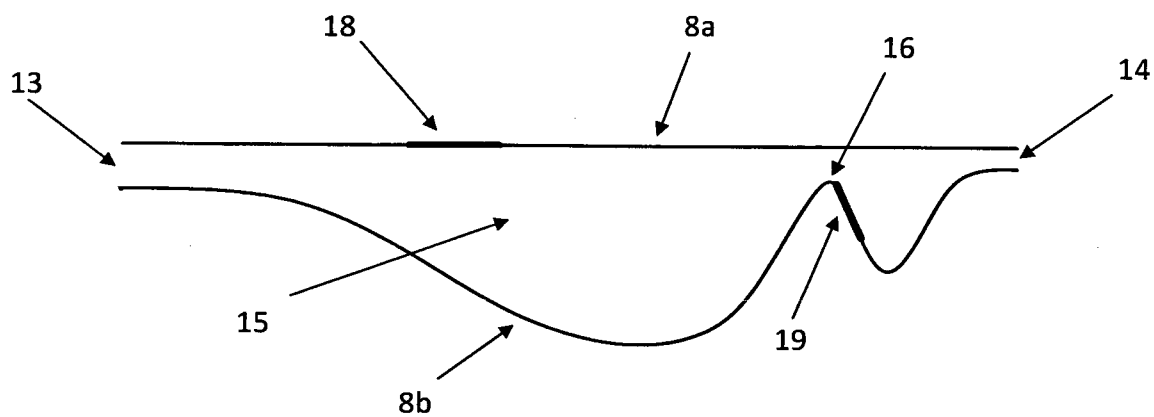


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2015/050184

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N11/08
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014/137640 A1 (OKKELS FRIDOLIN [DK]) 22 May 2014 (2014-05-22) paragraphs [0096] - [0104]; figures 1-9 -----	1-20
A	US 3 952 577 A (HAYES WILLIAM F ET AL) 27 April 1976 (1976-04-27) column 14, paragraph 1 - column 15, paragraph 57 -----	1-20
A	GB 2 501 530 A (UNIV SHEFFIELD [GB]) 30 October 2013 (2013-10-30) paragraph [0029] ----- -/-	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search

7 September 2015

Date of mailing of the international search report

15/09/2015

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INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2015/050184

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KRISTIAN EJLEBJERG JENSEN ET AL: "Optimization of bistable viscoelastic systems", STRUCTURAL AND MULTIDISCIPLINARY OPTIMIZATION, vol. 49, no. 5, 29 November 2013 (2013-11-29), pages 733-742, XP055130802, ISSN: 1615-147X, DOI: 10.1007/s00158-013-1020-8 the whole document -----	1-20
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/DK2015/050184

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