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Method and apparatus for determining the flow of a flowing liquid

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The invention relates to a method and apparatus for determining the flow of a flowing liquid.

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Generic methods and apparatuses of differing configuration are known.

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Therefore it is known to measure the diffraction of a (small) laser beam through an (otherwise) heated zone of a fluid so as to establish the velocity of the fluid.

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Alternatively, it is known to measure the flow velocity of a fluid by means of an optionally optical detector arrangement positioned downstream of a heating point, which is also optionally generated optically, during the propagation time of a temporarily heated region from the heating point to the measuring point.

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Disadvantageously, in this case two different working locations as well as working equipment are needed, on the one hand for heating, on the other hand for detecting the heating. The object of the invention is therefore to develop an improved method as well as an improved apparatus for deter-

mining the flow of a flowing liquid whilst avoiding the disadvantages mentioned above.

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In accordance with the invention the above object is achieved with a method of the type mentioned at the outset in that the liquid is heated by means of an optical heating beam and the heating location is irradiated by an optical
45 detection beam, the optical axes of the heating and detection beams coinciding at least at the heating location, and the detection beam being absorbed by an array of detectors.

In order to achieve the above-mentioned object the invention further provides a generic apparatus, in which the device for heating an inner region of a defined inner region
50 of the liquid and an optical arrangement for guiding the beam of the laser are positioned in such a way that a measuring beam irradiates the heated region at the absolute location of heating thereof.
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Flow defines a distinguishing characteristic thereof, such as flow rate, flow velocity, volume flow rate or the like. As a result of partial absorption of an optical beam, e.g.
60 a laser beam, in the liquid, especially in water having an absorption coefficient of 0.46 m^{-1} at a wavelength of 970 nm, a lens is thermally induced in the heated region. The lens and especially its flow-induced properties are measured in order to determine the flow velocity. The measurement is taken by means of the unabsorbed light of the same
65 laser beam so the excitation beam and the measuring beam coincide. This method is a non-invasive, contact-free thermal measuring method for measuring the heat-induced modifications to the optical properties of the heated fluid. The
70 measurement is taken at the same absolute location as the

heating, i.e. the heating and measuring locations coincide or overlap. The laser beam is detected by an array of detectors comprising a plurality of individual detectors (at least two), a number of individual detectors simultaneously
75 detecting the light of the incident light beam. Apart from the diffusion through the heat-induced thermal lens in the liquid, this method can also be expanded by means of an optical lens or a group of optical lenses positioned outside the tube in front of the array of detectors. Different
80 properties of the heating region and not only its misalignment (movement), but also its deformation, i.e. changes in shape within the heated zone, can be detected, this deformation resulting from the flow movement. In accordance with the invention the refractive index of the induced thermal
85 lens is not therefore merely determined globally by the diffraction of the light beam, but a global measurement over a wider region is taken and the flow-induced properties, especially the deformations of said lens are measured. The liquid is heated (in a contact-free manner) by
90 means of an optical beam, in particular the light of the beam heating and penetrating the liquid being detected.

In accordance with preferred configurations it is provided for the heating and detector beams to be emitted by the
95 same radiation source or to be emitted by different radiation sources. In the latter case, the sources of radiation can have the same or different frequency ranges. The heating and detection beams may be generated by means of a light source by splitting the beam, by filtration through
100 different optical filters and/or by different divergence via different focusing optics.

Therefore the device for heating a region of the liquid can also be a radiation source or light source, such as a laser, which coincides with the measuring light source, in particular the beam guidance being such that the heating and detection beams are the same i.e. there is no splitting of the beams of a radiation or light source.

In a preferred development it may be provided for the detection beam to have a greater mean diameter than the heating beam.

The optical beam can be focused inside the tube and therefore into the liquid flow, or else outside the tube or may penetrate the tube as a parallel beam.

In a preferred development of the invention it may be provided for a number of measurements to be taken temporally sequentially by means of the array of detectors. If the light source is a modulated or pulsed laser, as is provided in the preferred configuration, temporally sequential measurements can be taken during one laser pulse. The temporal development of the heating in the heating region can thus be detected, this development being influenced by the flow velocity.

While in principle it may be provided for detection to take place via a linear array of detectors, the alignment of a linear array of detectors being provided in the flow direction, a preferred configuration provides for detection to take place via a planar (two-dimensional) array of detectors.

135 Developments of the method according to the invention provide for the flow to be determined from a received profile of the optical beam, in particular statistical moments of the received signals being determined, such as mean value, variance, skewness and/or kurtosis, and the flow velocity
140 of the liquid being determined by determining the decrease in statistical moments. Each determined (statistical) moment is connected to a different characteristic of the beam shape and therefore of the shape of the thermal lens and therefore of the flow velocity. Alternatively to the flow
145 values from the exponential behaviour of statistical moments over time, a phase shift in the statistical moments can be determined at a defined laser excitation frequency. Therefore it may be provided for the shift in the mean value of the position of the optical beam to be determined
150 as a measure for the flow and/or for the decrease in the variance of the optical beam to be determined with the flow. Other preferred developments of the invention provide for the intensity of the optical beam to be modulated and for the phase shift of the modulation to be determined so
155 the optical beam is modulated by numerous frequencies and/or the optical beam is modulated stochastically.

Other advantages and features of the invention will emerge from the claims and from the following description, in
160 which embodiments of the invention are explained in detail with reference to the drawings, in which:

Fig. 1 is a schematic overview of the apparatus according to the invention;
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Fig. 2.1 to 2.7 show different configurations of the optical heating and detection beams ir-

radiating the flowing liquid, partly as a parallel beam, partly focused;

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Fig. 3.1, 3.2

show two configurations of the invention with different radiation sources for the heating and detection beams, these beams penetrating as a parallel beam in Fig. 3.1 and being focused on a region inside the liquid in Fig. 3.2;

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Fig. 4

shows the cross-sectional ratios of the measuring and heating beams when they don't coincide;

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Fig. 5

shows the development of the distribution curve of the measuring beam at different points of time in the flow direction;

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Fig. 6.1

shows the mean value for different flow rates (in ml/min);

190 Fig. 6.2

shows the standard deviation for different flow courses (in ml/min); and

Fig. 7

shows the change in the phase relation between the initial modulation and the received optical radiation.

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An apparatus 1 according to the invention comprises an optical arrangement 2, a laser electronic system 3 arranged upstream of said optical arrangement, an amplifier arrangement 4, an electronic evaluation device 5 as well as an in-

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terface arrangement 6. Additionally, a power supply 7 is provided for the individual electric and electronic parts.

205 A tube 2.1 guiding a liquid 8 runs through the optical arrangement 2 and has transparent walls 2.1.1, for example made of glass, at least in the measuring region for the measuring beam 2.3.

210 The optical arrangement comprises a laser 2.2 as an optical light source, which is operated for example with a wavelength of 970 ± 15 nm and with an output of 100mW. The optical beam 2.3 or the laser beam is parallelised by means of a first lens 2.4, irradiates the tube 2.1 and falls on an array of detectors 2.5 comprising a number of individual
215 detectors. The array of detectors 2.5 is connected to an electronic amplifier 4.1.

The laser control 3 comprises a modulator 3.1 and a laser driver 3.2 to control the laser 2.2.

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An A/D converter 5.1 as well as a computer or processor, preferably in the form of a digital processor 5.2 are arranged in the evaluation device 5 downstream of the amplifier 4.1. An interface outputs the calculated data on a
225 display, a storage medium and/or a printer. Control lines 9.1, 9.2 are provided to adjust the laser control and the evaluation control and, if necessary, to feed back and control the laser operation.

230 The optical arrangement shown in Fig 2.1 corresponds to that in Fig 1 and comprises a lens 2.2 for parallelising the optical beam, which irradiates the tube 2.1 as a parallel beam and therefore irradiates the liquid 8 which flows

through said tube. The direction of the liquid flow is denoted by S.

In the configuration of Fig. 2.2 an additional lens 2.6 is provided in front of the tube 2.1 and focuses the beam 2.2 inside the liquid 8, the beam exiting the liquid divergently and striking the array of detectors 2.5.

In the configuration of Fig. 2.3, in addition to the two lenses 2.4 and 2.6 a further lens 2.7 is provided on the side of the tube 2.1 remote away from the laser 2.2 and expands the beam 2.2 further.

The configuration of Fig. 2.4 differs from that of Fig. 2.2 and 2.3 in that the light beam is focused through the lens 2.6 on the laser side in front of the tube 2.1.

This corresponds to the configuration of Fig. 2.5, in which an expansion is also achieved via a lens 2.7 on the side of the tube 2.1 remote from the laser 2.2.

While in the configuration of Fig 2.2 and 2.3 the focus lies inside the liquid but on the side facing the laser 2.2 relative to the axis of symmetry, in the configuration of Fig 2.6 it lies inside the liquid on the side remote from the laser and facing the photo array 2.7, viewed from the axis of symmetry.

In turn and similarly to Fig. 2.1, the configuration of Fig. 2.7 comprises a parallel beam, which in this case is expanded via a lens 2.7 on the side remote from the laser in front of the array of detectors 2.5, as shown in the configurations of Fig. 2.5 and 2.6.

In the configuration described of Fig. 1 and 2.1 to 2.7 it is assumed that an optical beam or laser beam is involved, which not only heats the liquid 8 flowing in the tube 2.1, but also detects the optical lens produced by the heating process and of which the shape is influenced by the flow, i.e. the beam or laser beam also serves as a heating and measuring beam.

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Fig 3.1 and 3.2 show alternative configuration with respect to the configurations of Fig. 2.1 to 2.7, these alternative configurations comprising two different radiation or light sources 2.2, 2.8 for the detection beam 2.3 and the heating beam 2.10. The arrangement and the assembly for the detection beam 2.3 correspond to the configurations of Fig. 3.1 and Fig. 3.2 and to the configurations of Fig. 2.1 and 2.2 respectively, in such a way that reference is made to these in principle in the following description. Like parts are denoted by like reference numerals. One radiation source 2.2 is provided for the detection beam 2.3. A converging lens 2.4 is situated behind this in the direction of radiation and parallelises the detection beam 2.3 in the two configurations of Fig. 3.1 and 3.2. As an alternative and further development of the configurations of Fig. 2.1 and 2.2, this detection beam then passes through a mirror 2.11, which is partly permeable and is positioned at an angle of 45° to the direction of radiation, before it passes through the tube 2.1 and through the liquid 8 flowing through said tube. In the configuration of Fig. 3.1 the detection beam passes through the tube 2.1 as a parallel beam and through the liquid 8 foaming in said tube before reaching the array of detectors 2.5.

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300 In the configuration of Fig. 3.2 the detection beam 2.3 is
focused inside the tube 2.1, and therefore inside the liq-
uid 8 flowing through said tube, after passing through the
partly permeable mirror 2.11 by means of the converging
305 lens 2.6 and reaches the array of detectors 2.5 as a diver-
gent beam.

The frequency and power of the detection beam are chosen in
such a way that they do not considerably heat the liquid 8.

310 For this purpose a second radiation or light source 2.8 is
provided, which radiates a heating beam 2.10. Initially,
this beam passes through a converging lens 2.9 and is par-
allelised by this, similarly to the beam 2.3 passing
through the converging lens 2.4. It then reaches the side
315 of the partly permeable mirror 2.11 facing the tube 2.1, is
reflected and therefore deflected by 90° in such a way that
its optical axis coincides with that of the detection beam
2.3 after this reflection. In the configuration of Fig 3.2
the heating beam 2.10 also passes through the converging
320 lens 2.6 and is focused inside the liquid 8, whilst in the
configuration of Fig. 3.1 it enters the liquid as a paral-
lel beam.

While as a simplification in Fig 3.1 and 3.2 the beams 2.3
325 and 2.10 are shown to have coincident cross-sectional di-
mensions and beam guidance after reflection, these can vary
as shown in Fig. 4 and as explained below.

Additionally, if needed, it is also possible for the detec-
330 tion beam to pass through the liquid as a parallel beam and
for the heating beam 2.10 to focus inside the liquid or
vice versa, i.e. for the heating beam to pass through the

liquid as a parallel beam and for the detection beam to be focused inside or in another manner as shown in Fig. 2.3 to 2.6. In this case the partly permeable mirror 2.11 may optionally be positioned behind the converging lens 2.6 in accordance with the desired focus of the beam, either in the beam path of the detection beam 2.3 or in the beam path of the heating beam 2.10. Additionally, the configurations of Fig 2.3 and 2.5 to 2.7, i.e. a diverging lens 2.7 for the detection beam after it has passed through the tube 2.1 and the liquid 8, are also possible in the configuration of two different radiation sources for the detection beam 2.3 and the heating beam 2.8.

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The configuration of Fig. 4 provides two beams and a separate heating beam 2.3.1 in addition to the measuring beam 2.3. It is essential that the heating beam has a diameter that is no greater than that of the measuring beam 2.3, i.e. a diameter that is equal to or smaller than the diameter of the measuring beam 2.3. In the embodiment illustrated the measuring beam 2.3 and the heating beam 2.3.1 are guided coaxially. They may originate from one light source or from different light sources and may accordingly be positioned on the optical path shown.

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The laser 2.2 is a modulated or pulsed laser so the laser beam is a modulated or pulsed laser beam 2.3.

360 As a result of the provision of an array of detectors 2.5 comprising numerous individual detectors, the array of detectors 2.5 being a linear or planar array of detectors, not only is the local diffraction of the laser beam through the lens ascertained, but the global properties of the thermal lens formed by the heating process can thus be de-

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terminated by the numerous individual detectors. Numerous measurements are taken over a period of time - during a laser pulse - so the time response, which is basically determined by the flow velocity of the liquid, of the development of the thermal lens can be detected. In order to determine the flow behaviours more accurately, four statistical evaluations of the signals received are carried out by means of the evaluation device, in particular determination of the first moment as a mean value, of the second moment as a variance, of the third moment as statistical skewness and of the fourth moment as kurtosis or curvature.

A local increase in temperature, which is directly linked to laser intensity and causes non-uniform distribution of the temperature in the liquid, is obtained by irradiating light energy, especially laser energy, into the liquid. The effect of a thermal lens is thus induced, which influences the light beam and therefore modifies the intensity or power profile absorbed by the array of detectors. The temperature distribution changes with the flow of the liquid and, accordingly, so does the profile of the received light power. This change in conjunction with the laser control is used to determine flow properties of the flowing liquid.

If the liquid is not flowing, the intensity or power profile of the received radiation is symmetrical and the effect of the thermal lens consists of a decrease in the width of the intensity profile (however the laser beam could be widened depending on the physical configuration of the system and the laser focus). The temperature profile is no longer symmetrical if the liquid flows.

As shown in Fig 5, this results in a different laser intensity distribution from the position with a liquid at rest and is not symmetrical. These deviations are used in accordance with the invention in order to determine characteristics or properties of the liquid flow, e.g. flow rate or volume flow rate, flow velocity and flow rate being directly connected via the diameter of the tube.

In the case of pulse modulation of the laser, measurements are taken during a pulse and the signals received are processed. The duration and frequency of the pulse are preferably adapted to the time constants of the system. These constants depend upon the physical configuration of the system, such as the distance between the parts, the focus of the laser beam and the region of the flow rate to be determined. Since the temperature increases when the laser is switched on, the received profile of power or intensity of the laser beam changes over time. This change depends on the velocity of the fluid within the system and therefore on the flow rate. It was noticed that the change in the mean position or in the position mean value of the laser intensity distribution and the magnitude thereof (standard deviation) are related to the flow velocity. Accordingly, the (local) mean value and the standard deviation of the received light intensity may be determined in a conventional manner due to the light intensity received by the individual detector elements of the array of detectors, which detector elements are positioned one after another in the direction of the flow.

As can be seen in Fig. 6.1 and 6.2, these show an exponential decay and similar time response. Moments of higher order, i.e. skewness and kurtosis can also be determined and

are likewise related to the flow rate. Values of this type form an example of a projection of received data on a data subspace whereby different contributions can be separated
 435 into signals and the flow rate can thus be determined in an improved manner.

As can be seen in the drawings, the mean value can for example be approached by a model, such as $\mu(t) \cong \alpha_0 + \alpha \cdot e^{-t/\tau}$
 440 or $\mu(t) = \gamma + \sum \beta_i \tanh(\alpha_i t)$, the last model showing a better convergence and sensitivity being reduced compared to the initial conditions with respect to the exponential model.

The parameters of the formulae in the models have to be
 445 adapted to the flow rates, it being possible to draw on both linear and non-linear models.

The algorithm developed for a pulsed laser excitation suggests an exponential response of the system. In filter theory a response of this type corresponds to an auto-regressive first-order model. It was ascertained that the
 450 time constants of the exponential model, which shows the development of the mean value position, is closely related to the flow rate. Working on the assumption that the system responds as an auto-regressive first-order filter, the
 455 phase of the response will vary with the flow rate. It is therefore also possible to determine the flow rate if the initial laser power is changed with a cosine function and the phase shift is determined between the received mean laser power position (or moments of higher order) and the
 460 modulated initial signal. Problems can occur if the flow of liquid pumped through a pump is determined and the pump frequency lies close to the modulation frequency. This can be resolved by modulating the laser with two different fre-

465 quencies and determining the flow rate from both of them,
the received signal being filtered around each frequency.
Another solution may consist of detecting the interfering
interactions and changing the modulation frequency. Addi-
tionally, the different modes of vibration within the sen-
470 sor can be separated by means of a principle component ana-
lysis (PCA).

Fig. 7 shows the change in phase shift with velocity.

475 It is advantageous to use numerous modulation frequencies
to modulate the laser, it being possible therefore to
enlarge the range of the flow rates to be controlled. For
example the resolution is better at low flow rates of typi-
cally 0 to 6 ml/min (and an inner tube diameter of 4mm) at
480 a low modulation frequency of, for example, 10Hz, while the
measuring range can be expanded up to 25ml/min with a
higher modulation frequency of, for example, 80Hz.

Whilst with a pulsed laser the temporal information of the
485 received signals are taken into consideration to determine
the flow rate, with modulation of the initial intensity of
the laser both the temporal and frequency response at se-
lected frequencies are taken into consideration. In order
to utilise the entire time-frequency range, the noise to
490 control the laser can be taken into consideration stochas-
tically (e.g. white noise, filtered if necessary). A fur-
ther frequency range may thus be covered. By determining
the system's response and therefore the transfer function,
a connection can be drawn between this function and the
495 flow rate.

List of Reference Numerals

- | | | |
|-----|----------|---------------------------|
| 685 | 1. | Apparatus |
| | 2. | Optical arrangement |
| | 2.1. | Tube |
| | 2.1.1. | Walls |
| | 2.2. | Laser |
| 690 | 2.3. | Optical beam |
| | 2.3.1. | Heating beam |
| | 2.4. | Lens |
| | 2.5. | Array of Detectors |
| | 2.6. | Lens |
| 695 | 2.7. | Lens |
| | 2.8. | Radiation or Light Source |
| | 2.9. | Converging Lens |
| | 2.10. | Heating Beam |
| | 2.11. | Mirror |
| 700 | 3. | Laser Electronic System |
| | 3.1. | Modulator |
| | 3.2. | Laser Driver |
| | 4. | Amplifier Arrangement |
| | 4.1. | Amplifier |
| 705 | 5. | Evaluation Device |
| | 5.1. | A/D Converter |
| | 5.2. | Digital Processor |
| | 6. | Interface Arrangement |
| | 7. | Power Supply |
| 710 | 8. | Liquid |
| | 9.1, 9.2 | Control Lines |

Claims

- 500 1. Method for determining the flow of a flowing liquid
- the liquid being heated by means of an optical heating beam,
 - the heating location being irradiated by an optical
 - 505 detection beam,
- characterised in that
- the optical axes of the heating and detection beams
 - 510 coincide at least at the heating location, and
 - the detection beam is absorbed by an array of detectors, and
 - 515 - at least the statistical moment of the variance is determined.
- 520 2. Method according to claim 1, characterised in that the heating and detector beams are emitted from the same radiation source.
- 525 3. Method according to claim 1, characterised in that the heating and detector beams are emitted from different radiation sources.
4. Method according to any one of claims 1 to 3, characterised in that the detection beam has a greater mean diameter than the heating beam.

- 530 5. Method according to any one of the preceding claims,
characterised in that the optical beam or the laser
beams is/are focused on a region inside the liquid.
- 535 6. Method according to any one of claims 1 to 4, charac-
terised in that the one or more beams irradiating the
liquid are parallel beams.
- 540 7. Method according to any one of the preceding claims,
characterised in that the one or more beams are modu-
lated optical beams.
- 545 8. Method according to any one of the preceding claims,
characterised in that multiple temporally sequential
measurements are taken by the array of detectors.
- 550 9. Method according to claims 7 and 8 characterised, in
that multiple temporally sequential measurements are
taken during a light pulse in order to determine the
temporal development of the refractive index of the
heating region in the liquid.
- 555 10. Method according to any one of the preceding
claims, characterised in that the detection is carried
out by means of a linear array of detectors.
- 560 11. Method according to any one of claims 1 to 9,
characterised in that the detection is carried out by
means of a planar (two-dimensional) array of detec-
tors.

12. Method according to any one of the preceding claims, characterised in that the flow rate is determined from a received profile of the optical beam.
- 565 13. Method according to any one of the preceding claims, characterised in that the flow velocity of the liquid is determined by determining the decrease in statistical moments.
- 570 14. Method according to any one of the preceding claims, characterised in that statistical moments of the received signals are determined, such as mean value, variance and/or kurtosis.
- 575 15. Method according to claim 14, characterised in that the shift in the mean value of the position of the optical beam is determined as a measure for the flow rate.
- 580 16. Method according to either claim 14 or claim 15, characterised in that the modification of the variance of the optical beam is determined with the flow rate.
- 585 17. Method according to any one of claims 1 to 16 characterised in that the intensity of the optical beam is modulated and the phase shift of the modulation and of the measurement is determined.
- 590 18. Method according to claim 17, characterised in that the optical beam is modulated with numerous frequencies.

19. Method according to either claim 17 or claim 18, characterised in that the optical beam is stochastically modulated.
- 595
20. Apparatus for determining the flow rate of a liquid, comprising a tube (2.1), which is flowed through by a liquid (8) and has a wall (2.1.1), which is transparent, at least in part, for a measuring radiation, and comprising a device for heating at least a region inside the liquid (8), a laser (2.2) for producing a measuring radiation and an electronic evaluation device (5), characterised in that the device for heating a defined inner region of the liquid (8) and an optical arrangement (2.4, 2.6) guiding the beam (2.3) of the laser (2.2) are positioned in such a way that a measuring beam (2.3) irradiates the heated region at the absolute location of heating thereof, in that an array of detectors (2.5) is provided for receiving the measuring radiation, and in that the evaluation device is configured for determining at least the statistical moment of the variance.
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21. Apparatus according to claim 20, characterised in that the device for heating the flowing liquid is a laser (2.2).
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22. Apparatus according to either claim 20 or claim 21, characterised in that the laser (2.2), which produces the measuring beam (2.3), is the device for heating the liquid.
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23. Apparatus according to claim 22, characterised in that the optical arrangement (2.4, 2.6) is such that
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the optical beam (2.3) ²¹ is not split when transmitted through the liquid (8).

630 24. Apparatus according to any one of claims 20 to 23, characterised by a focusing lens (2.6) for focusing the laser beam inside the liquid flow (8).

635 25. Apparatus according to any one of claims 20 to 23, characterised by a lens (2.4) for parallelising and irradiating the liquid (8) by means of a parallel beam.

640 26. Apparatus according to any one of claims 20 to 25 characterised in that the one or more lasers (2.2) are modulated lasers.

645 27. Apparatus according to any one of claims 20 to 26, characterised in that it is configured for taking multiple temporally sequential measurements.

650 28. Apparatus according to claims 26 and 27 characterised in that it is configured for taking multiple temporally sequential measurements during a laser pulse.

29. Apparatus according to any one of claims 20 to 28, characterised in that the array of detectors (2.5) is a linear array of detectors.

655 30. Apparatus according to any one of claims 20 to 28, characterised in that the array of detectors (2.5) is planar/two-dimensional.

31. Apparatus according to any one of claims 20 to
660 30, characterised in that the evaluation device is
configured for determining statistical moments of the
received signals, such as mean value, variance, sta-
tistical skewness and/or kurtosis.