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(54) Title: ULTRASONIC FLOW SENSOR AND THERMAL ENERGY SENSOR WITH NON-INVASIVE IDENTIFICATION OF NO-FLOW AND IMPROVED ACCURACY

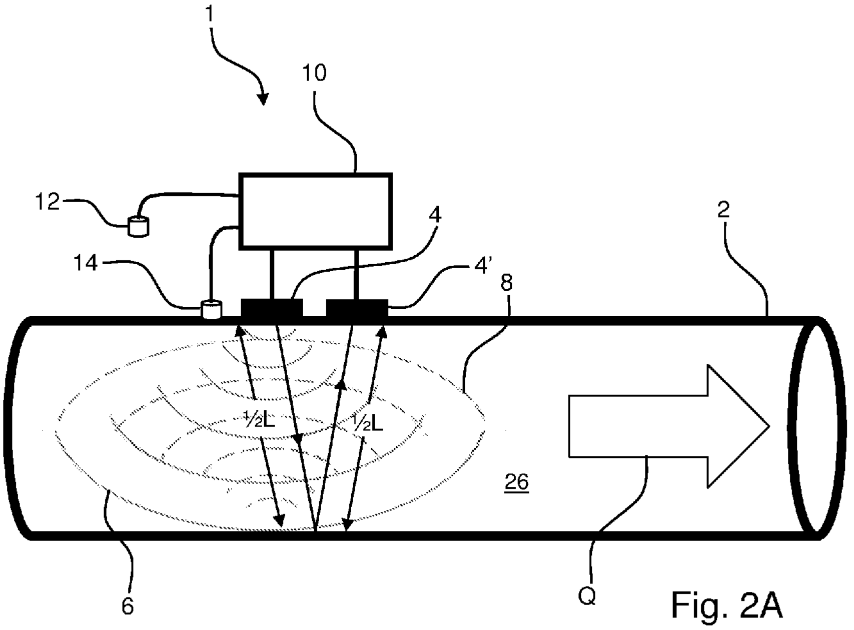

Fig. 2A

(57) **Abstract:** 1. An ultrasonic flow sensor (1) configured to measure the flow (Q) of a fluid (26) flowing through a tubular structure (2) Is disclosed. The flow sensor (1) comprises - a first detection unit (34) arranged to transmit and receive ultrasonic waves (6, 8) by using at least one ultrasonic transducer (4, 4'); - a temperature sensor (14) arranged and configured to detect the temperature (T_f) of the fluid (26); - a temperature sensor (12) arranged and configured to detect the temperature (T_s) of the surroundings (the ambient temperature); - a data processor (10) configured to receive data detected by the at least one ultrasonic transducer (4, 4') and the temperature sensors (12, 14). The flow sensor (1) is configured to: - determine the time-of-flight (t, t_1, t_2)

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of the ultrasonic waves (6, 8) and calculate a change in the speed of sound on the basis of the time-of-flight (t, t_1, t_2); - calculate the expected change in speed of sound (c) as function of the detected temperature (T_f) of the fluid (26) and - determine if the expected change in speed of sound (c) corresponds to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2); - identify a no-flow state, in which there is no flow of the fluid (26) when the following criteria are meet: A) the expected change in speed of sound (c) corresponds to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), and B) the temperature difference (ΔT_{sf}) between the surroundings and the fluid (26) is below a predefined level which is pre-set at a fixed level between 0.01 degree Celsius and 0.5 degree Celsius.

Ultrasonic Flow Sensor and Thermal Energy Sensor with Non-Invasive Identification of No-Flow and Improved Accuracy

Field of invention

The present invention relates to ultrasonic flow sensors in general and in particular to clamp-on ultrasonic flow sensors. The present invention also relates to thermal energy meters using an ultrasonic flow sensor and to clamp-on ultrasonic thermal energy meters.

Prior art

Flow measurement is widespread used for measuring flow in industry, buildings and utility grids. Flow can be detected by using various types of flow sensors. The prior art flow sensors include mechanical flow sensors and ultrasonic flow sensors. Ultrasonic flow sensors are mainly used in two versions, namely delta-time-of-flight for measuring on pure fluids (water, gas, industry liquids, etc.) and Doppler effect for measuring fluids containing many particles (slurry, liquids with air bubbles, etc.).

In state-of-the-art ultrasonic flow measurement, there are known limitations which limit the use of the technology. One of these limitations is that it is difficult to detect no-flow (the fluid stands still in the pipe), which is needed to identify the off-set of the sensor.

Even though prior art ultrasonic flow sensors normally are reliable and accurate, it would be advantageous to improve the measurement the accuracy. Moreover, it would be an advantage to provide an ultrasonic thermal energy meter having an improved accuracy.

It is an object of the invention is to provide a method and an ultrasonic flow sensor that can provide a detection of no-flow. It is also an object of the invention to provide method and an ultrasonic flow sensor that is capable of providing a higher accuracy than the solutions known in the prior art. It is also an object of the invention is to provide an ultrasonic thermal energy meter that has a higher accuracy than the known ultrasonic thermal energy meter.

Summary of the invention

The object of the present invention can be achieved by an ultrasonic flow sensor as defined in claim 1 and by a method as defined in claim 19. Preferred embodiments are defined in the dependent subclaims, explained in the following description and illustrated in the accompanying drawings.

The flow sensor according to the invention is an ultrasonic flow sensor configured to measure the flow of a fluid flowing through a tubular structure, said flow sensor comprising:

- a first detection unit arranged to transmit and receive ultrasonic waves by using at least one ultrasonic transducer;
- a temperature sensor arranged and configured to detect the temperature of the fluid;
- a temperature sensor arranged and configured to detect the temperature of the surroundings (the ambient temperature);
- a data processor configured to receive data detected by the at least one ultrasonic transducer and the temperature sensors,

wherein the flow sensor is configured to:

- determine the time-of-flight of the ultrasonic waves and calculate a change in the speed of sound on the basis of the time-of-flight;
- calculate the expected change in speed of sound as function of the detected temperature of the fluid and
- determine if the expected change in speed of sound corresponds to the change in speed of sound calculated on the basis of the time-of-flight;
- identify a no-flow state, in which there is no flow of the fluid when the following criteria are meet:

A) the expected change in speed of sound corresponds to the change in speed of sound calculated on the basis of the time-of-flight, and

B) the temperature difference between the surroundings and the fluid is below a predefined level which is pre-set at a fixed level between 0.01 degree Celsius and 0.5 degree Celsius.

Hereby, it is possible to provide a detection of no-flow. Accordingly, the off-set of the flow sensor can be identified.

The tubular structure may be a pipe or another structure, through which the fluid is flowing. In one embodiment, the tubular structure is a pipe. In one embodiment, the tubular structure is a hose. In an embodiment, the tubular structure is a container. In one embodiment, the tubular structure is a box.

The flow sensor according to the invention is a flow sensor configured to measure the flow of a fluid. In one embodiment, the fluid is a liquid. In one embodiment, the fluid is a water-containing liquid. In an embodiment, the fluid is a gas.

The data processor may be a micro-processor.

In an embodiment, the no-flow state, is used to calibrate the ultrasonic flow measurement calculation(s) of the flow sensor, to ensure stability and correct ultrasonic flow measurement of the flow sensor.

In an embodiment, the ultrasonic flow sensor is configured to calculate a corrected value of the change in the density of the fluid on the basis of the change in speed of sound calculated on the basis of the time-of-flight, if the expected speed of sound does not correspond to the change in speed of sound calculated on the basis of the time-of-flight. Hereby, it is possible to provide an ultrasonic flow sensor that is capable of providing a higher accuracy than the solutions known in the prior art.

In an embodiment, the ultrasonic flow sensor is configured to calculate a corrected value of the specific heat capacity of the fluid on the basis of the corrected value of the density, if the expected change in speed of sound does not correspond to the change in speed of sound calculated on the basis of the time-of-flight. Hereby, it is possible to provide an ultrasonic flow sensor that is capable of providing a higher accuracy than the solutions known in the prior art.

In an embodiment, the ultrasonic flow sensor is configured to calculate a corrected value of the flow of the fluid on the basis of the change in speed of sound calculated on the basis of the time-of-flight, if the expected change in speed of sound does not correspond to the change in speed of sound calculated on the basis of the time-of-flight. Hereby, it is possible to provide an ultrasonic flow sensor that is capable of providing a higher accuracy than the solutions known in the prior art.

In an embodiment, the first detection unit is configured to detect flows above a predefined lower flow level representing the lower flow that can be measured by using the first detection unit, wherein the flow sensor comprises a second detection unit that comprises:

- a first temperature sensor arranged and configured to detect the temperature of the surroundings (the ambient temperature);
- a data processor connected to the temperature sensors,

wherein the second detection unit is configured to estimate the flow below the lower flow level on the basis of the temperature difference between the surroundings and a fluid, wherein the temperature difference between is measured by the first temperature sensor and the second temperature sensor, wherein the second detection unit is configured to estimate the flow below the lower flow level on the basis of one or more measurements made in a flow-calibration-area, in which flow-calibration-area the flow sensor can detect the flow that depends on the temperature difference, wherein the one or more measurements made in the flow-calibration-area are used to determine one or more parameters required to determine how the flow depends on the temperature difference in the flow-calibration-area and in the flow area below the flow-calibration-area.

Hereby, it is possible to provide a sensor that can detect flows in a larger flow range than the prior art flow sensors. The flow sensor according to the invention can in particular detect flows below the lower flow level.

In an embodiment, the second detection unit is configured to estimate the flow below the lower flow level on the basis of a single measurement and predefined data that includes the density and the specific heat capacity of the fluid.

In one embodiment, the second detection unit is configured to estimate the flow below the lower flow level on the basis of two single measurement.

Hereby, it is possible to use the two measurements to fit a curve describing the relationship between the flow and the temperature difference.

This can be done because the curve has a known shape (this follows by the relationship defined by equation (1) and equation (6) as shown in and explained with reference to Fig. 8).

In an embodiment, the second detection unit is configured to estimate the flow below the lower flow level on the basis of two or more measurements made in a flow-calibration-area.

In an embodiment, the flow sensor is configured to regularly or continuously:

- carry out the one or more measurements in a flow-calibration-area and
- update the more parameters required to determine how the flow depends on the temperature difference in the flow-calibration-area and in the flow area below the flow-calibration-area.

Hereby, it is possible to provide reliable flow measurements and on a regularly basis adjust the parameters according to changes of the ambient conditions (e.g. an increased ventilation). The flow sensor is configured to automatically perform a required number of measurements in the flow-calibration-area and calculate and update the more parameters required to determine how the flow depends on the temperature difference in the flow-calibration-area and in the flow area below the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every second, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every 5 seconds, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every 10 seconds, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every 30 seconds, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every minute, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every 2 minutes, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every 5 minutes, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term “regularly or continuously” has to be understood as once every 15 minutes, in which attempts are made to provide one or more measurements in the flow-calibration-area.
In one embodiment, the term “regularly or continuously” has to be understood as once every 30 minutes, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In one embodiment, the term "regularly or continuously" has to be understood as once every hour, in which attempts are made to provide one or more measurements in the flow-calibration-area.

In an embodiment, the dependency between the flow (Q) and the temperature difference (ΔT_{sf}) is defined by of the following equations:

$$\Delta T_{sf}(Q) = \Delta T_B\left(1 - e^{-C_1 Q}\right) \quad \text{or} \quad Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right)$$

where C_1 is a constant and ΔT_B is a temperature difference corresponding to a base flow level. In Fig. 8, the base flow level Q_B is illustrated.

These equations have two unknowns:

- The temperature difference ΔT_B corresponding to the base flow level Q_B and
- The constant C_1.

Accordingly, two measurements made in the flow-calibration-area provides sufficient information to determine the dependency between the flow (Q) and the temperature difference (ΔT_{sf}).

In an embodiment, a (second) temperature sensor is arranged and configured to detect the temperature of the fluid by measuring a temperature at the outside of the tubular structure. Hereby it is possible to provide the flow sensor as a clamp-on type flow sensor that can be mounted on the outside of the tubular structure (e.g. a pipe). Accordingly, there is no need for bringing the second temperature sensor into direct contact with the fluid.

In an embodiment, the data processor and a (second) temperature sensor are arranged inside a housing. Hereby, it is possible to provide a simple, easy mountable and robust flow sensor.

In an embodiment, the (first) temperature sensor is arranged in the housing. Hereby, all components of the flow sensor can be provided in a single housing.

In an embedment, the (first) temperature sensor is arranged outside the housing. Hereby, it is possible to take into consideration the heat transfer caused by convection.

In an embodiment, the second detection unit comprises an intermediate temperature sensor arranged and configured to detect an intermediate temperature of a position inside the housing, wherein said position is expected to have a temperature between the ambient temperature and the temperature of the fluid. Hereby, it is possible to provide additional information and thus provide an improved estimation of the flow in the low flow range.

In one embodiment, the flow sensor is a clamp-on flow sensor configured to measure the flow of the fluid from outside the tubular structure.

The flow sensor is an ultrasonic flow sensor and the first detection unit comprises at least one ultrasonic transducer arranged to transmit ultrasonic waves and least one ultrasonic transducer arranged to receive ultrasonic waves.

In one embodiment, the flow sensor is configured to automatically calculate the distance L that the transmitted ultrasonic waves and receive ultrasonic waves travel in the fluid on the basis of a detected value of the speed of sound c. Hereby, it is possible to measure the flow in a pipe without knowing the exact dimensions of the pipe. It is also possible to perform accurate measurements, even if sediments are provided at inside surface of a pipe over time.

The thermal energy meter according to the invention comprises a flow sensor according to the invention.

In an embodiment, the second detection unit is integrated in the first detection unit. In an embodiment, the second detection unit and the first detection unit are provided as separated units.

In one embodiment, second detection unit is communicatively connected to a storage or an external device containing information about how the flow depends on the temperature difference, wherein the data processor is configured to access and use said information in such a manner that the data processor can determine the flow on the basis of the temperature difference.

The method according to the invention is a method for measuring the flow of a fluid flowing through a tubular structure by means of an ultrasonic flow sensor comprising a first detection unit provided with:
- at least one ultrasonic transducer arranged to transmit and receive ultrasonic waves by using at least one ultrasonic transducer, wherein the ultrasonic flow sensor comprises a temperature sensor arranged and configured to detect the temperature of the fluid,

wherein the method comprises the following steps:
- determining the time-of-flight of the ultrasonic waves;
- calculating a change in the speed of sound on the basis of the time-of-flight;
- calculating the expected change in speed of sound as function of the detected temperature of the fluid and
- determining if the expected change in speed of sound corresponds to the change in speed of sound calculated on the basis of the time-of-flight;
- identifying a no-flow state, in which there is no flow of the fluid when the following criteria are meet:
  A) the expected change in speed of sound corresponds to the change in speed of sound calculated on the basis of the time-of-flight, and
  B) the temperature difference between the surroundings and the fluid is below a predefined level which is pre-set at a fixed level between 0.01 degree Celsius and 0.5 degree Celsius.

Hereby, it is possible to provide a detection of no-flow. Accordingly, the off-set can be identified.

In an embodiment, the no-flow state, is used to calibrate the ultrasonics flow measurement calculation of the said flow sensor, to ensure stability and correct ultrasonic flow measurement of the flow sensor.

In one embodiment, the ultrasonic flow sensor is configured to calculate a corrected value of the change in the density of the fluid on the basis of the change in speed of sound calculated on the basis of the time-of-flight, if the expected speed of sound does not correspond to the change in speed of sound calculated on the basis of the time-of-flight. Hereby, it is possible to improve the flow measurement accuracy.

Hereby, it is possible to determine a corrected value of the density of the fluid and hereby provide more accurate measurements.

In an embodiment, the method comprises the step of calculating a corrected value of the specific heat capacity of the fluid on the basis of the corrected value of the density, if the expected change in speed of sound does not correspond to the change in speed of sound calculated on the basis of the time-of-flight. Hereby, it is possible to provide measurements with an improved accuracy.

In one embodiment, the method comprises the step of calculating a corrected value of the flow of the fluid on the basis of the change in speed of sound calculated on the basis of the time-of-flight, if the expected change in speed of sound does not correspond to the change in speed of sound calculated on the basis of the time-of-flight. Hereby, it is possible to improve the flow measurement accuracy.
In an embodiment, the first detection unit is configured to detect flows above a predefined lower flow level representing the lowest flow that can be measured by using the first detection unit, wherein the method comprises the steps of applying a second detection unit to:

- detect the temperature of the surroundings (the ambient temperature) by means of a temperature sensor;
- detect the temperature of the fluid by means of a temperature sensor arranged and configured to detect the temperature of the fluid;
- estimating the flow below the lower flow level on the basis of the

temperature difference between the surroundings and a fluid measured by the temperature sensors,

wherein the method comprises the following steps:

a) performing one or more flow measurements by means of the first detection unit in a flow-calibration-area, in which flow-calibration-area the flow sensor can detect the flow that depends on the temperature difference;

b) applying the one or more measurements made in the flow-calibration-area to determine one or more parameters required to determine how the flow depends on the temperature difference in the flow-calibration-area and in the flow area below the flow-calibration-area and

c) estimating the flow below the lower flow level on the basis of the one or more measurements made in the flow-calibration-area.

Hereby, it is possible to detect lower flows than in the prior art.

In an embodiment, the method comprises the step of performing two or more flow measurements in the flow-calibration-area.

In an embodiment, the method comprises the step of regularly or continuously:

- carrying out the one or more measurements in a flow-calibration-area and
- updating the more parameters required to determine how the flow depends on the temperature difference in the flow-calibration-area and in the flow area below the flow-calibration-area.

In one embodiment, the dependency between the flow (Q) and the temperature difference (ΔT_{sf}) is defined by of the following equations:

$$\Delta T_{sf}(Q) = \Delta T_B\left(1 - e^{-C_1 Q}\right) \quad \text{or} \quad Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right)$$

where C_1 is a constant and ΔT_B is a temperature difference corresponding to a base flow level.

In an embodiment, the temperature of the fluid is measured by a temperature sensor arranged at the outside of the tubular structure.

In an embodiment, the method comprises the step of detecting an intermediate temperature by means of an intermediate temperature sensor arranged in a position inside a housing, wherein the housing houses the temperature sensor that is used to detect the temperature of the fluid and the intermediate temperature sensor, wherein the intermediate temperature is expected to have a value between the ambient temperature and the temperature of the fluid.

In an embodiment, the method comprises the steps of measuring the density and/or the estimated inhomogeneity of the fluid prior to measuring the flow.

Hereby, it is possible to improve the flow measurements and take into account the density and/or inhomogeneity of the fluid.

In one embodiment, the method comprises the step of calculating a corrected value of the specific heat capacity of the fluid if the detected value of the speed of sound c does not correspond to the expected speed of sound c as function of the detected temperature of the fluid. Hereby, it is possible to apply the flow sensor to provide a heat energy meter having an improved accuracy. Using a corrected value of the specific heat capacity of the fluid will ensure that the heat energy meter delivers the most accurate measurements.

In one embodiment, the method is carried out by using a clamp-on flow sensor configured to measure the flow of the fluid from outside the tubular structure.

In one embodiment, the method comprises the step of automatically calculating the distance L that the transmitted ultrasonic waves and receive ultrasonic waves travel in the fluid on the basis of a detected value of the speed of sound c (and optionally the measured time of flight). Hereby, it is possible to measure the flow in a pipe without knowing the exact dimensions of the pipe. It is also possible to perform accurate measurements, even if sediments are provided at inside surface of a pipe over time.

The method for measuring the thermal energy of a fluid, applies a method according to the invention to detect the flow of the fluid.

The flow sensor according to the invention is a flow sensor configured to measure the flow of a fluid. In one embodiment, the fluid is a liquid. In one embodiment, the fluid is a water-containing liquid. In one embodiment, the fluid is a gas.

The fluid is flowing through a tubular structure. In one embodiment, the tubular structure is a pipe. In one embodiment, the tubular structure is a hose. In one embodiment, the tubular structure is a container. In one embodiment, the tubular structure is a box.

The first detection unit may a structure of a positive displacement meter that requires fluid to mechanically displace components of the mechanical flow detection unit in order to provide flow measurements. In one embodiment, the first detection unit is a turbine. In one embodiment, the first detection unit is an impeller.

The first detection unit may a structure of an ultrasonic flow sensor. In one embodiment, the first detection unit comprises one or more ultrasonic transducers. In one embodiment, the first detection unit comprises one or more ultrasonic transmitters and one or more ultrasonic receivers.

The data processor may be a micro-processor.

In one embodiment, the second detection unit contains a storage containing information about how the flow depends on the temperature difference, wherein the data processor is configured to access and use said information in such a manner that the data processor can determine the flow on the basis of the temperature difference. In the flow range below the lower flow level, the second detection unit can detect the flow on the basis of the temperature difference value. This can be accomplished, when the relationship between the flow and the temperature difference is known and stored in the storage.

The expected speed of sound depends on the detected temperature of the fluid) and can be calculated by using a predefined relationship between the speed of sound as function of the temperature of the fluid. If the fluid is pure water, by way of example, the relationship between the expected speed of sound as function of the detected temperature of the fluid would be defined as illustrated in Fig. 7.

If the fluid is different from pure water (e.g. water containing salt, sugar or another substance), a different predefined relationship between the expected speed of sound as function of the detected temperature of the fluid can be used.

The expected speed of sound can be compared with a detected value of the speed of sound simply by detecting the speed of sound and making the comparison. The detection can be carried out by using the following formular (16):

(16) $c=\frac{L}{2}\frac{t_2+t_1}{t_2t_1}$ where c is the sound of speed, L is the distance the sound signal travels and t_1 and t_2 are the transit time for the sound signal transmitted and reflected, respectively.

The corrected value of the density and the flow is calculated if the detected value of the speed of sound does not correspond to the expected speed of sound. The corrected value of the density can be calculated by using the following equation (18):

(18) $c=\sqrt{\frac{K}{\rho}} \Rightarrow \rho=\sqrt{\frac{K^2}{c^2}}$, where K is the Bulk Modulus of Elasticity of the fluid and ρ is the density of the fluid.

In one embodiment, the flow sensor is configured to calculate a corrected value of the specific heat capacity of the fluid if the detected value of the speed of sound c does not correspond to the expected speed of sound c as function of the detected temperature of the fluid. Hereby, it is possible to apply the flow sensor to provide a heat energy meter having an improved accuracy. Using a corrected value of the specific heat capacity of the fluid will ensure that the heat energy meter delivers the most accurate measurements.

In one embodiment, the fluid is a liquid. In one embodiment, the fluid is a water-containing liquid. In one embodiment, the fluid is a gas.

In one embodiment, the method comprises the following steps:

- storing information about how the flow depends on the temperature difference;
- using said information to determine the flow on the basis of the temperature difference.

Hereby, the stored information can be used to provide a flow estimation in a simple and reliable manner. The information may be stored in an external device. In one embodiment, the information is stored in a web-based service.

In one embodiment, the method comprises the following steps:

- storing in the second detection unit information about how the flow depends on the temperature difference;
- using said information to determine the flow on the basis of the temperature difference.

Hereby, the stored information can be used to provide a flow estimation in a simple and reliable manner.
In one embodiment, the method is carried out by means of a flow sensor comprising a data processor, wherein the data processor and the second temperature sensor are arranged inside a housing.

In one embodiment, the method is carried out by using a flow sensor, in which the first temperature sensor is arranged in the housing.

In one embodiment, the method is carried out by using a flow sensor, in which the first temperature sensor is arranged outside the housing.

In one embodiment, the method comprises the following steps:
- performing one or more measurements on a sample of the fluid;
- applying the one or more measurements to calculate the density and/or estimated inhomogeneity of the fluid prior to measuring the flow.

In one embodiment, the estimated inhomogeneity of the fluid corresponds to the content of one or more substrates in the fluid. The substrate may one of the following more substances: sugar, salt, ethylene glycol, glycerol or propylene glycol.

Description of the drawings

The invention will become more fully understood from the detailed description given herein below. The accompanying drawings are given by way of illustration only, and thus, they are not limitative of the present invention. In the accompanying drawings:

Fig. 1A	shows a graph depicting the temperature difference between the surroundings and a fluid flowing through a pipe as function of the fluid flow through the pipe;
Fig. 1B	shows the low flow portion of the graph shown in Fig. 1A;
Fig. 2A	shows a schematic view of a clamp-on type flow sensor according to the invention;
Fig. 2B	shows a schematic view of another clamp-on type flow sensor according to the invention;
Fig. 3A	shows a schematic view of a flow sensor according to the invention;
Fig. 3B	shows a schematic view of another flow sensor according to the invention;
Fig. 4A	shows a schematic view of a clamp-on type flow sensor according to the invention mounted on the outside of a pipe;
Fig. 4B	shows a schematic view of another flow sensor according to the invention;
Fig. 5A	shows a schematic view of a flow sensor according to the

	invention;
Fig. 5B	shows a schematic view of another flow sensor according to the invention;
Fig. 6A	shows a schematic view of a flow sensor according to the invention;
Fig. 6B	shows a schematic view of another flow sensor according to the invention;
Fig. 7	shows a graph depicting the speed of sound in water as function of the temperature of the water and
Fig. 8	shows the flow as function of the temperature difference.

Detailed description of the invention

Referring now in detail to the drawings for the purpose of illustrating preferred embodiments of the present invention, a graph 28 depicting the temperature difference ΔT_{sf} between the surroundings and a fluid flowing through a pipe as function of the fluid flow Q through the pipe is illustrated in Fig. 1A.

It can be seen that the graph 28 (indicated with a solid line) extends above a lower flow level Q_A. The lower flow level Q_A represents the lowest flow that can be measured by using prior art flow sensors. Below this lower flow level Q_A, the graph 28, however, has been extrapolated. This lower area 30 is indicated with a dotted ellipse.

Fig. 1B illustrates the low flow portion 30 of the graph 28 shown in Fig. 1A. While the prior art flow sensors are not capable of detecting flow below the lower flow level Q_A, the flow sensor and method according to the invention is capable of providing flow measurements below this lower flow level Q_A.

Above a base flow level Q_B the graph 28 shows that the temperature difference ΔT_{sf} is constant and thus independent of the flow Q.

In the flow-calibration-area B_2 between the lower flow level Q_A and the base flow level Q_B the temperature difference ΔT_{sf} increases as function of the flow Q. In this flow-calibration-area B_2, a first flow sensor measurement M_1 and a second flow sensor measurement M_2 are indicated.

It is possible to use one or more of the flow sensor measurements made in the flow-calibration-area B_2 to determine the parameters required to determine how the flow Q depends on the temperature difference ΔT_{sf} in the flow-calibration-area B_2 and in the flow area B_1 below the flow-calibration-area B_2.

The temperature difference ΔT_{sf} as function of the flow Q is given by the following equation (1)

(1) $$\Delta T_{sf}(Q) = \Delta T_B\left(1 - e^{-C_1 Q}\right)$$

where ΔT_B is a temperature difference corresponding to the base flow level Q_B and C_1 is a constant.

By performing two measurements M_1 and M_2, it is possible to determine the two unknown ΔT_B and C_1 from equation (1).

Therefore, it is possible to determine a flow Q_{M3} in the flow area B_1, in which the flow sensor cannot provide any measurements. The flow Q_{M3} can be determined on the basis of a measured temperature difference ΔT_{M3} detected by the flow sensor. The flow Q_{M3} can be determined by using equation (1) or the following equation (2) defining the flow Q as function of the detected temperature difference ΔT_{sf}:

(2) $$Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right)$$

where C_1 is a constant and ΔT_B is a temperature difference corresponding to the base flow level Q_B.

The flow sensor and method according to the invention estimates flows Q below the lower flow level Q_A by measuring the temperature difference ΔT_{sf} between the surroundings and a fluid flowing through the pipe. The estimation is possible because one or more flow measurements M_1, M_2 made in the flow-calibration-area B_2 are used to determine the unknown in equation (1) or equation (2). Accordingly, any flow Q in the flow area B_1 can be calculated by using equation (2).

In Fig. 1B it can be seen that a first flow Q_1 is detected on the basis of a first measured temperature difference ΔT_1. Likewise, Fig. 1B shows that a second flow Q_2 is detected on the basis of a second measured temperature difference ΔT_2.

The lower flow level Q_A corresponds to a measured temperature difference ΔT_A. Likewise, the base flow level Q_B corresponds to a higher measured temperature difference ΔT_B.

The temperature difference can be detected by using temperature sensors of the sensor according to the invention. This shown in and explained with reference to Fig. 2A, Fig. 2B, Fig. 3A, Fig. 3B and Fig. 4B.

In one example, in the flow-calibration-area B_2 , a flow sensor according to the invention used to measure water at 20°C is applied to make a measurement point M_2 corresponds to a flow Q_{M2} of 2 ml/s (which is 0.000002 m^3/s) and a temperature difference ΔT_{M2} of 10°C.

relationship between the temperature difference ΔT_{sf} between the surroundings and the fluid and the flow Q is given by equation (2):

$$Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{dt_B}\right) \tag{2}$$

If $C_1 = 5.02\,\frac{min}{cm^3}$ and $dt_B = 10.02°C$ one can calculate the following values:

Table 1

ΔT_{sf} [°C]	0.980	2.224	3.652	4.446
Flow [cm^3/min]	0.020	0.050	0.116	0.572

In another example, below the lower flow level Q_A, the relationship between the temperature difference ΔT_{sf} and the flow Q is given by the equation (2), where $C_1 = 4.88\ and\ dt_B = 12.54°C$ one can calculate the following values:

Table 2

ΔT_{sf} [°C]	1.124	2.462	3.866	5.562
Flow [cm^3/min]	0.019	0.045	0.076	0.120

Fig. 2A illustrates a schematic view of a clamp-on type flow sensor 1 according to the invention. The flow sensor 1 is arranged to detect the flow of a fluid 26 (e.g. a liquid) in the pipe 2. The flow sensor 1 comprises a data processor 10.

The flow sensor 1 comprises a first temperature sensor 12 arranged to detect the ambient temperature (the temperature in the surrounding of the pipe 2. The flow sensor 1 comprises a second temperature sensor 14 arranged to detect the temperature of the fluid 26. The flow sensor 1 comprises a first ultrasonic wave generator 4 and a second and a second ultrasonic wave generator 4′. The wave generators are formed as piezo transducers 4, 4′ arranged and configured to generate ultrasonic waves, which are introduced into the fluid 26 at an angle to the direction of flow Q. The flow sensor 1 may be either a Doppler effect type flow sensor 1 or a propagation time measuring type flow sensor 1. It is indicated that both ultrasonic waves 6, 8 travel a distance ½L. Accordingly, the total distance of travel is L.

The piezo transducers 4, 4′ are operated as a transducer to detect the flow Q through a pipe by using acoustic waves 6, 8. In one embodiment, the flow sensor 1 comprises several piezo transducers 4, 4′ in order to be less dependent on the profile of the flow Q in the pipe 2. The operating frequency may depend on the application and be in the frequency range 100-200kHz for gases and in a higher MHz frequency range for liquids.

In one embodiment, the flow sensor 1 is a Doppler effect flow sensor 1. In this embodiment, the flow sensor 1 comprises a single piezo transducer only. In this case the second piezo transducer 4′ can be omitted and the first piezo transducer 4 is used both sending ultrasonic waves 6 and for receiving ultrasonic waves 8. In a Doppler effect type flow sensor 1, when the transmitted wave 6 is reflected by particles or bubbles in the fluid, its frequency is shifted due to the relative speed of the particle. The higher the flow speed of the liquid, the higher the frequency shift between the emitted and the reflected wave.

In one embodiment, the flow sensor 1 is a Doppler effect flow sensor 1 that comprises several piezo transducers 4, 4′. In this case one piezo transducer 4 can be used to transmit an ultrasonic wave 6, while the other piezo transducer 4′ can be used to receive the reflected ultrasonic wave 8.

In one embodiment, the flow sensor 1 is a propagation type flow sensor 1. In this embodiment, the flow sensor 1 applies two piezo transducers operating as both transmitter and receiver arranged diagonally to the direction of flow Q. Transmission of ultrasonic waves in the flowing medium causes a superposition of sound propagation speed and flow speed. The flow speed proportional to the reciprocal of the difference in the propagation times in the direction of the flow Q and in the opposite direction. The propagation type measuring method is independent of the sound propagation speed and thus also the medium. Accordingly, it possible to measure different liquids or gases with the same settings.

The temperature sensors 12, 14 and the piezo transducers 4, 4′ are connected to the data processor 10. Accordingly, the data processor 10 can process data from the temperature sensors 12, 14 and the piezo transducers 4, 4′ and hereby detect the flow based on the data. In the low flow

In Fig. 2A, the second temperature sensor 14 is arranged outside the pipe 2. The second temperature sensor 14 is thermally connected to the pipe 2. Accordingly, the second temperature sensor 14 is capable of measuring the temperature of the pipe 2. The temperature of the pipe 2 will normally correspond to or be very close to the temperature of the fluid 26 in the pipe 2.

In the low flow area below the lower flow level of the flow sensor 1, the flow sensor 1 determines the flow on the basis of the temperature measurements made by the first temperature sensor 12 and the second temperature sensor 14. In fact, below the lower flow level of the flow sensor 1, the flow sensor 1 determines the flow on the basis of the temperature difference ΔT_{sf} defined as the difference between the temperatures detected by the first temperature sensor 12 and the second temperature sensor 14.

(9) $\Delta T_{sf} = |T_s - T_f|$

where T_s is the temperature of the surroundings measured by the first temperature sensor 12 and T_f is the temperature of the fluid 26 measured by the second temperature sensor 14.

Fig. 2B illustrates a schematic view of a clamp-on type flow sensor 1according to the invention. The flow senor 1 shown in Fig. 2B basically corresponds to the one shown in Fig. 2A. The temperature sensor 14, however, is in contact with the fluid 26 inside the pipe 2. A structure extends through the wall of the pipe 2. The temperature sensor 14 is connected to the data processor 10 via a wire extending through said structure. It is indicated that both ultrasonic waves 6, 8 travel a distance ½L. Accordingly, the total distance of travel is L.

Fig. 3A illustrates a schematic view of a heat energy meter 5 according to the invention. The heat energy meter 5 comprises a flow sensor 1 according to the invention. The flow sensor 1 comprises a housing 20 that is attached to a pipe 2. The flow sensor 1 is arranged and configured to detect the flow Q of the fluid 26 (e.g. a water containing liquid) in the pipe 2.

The flow sensor 1 comprises a first temperature sensor 12 arranged to detect the temperature T_s of the surroundings (e.g. the ambient temperature). The flow sensor 1 comprises a second temperature sensor 14 arranged to detect the temperature T_f of the fluid 26 in the pipe 2. The flow sensor 1 comprises a third temperature sensor 16 arranged to detect an intermediate temperature T_i that is expected to have a value between the ambient temperature T_s and the temperature T_f of the fluid

26.

The flow sensor 1 comprises a first ultrasonic wave generator 4 and a second and a second ultrasonic wave generator 4′ formed as piezo transducers 4, 4′ that are arranged and configured to generate ultrasonic waves transmitted into the fluid 26 at an angle to the direction of flow Q. The piezo transducers 4, 4′ are used in the same manner as shown in and explained with reference to Fig. 2A and Fig. 2B.

The flow sensor 1 comprises a data processor 10 connected to the piezo transducers 4, 4′ and to the temperature sensors 12, 14, 16. Therefore, the data processor 10 can process data from the temperature sensors 12, 14 and the piezo transducers 4, 4′ and hereby detect the flow based on the data.

The third temperature sensor 16 arranged provides temperature measurements that can be applied to provide an improved estimation of the flow below the lower flow level of the flow sensor 1. The improved estimation can be accomplished by using two temperature differences:

- the difference ΔT_{sf} between the surroundings and the fluid 26:
  (10) $\Delta T_{sf} = |T_s - T_f|$ and
- the temperature difference ΔT_{if} between the intermediate point in the housing 20 and the fluid 26:
  (11) $\Delta T_{if} = |T_i - T_f|$

The heat energy meter 5 an external temperature sensor 17 thermally connected to a pipe 3. By measuring the temperature of the fluid in the supply pipe 3 and the temperature of the fluid 26 in the return pipe 2, it is possible to calculate the consumed heat quantity (heat energy). The external temperature sensor 17 may be connected to the data processor 10 by a wired connection as shown in Fig. 3A or by a wireless connection as shown in Fig. 3A.

Fig. 3B illustrates a schematic view of another heat energy meter 5 according to the invention. The heat energy meter 5 comprises a flow sensor 1 according to the invention. The flow sensor 1 basically corresponds to the one shown in Fig. 3A. The first temperature sensor 12, however, is placed on the outside surface of the housing 20. The heat energy meter 5 an external temperature sensor 17 that is attached to the outside surface of a supply pipe 3. Accordingly, the temperature sensor 17 is thermally connected to the supply pipe 3. By measuring the temperature of the fluid in the supply pipe 3 and the temperature of the fluid 26 in the return pipe 2, it is possible to calculate the consumed heat quantity (heat energy).

Fig. 4A illustrates a schematic view of a clamp-on type flow sensor 1 according to the invention. The flow sensor 1 is mounted on the outside of a pipe 2. The flow sensor 1 comprises a housing 20 having a contact structure that matches the outer geometry of the pipe 2. A thermal connection structure (e.g. a metal layer) is attached to the contact structure. Hereby, the thermal connection structure reduces the thermal resistance and therefore provides an improved and effective heat transfer between the pipe 2 and the temperature sensors (not shown) of the flow sensor 2.

In one embodiment, the thermal connection structure is a metal foil, coated with thermal adhesive on each side. Such thermal connection structure is capable of provide a permanent bond and reduce the thermal resistance by filling micro-air voids at the interface. In one embodiment, the thermal connection structure is thermally conductive aluminium tape. The thermal connection structure may be thermally conductive double-sided structural adhesive aluminium tape.

Fig. 4B illustrates a schematic view of a flow sensor 2 according to the invention. The flow sensor 2 comprises a mechanical flow detection unit 24 that is arranged inside a pipe 3 and thus submerged into the fluid 26.

The flow sensor 1 is a positive displacement meter that requires fluid to mechanically displace components of the mechanical flow detection unit 24 in order to provide flow measurements. The mechanical flow detection unit 24 can be a turbine or impeller. The activity and rotational speed of the turbine or impeller can either by using a direct connection to a data processor 10 or by means of a detection member (not shown) arranged and configured to measure the angular velocity og the turbine or impeller. The flow sensor 1 may be a turbine flow meter, a single jet flow meter or a paddle wheel flow meter by way of example. The mechanical flow detection unit 24 constitutes a first detection unit 34. The data processor 10 and the temperature sensors 12, 14 constitute the second detection unit 36.

The flow sensor 1 comprises a first temperature sensor 12 arranged and configured to detect the temperature of the surroundings (the ambient temperature). The flow sensor 1 comprises a second temperature sensor 14 arranged and configured to detect the temperature of the fluid 26 inside the pipe 3. The second temperature sensor 14 bears against the outside portion of the wall of the pipe 3. In another embodiment, however, the second temperature sensor 14 may be arranged inside the pipe 3. In a further embodiment, the second temperature sensor 14 may be integrated into the wall of the pipe 3.

The flow sensor 1 comprises a pipe 3 provided with a first flange 18 and a second flange 18′. These flanges 18, 18′ are configured to be mechanically connected to corresponding flanges 19, 19′ of two pipes 2, 2′. In one embodiment, the flanges 18, 18′ are replaced with similar attachment structures designed to attach the flow sensor 1 to pipes 2, 2′.

In one embodiment, the distal portions of the pipes 2, 2′ are provided outer threads while the distal portions of the pipe 3 of the flow sensor 3 are provided with corresponding inner threads allowing the pipe 3 to be screwed onto the pipes 2, 2′.

In one embodiment, the distal portions of the pipes 2, 2′ are provided inner threads while the distal portions of the pipe 3 of the flow sensor 3 are provided with corresponding outer threads allowing the pipe 3 to be screwed onto the pipes 2, 2′.

Fig. 5A illustrates a schematic view of a flow sensor 1 according to the invention. The flow sensor 1 basically corresponds to the one shown in Fig. 3A.

Fig. 5B illustrates a schematic view of a flow sensor 1 according to the invention. The flow sensor 1 basically corresponds to the one shown in Fig. 3B.

In Fig. 5A and Fig. 5B, the housing 20, however, comprises a portion that bears against the pipe 2, while the second temperature sensor 14 as well as the piezo transducers 4, 4′ extends through said portion of the housing 20 in order to be directly connected to the outside portion of the pipe 2, when the flow sensor 1 is attached to the pipe 2. It is possible to apply clamping structures such as cable tie or hose clamps to clamp the flow sensor to the pipe 2.

The piezo transducers 4, 4′ constitute a first detection unit 34. The data processor 10 and the temperature sensors 12, 14, 16 constitute the second detection unit 36.

The flow sensor 1 according to the invention uses the fact that the fluid 26 in most cases transports heat between the physical zones it flows through and that these physical zones have different temperatures. By detecting the temperature difference between these zones, it is possible to provide an alternative measure for the flow rate.

Accordingly, the flow sensor 1 and the method according to the invention can detect flow in the low flow range, in which the prior art flow sensors cannot detect any flow.

Moreover, the flow sensor 1 and the method according to the invention can provide an improved (more accurate) flow detection in general by using the temperature difference between the above-mentioned zones.

The heat transfer rate **q** (corresponding to E/t) from the fluid to the surroundings is defined in the following equation (12):

(12) $q = UA\Delta T_{sf}$

where $\Delta \mathbf{T}_{\mathbf{sf}}$ is the temperature difference between the surroundings and the fluid 26; **A** is the surface area where the heat transfer takes place and **U** is the heat transfer coefficient.

The heat transfer coefficient U is defined in the following equation (13):

(13) $U = \frac{k}{s}$,

where **k** is the thermal conductivity of the material through which the heat transfer takes place and **s** is the thickness of the material through which the heat transfer takes place.

The working principle of a Doppler Effect flow sensor 1 is shown in and briefly explained with reference to Fig. 6A. Doppler Effect flow sensors are affected by changes in the sonic velocity of the fluid 26. Accordingly, Doppler Effect flow sensors are sensitive to changes in density and temperature of the fluid 26. Therefore, many prior art Doppler Effect flow sensors are unsuitable for highly accurate measurement applications. The invention, however, makes it possible to detect the temperature and speed of sound of the fluid 26 and compensate for temperature and fluid (density) changes and thus provide an improved accuracy. Likewise, the invention, makes it possible to detect the density of the fluid 26 (via measurement made on a sample of the fluid 26) and compensate for temperature and/or fluid (density) changes in order to even further improve the accuracy of the flow sensor 1.

The Doppler Effect flow sensor 1 is a time-of-flight ultrasonic flow sensor that measures the time for the sound to travel between a transmitter 4 and a receiver 4′. In a typical setup, like the one illustrated in Fig. 6A, two transducers (transmitters/receivers) 4, 4′ are placed on each side of the pipe 2 through which the flow Q is to be measured. The transmitters 4, 4′ transmit pulsating ultrasonic waves 6 in a predefined frequency from one side to the other. The average fluid velocity V is proportional to the difference in frequency.

Accordingly, the fluid velocity V can be expressed as:

(14) $$V = \frac{t_2 - t_2}{t_1 t_2} \frac{L}{2\cos(\phi)}$$

where t_1 is the transmission time for the transmission time downstream, t_2 is the transmission time upstream, L is the distance between the transducers and ϕ is the relative angle between the transmitted ultrasonic beam 6 and the fluid flow Q.

The flow Q can be calculated as the product between the fluid velocity V and the cross-sectional area A_{pipe} of the pipe 2:

(15) $$Q = VA_{pipe}$$

At the same time the speec of sound c is given by the following equation (16):

(16) $$c = \frac{L}{2} \frac{t_2 + t_1}{t_2 t_1}$$

The flow sensor 1 shown in Fig. 6A comprises a first temperature sensor 12 arranged to detect the ambient temperature (the temperature in the surrounding of the pipe 2. The flow sensor 1 comprises a second temperature sensor 14 arranged to detect the temperature of the fluid 26. The flow sensor 1 comprises a data processor 10. Even though it is not shown in Fig. 6B, the temperature sensors 12, 14 and the two transducers 4, 4′ are connected to the data processor 10. Accordingly, the data processor 10 can process data and calculate the flow Q based on data from the temperature sensors 12, 14 and the two transducers 4, 4′.

The working principle of a Doppler Effect flow sensor 1 measuring the flow in a fluid containing particles 32 fluids shown in and briefly explained with reference to Fig. 6B.

The fluid velocity V can be calculated by using the following equation (17):

(18) $$V = \frac{c(fr - ft)}{2\,ft\cos(\phi)},$$

where fr is the frequency of the received wave; ft is the frequency of the transmitted wave; ϕ is the relative angle between the transmitted ultrasonic beam and the fluid flow Q and c is the velocity of sound in the fluid 26.

The flow Q can be calculated as the product between the fluid velocity V and the cross-sectional area A_{pipe} of the pipe 2:

(15) $$Q = VA_{pipe}$$

Equation 15 and 16 can also be used when calculating the flow by using the flow sensor shown in Fig. 2A, Fig. 2B, Fig. 3A and Fig. 3B.

Fig. 7 illustrates a graph depicting the speed of sound c in water as function of the temperature T of the water. Similar graphs can, however, be made for other liquids. In the following, water is just representing on possible fluid and water may be replaced with another liquid.

If the dimensions of the tubular structure (e.g. pipe, through which a flow Q of water is flowing, are not known, an estimation of the distance L that the sound travels in the water is needed. This problem is in particular relevant for ultrasonic clamp-on sensors. Over time, sediments may be provided at inside surface of a pipe. This will gradually decrease the distance L. Accordingly, the invention makes it possible to estimation of the distance L under such conditions.

By determining the speed of sound c in the water, is possible to estimate the distance L and hereby improve the accuracy of the detected speed V and flow Q of the water. Accordingly, changes in the speed of sound c in the water is highly relevant.

When the speed of sound c is detected, it is possible to calculate the distance L that the sound travels in the water.

The speed of sound c is given by the following formula (12):

$$(18) \qquad c = \sqrt{\frac{K}{\rho}}$$

Where K is the Bulk Modulus of Elasticity and ρ is the density.

Since the density of water depend on the temperature T, the speed of sound c depends on the temperature T. Moreover, the speed of sound c depends on the concentration of substances (e.g. glycol) in the water.

When the inclination angle α is known, the average speed V of the water (in the tube measured by delta time of flight) can be by using the following equation (19):

$$(19) \qquad V = \frac{L}{2\cos(\phi)} \frac{t_2 - t_1}{t_2 t_1}$$

When the speed of sound c is known. L can be calculating or estimated by using the following equation (16) (since t_1 and t_2 are being measured).

$$(16) \qquad c = \frac{L}{2} \frac{t_2 + t_1}{t_2 t_1}$$

Accordingly, the flow Q can be calculated as the product between the average speed V of water and the cross-sectional area A_{pipe} of the pipe 2:

$$(15) \qquad Q = VA_{pipe}$$

The measured fluid temperature T and the measured time-of-flight can be used to determine the density ρ and the speed of sound c by using equation (18).

If the flow sensor is calibrated in pure water at a temperature T_2 of 26°C, Fig. 7 shows that the speed of sound $c(T_2)$ is 1500 m/s. If a lower temperature T_1 of 21.5°C is detected, the speed of sound $c(T_1)$ is 1485 m/s. Accordingly, by calibrating the flow sensor by using a fluid (e.g. a liquid such as water) at a known temperature T and density ρ, a simple temperature measurement is sufficient to detect the speed of sound c by using equation (18).

$$c=\sqrt{\frac{K}{\rho}} \qquad (18)$$

The specific heat capacity of the fluid (e.g. water) depends on the content of additional substances (e.g. sugar, salt, ethylene glycol, glycerol or propylene glycol).

When the speed of sound c is known, it is possible to calculate the specific heat capacity of the fluid (e.g. water) having additional substances on the basis of the detected density of the fluid. Hereby, it is possible to make a heat energy meter having a flow sensor according to the invention more accurate.

It may be an advantage to measure content of additional substances (e.g. sugar, salt, ethylene glycol, glycerol or propylene glycol). Hereby, it would be possible to calibrate the flow sensor on the basis of the measurements.

Example 1

If the flow sensor being used in pure water detects a flow Q of 1 liter/minute at a temperature T_2 of 26°C, Fig. 7 shows that the speed of sound $c(T_2)$ is 1500 m/s.

When the speed of sound c (1500 m/s) is known. L can be calculating by using the following equation (16) (since t_1 and t_2 are detected by the flow sensor).

(16) $$c = \frac{L}{2}\frac{t_2 + t_1}{t_2 t_1}$$

When the flow sensor is used at a later point in time, the expected speed of sound c, at the same temperature T_2 of 26°C would be 1500 m/s. If, however, the detected speed of sound c is 1485 m/s calculated by using equation (16) and the known L, the decreased speed of sound is approximately 1 %. This may be caused by a change in the density ρ of the water. If we presume that the Bulk Modulus of Elasticity K is constant, equation (18) will give us that the density ρ is increased with approximately 2 % (by using equation 18).

If the flow sensor is used in a heat energy meter, it would be possible to correct the specific heat capacity of the water based on the detected density of the water. It can be concluded that the content of additional substances (e.g. sugar, salt, ethylene glycol, glycerol or propylene glycol) has increased. Accordingly, it is possible to improve the accuracy of the heat energy meter. This is relevant since the content of additional substances (e.g. sugar, salt, ethylene glycol, glycerol or propylene glycol) may vary as function of time. If the flow sensor is configured to automatically detect changes in the density of the fluid, the flow sensor is used in a heat energy meter will be capable of providing a high accuracy even when the content of additional substances varies over time.

Fig. 8 illustrates a graph depicting the flow Q detected by means of a flow sensor according to the invention as function of the temperature difference ΔT_{sf}.

The lower flow level Q_A represents the lowest flow that can be measured by using prior art flow sensors. Prior art flow sensors are not capable of detecting flow below the lower flow level Q_A, the flow sensor and method according to the invention, however, is capable of providing flow measurements below this lower flow level Q_A.

Above a base flow level Q_B the graph shows that the temperature difference ΔT_{sf} is constant and thus independent of the flow Q.

In the flow-calibration-area B_2 between the lower flow level Q_A and the base flow level Q_B the temperature difference ΔT_{sf} increases as function of the flow Q. In this flow-calibration-area B_2, a first flow sensor measurement M_1 and a second flow sensor measurement M_2 are indicated.

These flow sensor measurements M_1 and M_2 are made in the flow-calibration-area B_2 in order to determine the parameters required to determine how the flow Q depends on the temperature difference ΔT_{sf} in the flow-calibration-area B_2 and in the flow area B_1 below the flow-calibration-area B_2. The relationship between the flow Q and temperature difference ΔT_{sf} is given by equation (2):

$$Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right) \tag{2}$$

It is possible to measure temperature differences ΔT_1, ΔT_{M3} and ΔT_2 and calculate the flow Q by using equation (2).

List of reference numerals

1	Flow sensor
2, 2′, 3	Pipe
4, 4′	Ultrasonic transducer (piezo transducer)
5	Thermal energy meter
6	Ultrasonic vibration wave
8	Reflected ultrasonic vibration wave
10	Data processor (e.g. a micro-processor)
12	Temperature sensor
14	Temperature sensor
16	Temperature sensor
18, 18′	Flange
19, 19′	Flange
20	Housing
22	Thermal connection structure (e.g. a metal layer)
24	Mechanical flow detection unit
26	Fluid
28	Graph
30	Low flow area
32	Particle
34, 36	Detection unit
T_s	Temperature of the surroundings
T_f	Temperature of the fluid
ΔT	Temperature difference
ΔT_{sf}	Temperature difference between the surroundings and the fluid
$\Delta T_1, \Delta T_2$	Temperature difference
ΔT_A, ΔT_B	Temperature difference
T_1, T_2	Temperature
M_1, M_2, M_3	Flow measurement
B_1	Flow area
B_2	Flow-calibration-area
c_p	Specific heat capacity
k	Thermal conductivity
U	Coefficient of heat transfer

A	Surface area
W	Volume
t	Time-of-flight
t′	Temperature compensated time-of-flight
Δt	Delta-time-of-flight
t_1, t_2	Time-of-flight
dt_1, dt_2	Temperature difference
dt_A, dt_B	Temperature difference
dt_{M1}, dt_{M2}	Temperature difference
dt_{M3}	Temperature difference
s	Thickness
Q	Flow
Q_1, Q_2	Flow
Q_A, Q_B	Flow
Q_{M1}, Q_{M2}	Flow
Q_{M3}	Flow
V	Fluid velocity
α	Angle
L	Distance

Claims

1. An ultrasonic flow sensor (1) configured to measure the flow (Q) of a fluid (26) flowing through a tubular structure (2), said flow sensor (1) comprising:

- a first detection unit (34) arranged to transmit and receive ultrasonic waves (6, 8) by using at least one ultrasonic transducer (4, 4′);
- a temperature sensor (14) arranged and configured to detect the temperature (T_f) of the fluid (26);
- a temperature sensor (12) arranged and configured to detect the temperature (T_s) of the surroundings (the ambient temperature);
- a data processor (10) configured to receive data detected by the at least one ultrasonic transducer (4, 4′) and the temperature sensors (12, 14),

characterised in that the flow sensor (1) is configured to:

- determine the time-of-flight (t, t_1, t_2) of the ultrasonic waves (6, 8) and calculate a change in the speed of sound on the basis of the time-of-flight (t, t_1, t_2);
- calculate the expected change in speed of sound (c) as function of the detected temperature (T_f) of the fluid (26) and
- determine if the expected change in speed of sound (c) corresponds to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2);
- identify a no-flow state, in which there is no flow of the fluid (26) when the following criteria are meet:
  A) the expected change in speed of sound (c) corresponds to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), and
  B) the temperature difference (ΔT_{sf}) between the surroundings and the fluid (26) is below a predefined level which is pre-set at a fixed level between 0.01 degree Celsius and 0.5 degree Celsius.

2. A flow sensor (1) according to claim 1, wherein the no-flow state, is used to calibrate the ultrasonic flow measurement calculation(s) of the said flow sensor (1), to ensure stability and correct ultrasonic flow measurement of the flow sensor (1).

3. A flow sensor (1) according to claim 1 or 2, wherein the ultrasonic flow sensor (1) is configured to calculate a corrected value of the change in the density (ρ) of the fluid (26) on the basis of the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), if the expected speed of sound (c) does not correspond to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2).

4. A flow sensor (1) according to claim 3, wherein the ultrasonic flow sensor (1) is configured to calculate a corrected value of the specific heat capacity (c_p) of the fluid (26) on the basis of the corrected value of the density (ρ), if the expected change in speed of sound (c) does not correspond to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2).

5. A flow sensor (1) according to one of the preceding claims 3-4, wherein the ultrasonic flow sensor (1) is configured to calculate a corrected value of the flow (Q) of the fluid (26) on the basis of the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), if the expected change in speed of sound (c) does not correspond to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2).

6. A flow sensor (1) according to one of the preceding claims, wherein the first detection unit (34) is configured to detect flows (Q) above a predefined lower flow level (Q_A) representing the lower flow (Q_A) that can be measured by using the first detection unit (34), wherein the flow sensor (1) comprises a second detection unit (36) that comprises:

- a first temperature sensor (12) arranged and configured to detect the temperature (T_s) of the surroundings (the ambient temperature);
- a data processor (10) connected to the temperature sensors (12, 14),

wherein the second detection unit (36) is configured to estimate the flow (Q) below the lower flow level (Q_A) on the basis of the temperature difference (ΔT_{sf}) between the surroundings and a fluid (26), wherein the temperature difference (ΔT_{sf}) between is measured by the first temperature sensor (12) and the second temperature sensor (14), wherein the second detection unit (36) is configured to estimate the flow (Q) below the lower flow level (Q_A) on the basis of one or more measurements (M_1, M_2) made in a flow-calibration-area (B_2), in which flow-calibration-area (B_2) the flow sensor (1) can detect the flow (Q) that depends on the temperature difference (ΔT_{sf}), wherein the one or more measurements (M_1, M_2) made in the flow-calibration-area (B_2) are used to determine one or more parameters required to determine how the flow (Q) depends on the temperature difference (ΔT_{sf}) in the flow-calibration-area (B_2) and in the flow area (B_1) below the flow-calibration-area (B_2).

7. A flow sensor (1) according to claim 6, wherein the second detection unit (36) is configured to estimate the flow (Q) below the lower flow level (Q_A) on the basis of a single measurement (M_1, M_2) and predefined data that includes the density (ρ) and the specific heat capacity (C_p) of the fluid (26).

8. A flow sensor (1) according to claim 6, wherein the second detection unit (36) is configured to estimate the flow (Q) below the lower flow level (Q_A) on the basis of two or more measurements (M_1, M_2) made in a flow-calibration-area (B_2).

9. A flow sensor (1) according to one of the claims 6-8, wherein the flow sensor (1) is configured to regularly or continuously:

- carry out the one or more measurements (M_1, M_2) in a flow-calibration-area (B_2) and
- update the more parameters required to determine how the flow (Q) depends on the temperature difference (ΔT_{sf}) in the flow-calibration-area (B_2) and in the flow area (B_1) below the flow-calibration-area (B_2).

10. A flow sensor (1) according to one of the preceding claims 6-9, wherein the dependency between the flow (Q) and the temperature dif-

ference (ΔT_{sf}) is defined by of the following equations:

$$\Delta T_{sf}(Q) = \Delta T_B\left(1 - e^{-C_1 Q}\right) \text{ or } Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right)$$

where C_1 is a constant and ΔT_B is a temperature difference corresponding to a base flow level.

11. A flow sensor (1) according to one of the preceding claims, wherein a (second) temperature sensor (14) is arranged and configured to detect the temperature (T_f) of the fluid (26) by measuring a temperature at the outside of the tubular structure (2).

12. A flow sensor (1) according to one of the preceding claims, wherein the data processor (10) and the second temperature (14) sensor are arranged inside a housing (20).

13. A flow sensor (1) according to claim 12, wherein the first temperature sensor (12) is arranged in the housing (20).

14. A flow sensor (1) according to claim 12, wherein the first temperature sensor (12) is arranged outside the housing (20).

15. A flow sensor (1) according to one of the preceding claims, wherein the second detection unit (36) comprises:

- an intermediate temperature sensor (16) arranged and configured to detect an intermediate temperature (T_i) of a position inside the housing (20), wherein said position is expected to have a temperature between the ambient temperature (T_s) and the temperature (T_f) of the fluid (26).

16. A flow sensor (1) according to one of the preceding claims, wherein the flow sensor (1) is a clamp-on flow sensor (1) configured to measure the flow (Q) of the fluid (26) from outside the tubular structure (2).

17. A flow sensor (1) according to one of the preceding claims, wherein the flow sensor (1) is configured to automatically calculate the distance

(L) that the transmitted ultrasonic waves (6) and receive ultrasonic waves (8) travel in the fluid (26) on the basis of a detected value of the speed of sound (c).

18. A thermal energy meter (5) comprising a flow sensor (1) according to one of the preceding claims.

19. Method for measuring the flow (Q) of a fluid (26) flowing through a tubular structure (2) by means of an ultrasonic flow sensor (1) comprising a first detection unit (34) provided with:

- at least one ultrasonic transducer (4, 4′) arranged to transmit and receive ultrasonic waves (6, 8) by using at least one ultrasonic transducer (4, 4′), wherein the ultrasonic flow sensor (1) comprises a temperature sensor (14) arranged and configured to detect the temperature (T_f) of the fluid (26),

wherein the method comprises the following steps:

- determining the time-of-flight (t, t_1, t_2) of the ultrasonic waves (6, 8);
- calculating a change in the speed of sound on the basis of the time-of-flight (t, t_1, t_2);
- calculating the expected change in speed of sound (c) as function of the detected temperature (T_f) of the fluid (26) and
- determining if the expected change in speed of sound (c) corresponds to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2);
- identifying a no-flow state, in which there is no flow of the fluid (26) when the following criteria are meet:
  A) the expected change in speed of sound (c) corresponds to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), and
  B) the temperature difference (ΔT_{sf}) between the surroundings and the fluid (26) is below a predefined level which is pre-set at a fixed level between 0.01 degree Celsius and 0.5 degree Celsius.

20. Method according to claim 19, wherein the no-flow state, is used to

calibrate the ultrasonics flow measurement calculation of the said flow sensor (1), to ensure stability and correct ultrasonic flow measurement of the flow sensor (1).

21. Method according to claim 19 or 20, wherein the method comprises the step of calculating a corrected value of change in the density (ρ) of the fluid (26) on the basis of the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), if the expected speed of sound (c) does not correspond to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2).

22. Method according to one of the claims 19-21, wherein the method comprises the step of calculating a corrected value of the specific heat capacity (c_p) of the fluid (26) on the basis of the corrected value of the density (ρ), if the expected change in speed of sound (c) does not correspond to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2).

23. Method according to one of the claims 19-22, wherein the method comprises the step of calculating a corrected value of the flow (Q) of the fluid (26) on the basis of the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2), if the expected change in speed of sound (c) does not correspond to the change in speed of sound calculated on the basis of the time-of-flight (t, t_1, t_2).

24. Method according to one of the claims 19-23, wherein the first detection unit (34) is configured to detect flows (Q) above a predefined lower flow level (Q_A) representing the lowest flow (Q_A) that can be measured by using the first detection unit (34), wherein the method comprises the steps of applying a second detection unit (36) to:

- detect the temperature (T_s) of the surroundings (the ambient temperature) by means of a temperature sensor (12);
- detect the temperature (T_f) of the fluid (26) by means of a temperature sensor (14) arranged and configured to detect the temperature (T_f) of the fluid (26);

- estimating the flow (Q) below the lower flow level (Q_A) on the basis of the temperature difference (ΔT_{sf}) between the surroundings and a fluid (26) measured by the temperature sensors (12, 14),

wherein the method comprises the following steps:

a) performing one or more flow measurements (M_1, M_2) by means of the first detection unit (34) in a flow-calibration-area (B_2), in which flow-calibration-area (B_2) the flow sensor (1) can detect the flow (Q) that depends on the temperature difference (ΔT_{sf});

b) applying the one or more measurements (M_1, M_2) made in the flow-calibration-area (B_2) to determine one or more parameters required to determine how the flow (Q) depends on the temperature difference (ΔT_{sf}) in the flow-calibration-area (B_2) and in the flow area (B_1) below the flow-calibration-area (B_2) and

c) estimating the flow (Q) below the lower flow level (Q_A) on the basis of the one or more measurements (M_1, M_2) made in the flow-calibration-area (B_2).

25. Method according to claim 24, wherein the method comprises the step of performing two or more flow measurements in the flow-calibration-area (B_2).

26. Method according to claim 24 or 25, wherein the method comprises the step of regularly or continuously:

- carrying out the one or more measurements (M_1, M_2) in a flow-calibration-area (B_2) and
- updating the more parameters required to determine how the flow (Q) depends on the temperature difference (ΔT_{sf}) in the flow-calibration-area (B_2) and in the flow area (B_1) below the flow-calibration-area (B_2).

27. Method according to one of the preceding claims 24-26, wherein the dependency between the flow (Q) and the temperature difference (ΔT_{sf}) is defined by of the following equations:

$$\Delta T_{sf}(Q) = \Delta T_B\left(1 - e^{-C_1 Q}\right) \quad \text{or} \quad Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right)$$

where C_1 is a constant and ΔT_B is a temperature difference corresponding to a base flow level.

28. Method according to one of the claims 19-27, wherein the temperature (T_f) of the fluid (26) is measured by a temperature sensor arranged at the outside of the tubular structure (2).

29. Method according to one of the claims 19-28, wherein the method comprises the step of detecting an intermediate temperature (T_i) by means of an intermediate temperature sensor (16) arranged in a position inside a housing (20), wherein the housing (20) houses the temperature sensor (14) that is used to detect the temperature (T_f) of the fluid (26)
and the intermediate temperature sensor (16), wherein the intermediate temperature (T_i) is expected to have a value between the ambient temperature (T_s) and the temperature (T_f) of the fluid (26).

30. Method according to one of the preceding claims 19-29, wherein the method comprises the steps of measuring the density and/or the estimated inhomogeneity of the fluid (26) prior to measuring the flow (Q).

31. Method according to one of the preceding claims 19-30, wherein the method is carried out by using a clamp-on flow sensor (1) configured to measure the flow (Q) of the fluid (26) from outside the tubular structure (2).

32. Method according to one of the preceding claims 19-31, wherein the method comprises the step of automatically calculating the distance (L) that the transmitted ultrasonic waves (6) and receive ultrasonic waves (8) travel in the fluid (26) on the basis of a detected value of the speed of sound (c).

33. Method for measuring the thermal energy of a fluid (26), wherein the method applies a method according to one of the claims 19-32 to detect the flow (Q) of the fluid.

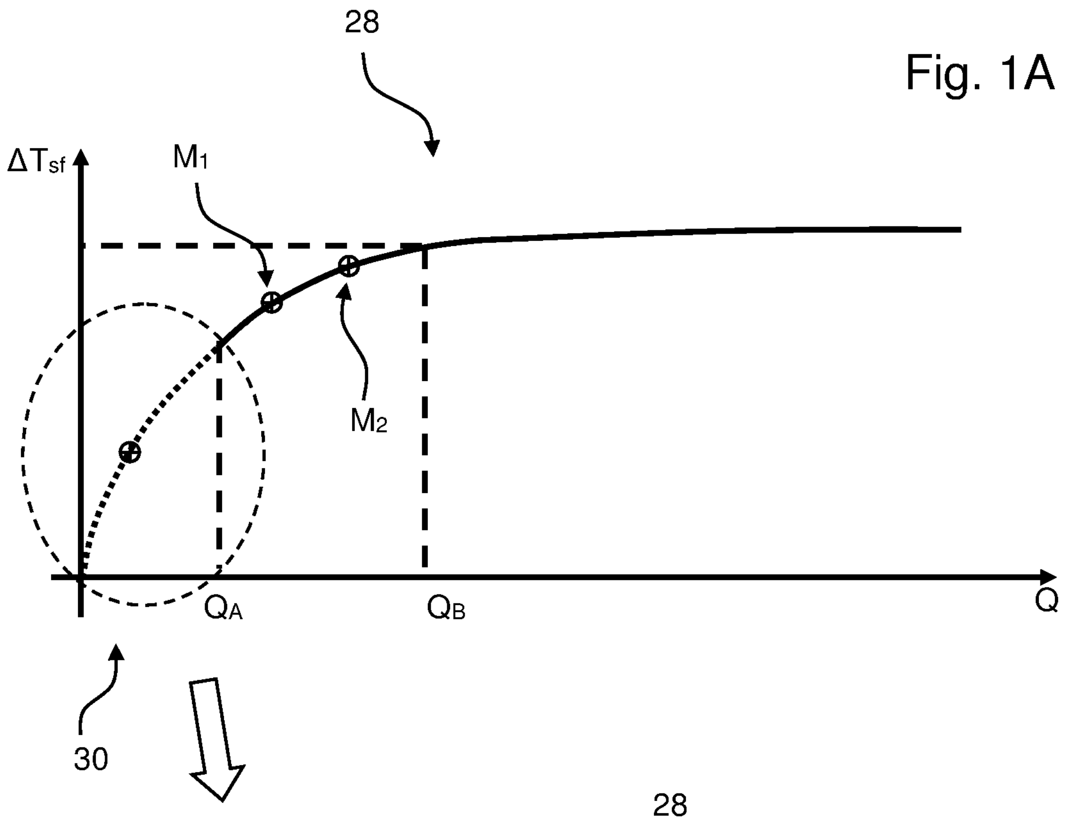

28
ΔTsf
M1
M2
QA
QB
Q
30

Fig. 1A

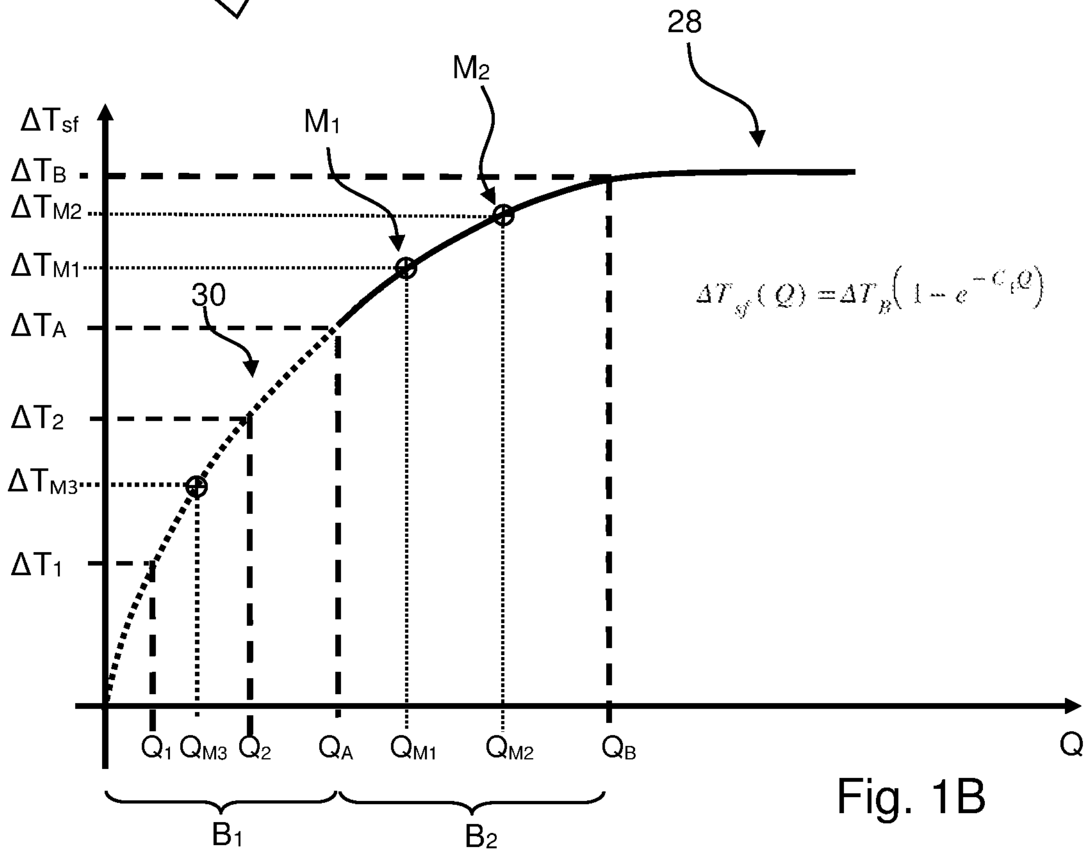

28
M2
M1
ΔTsf
ΔTB
ΔTM2
ΔTM1
30
ΔTA
ΔT2
ΔTM3
ΔT1
$\Delta T_{sf}(Q) = \Delta T_B\left(1 - e^{-C_f Q}\right)$
Q1
QM3
Q2
QA
QM1
QM2
QB
Q
B1
B2

Fig. 1B

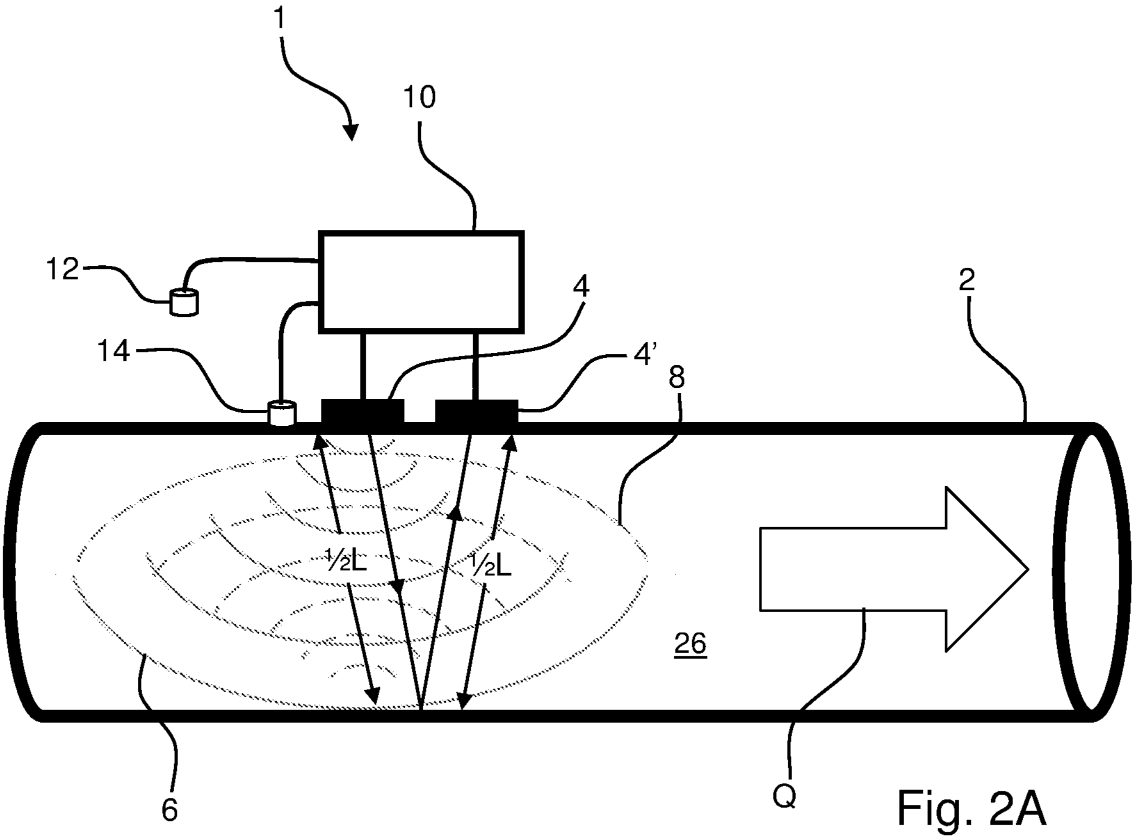


Fig. 2A

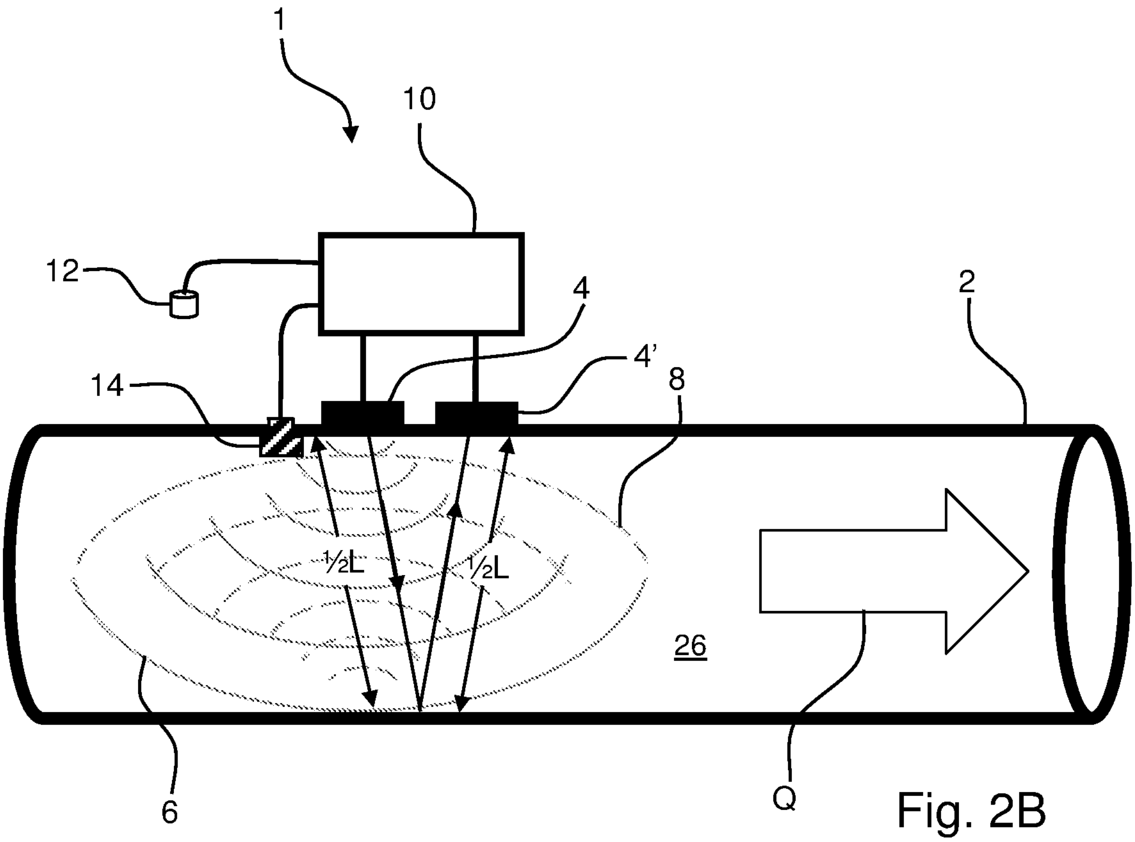
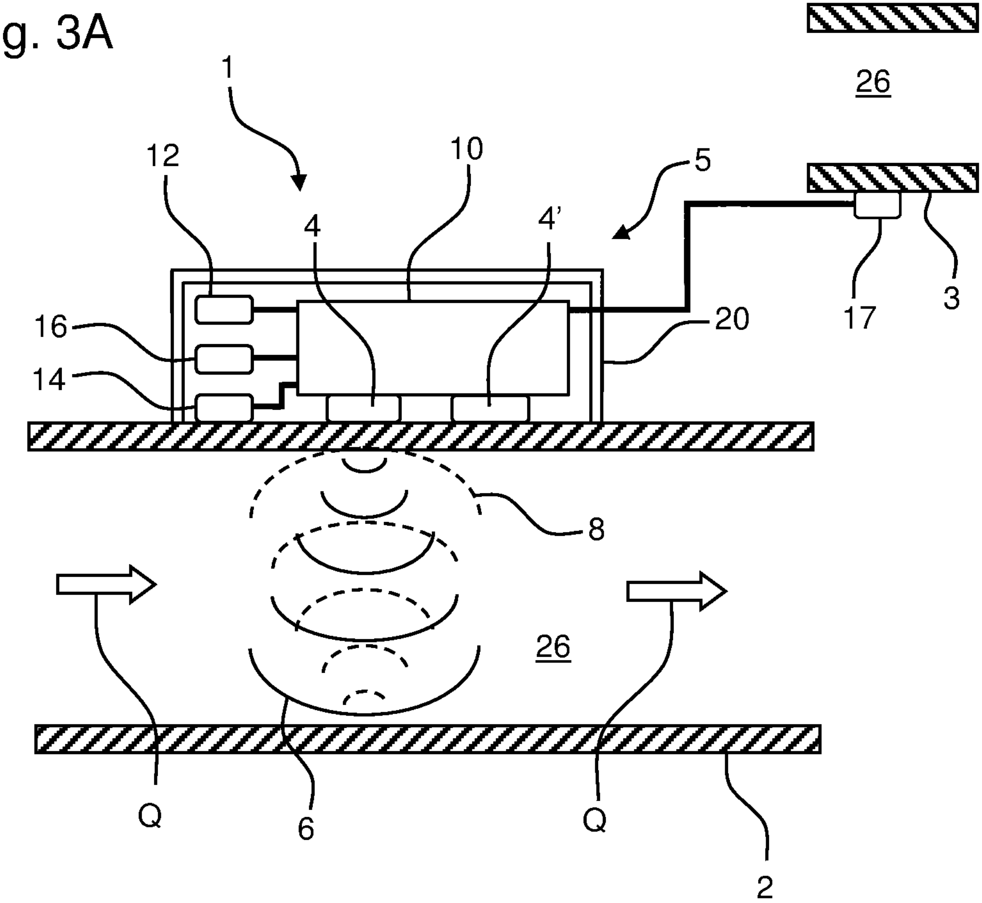


Fig. 2B

Fig. 3A


26
1
12
10
5
4
4'
17
3
16
20
14
8
26
Q
6
Q
2

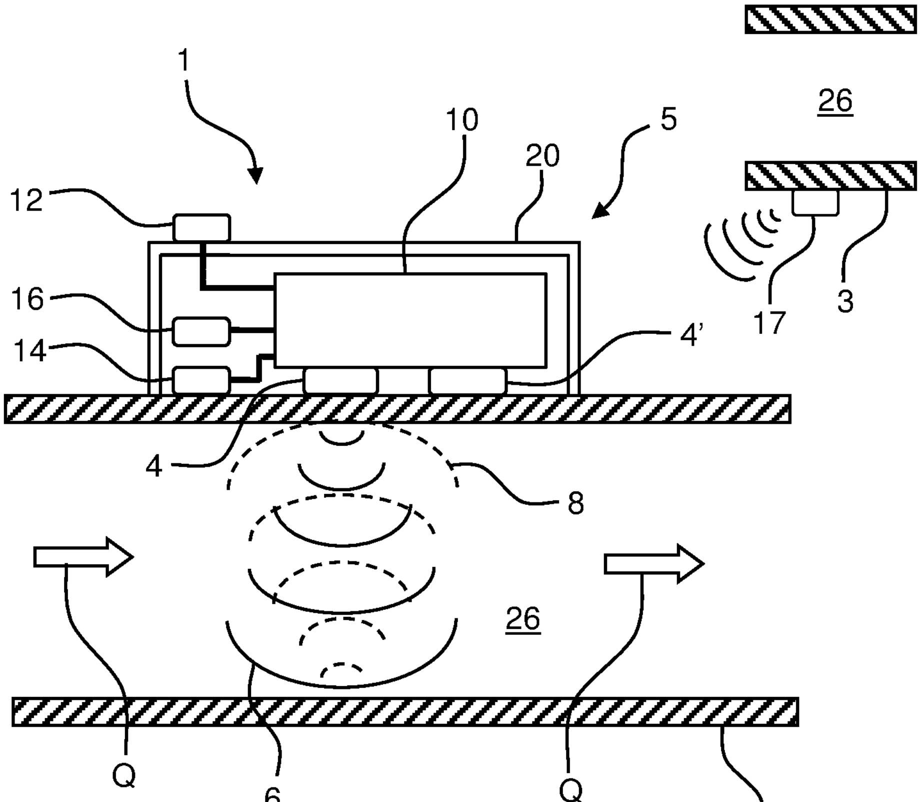
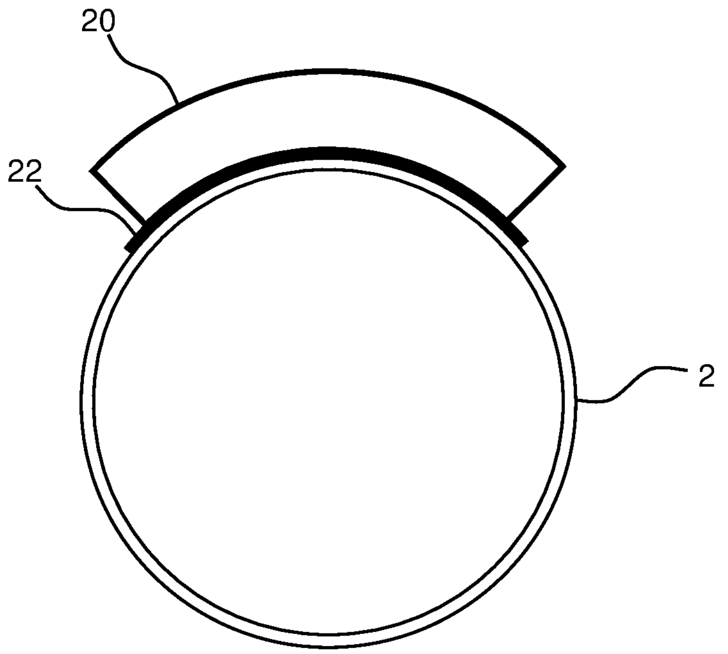

26
1
10
5
20
12
17
3
16
14
4'
4
8
26
Q
6
Q
2

Fig. 3B

Fig. 4A



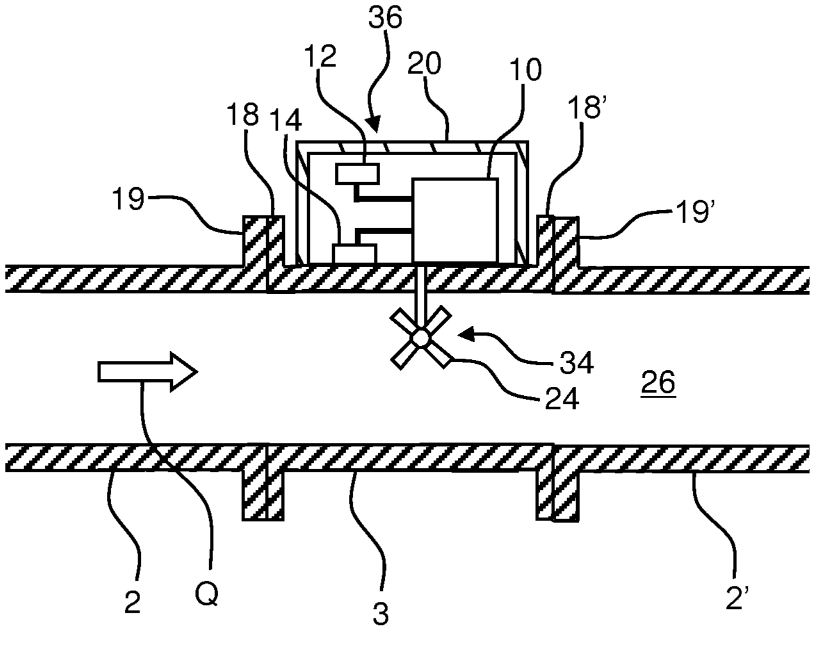
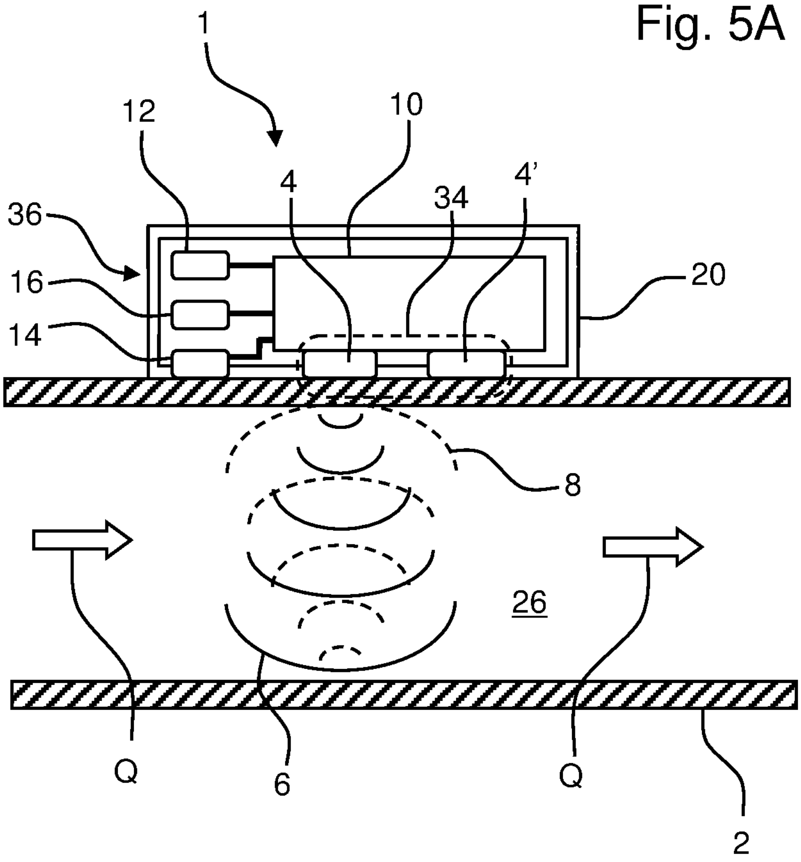


Fig. 4B

Fig. 5A



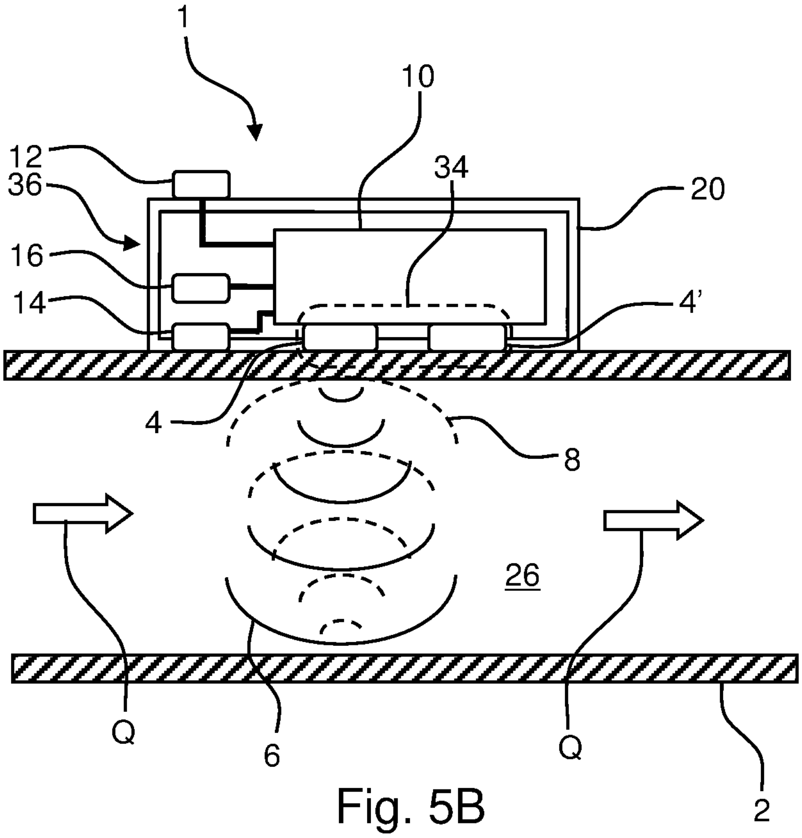


Fig. 5B

Fig. 6A

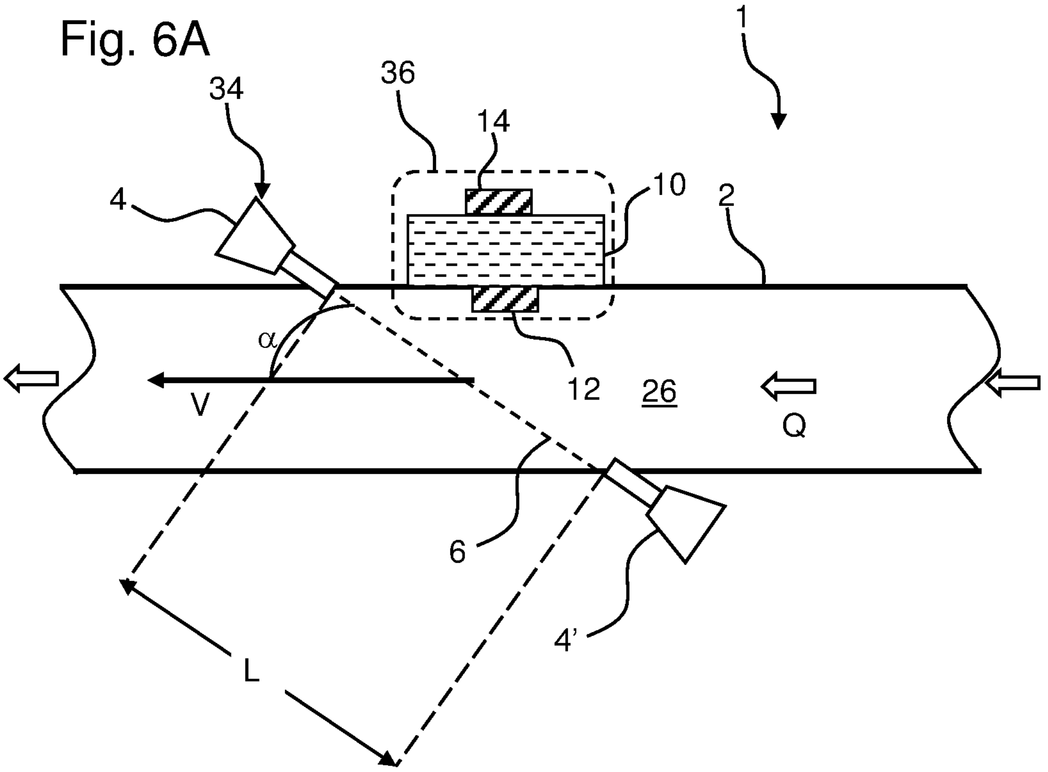


Fig. 6B

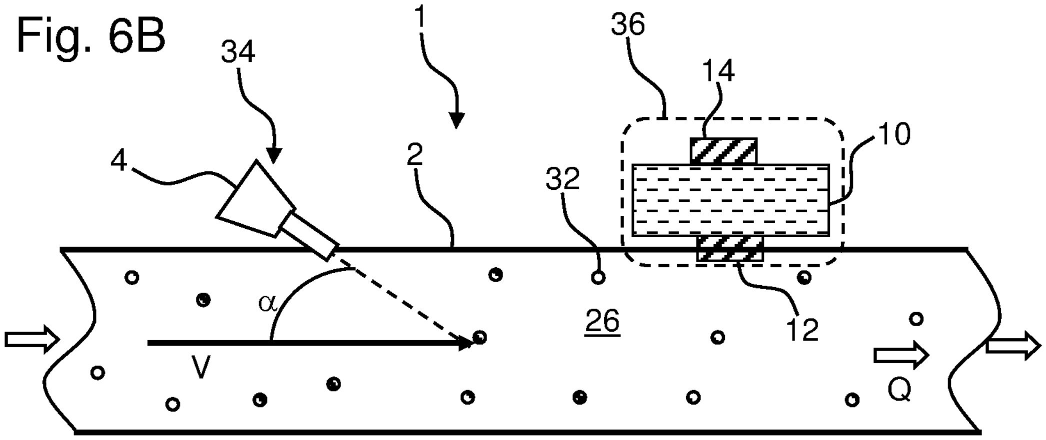


Fig. 7

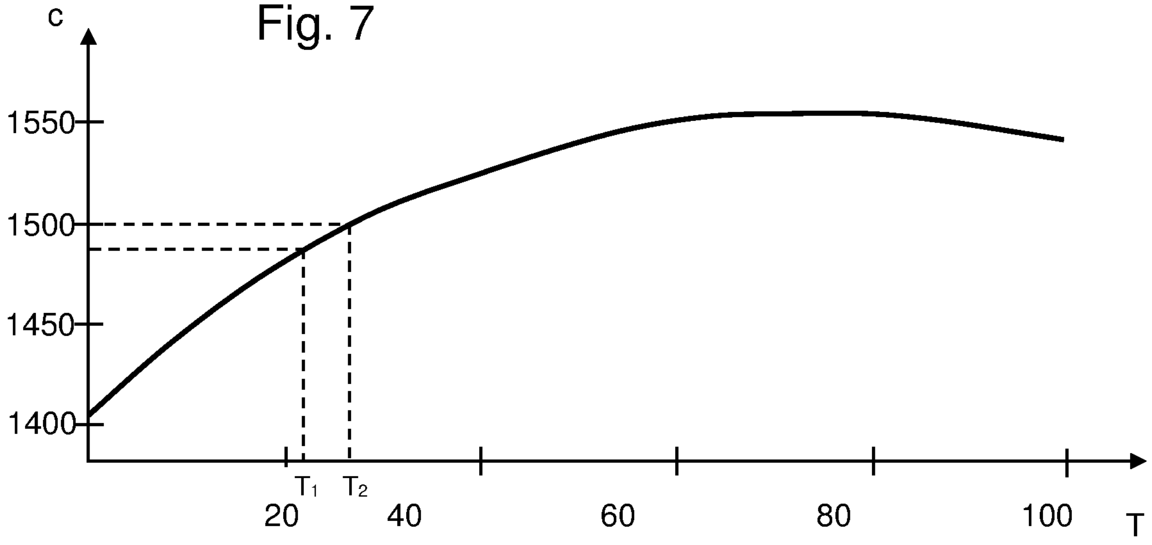
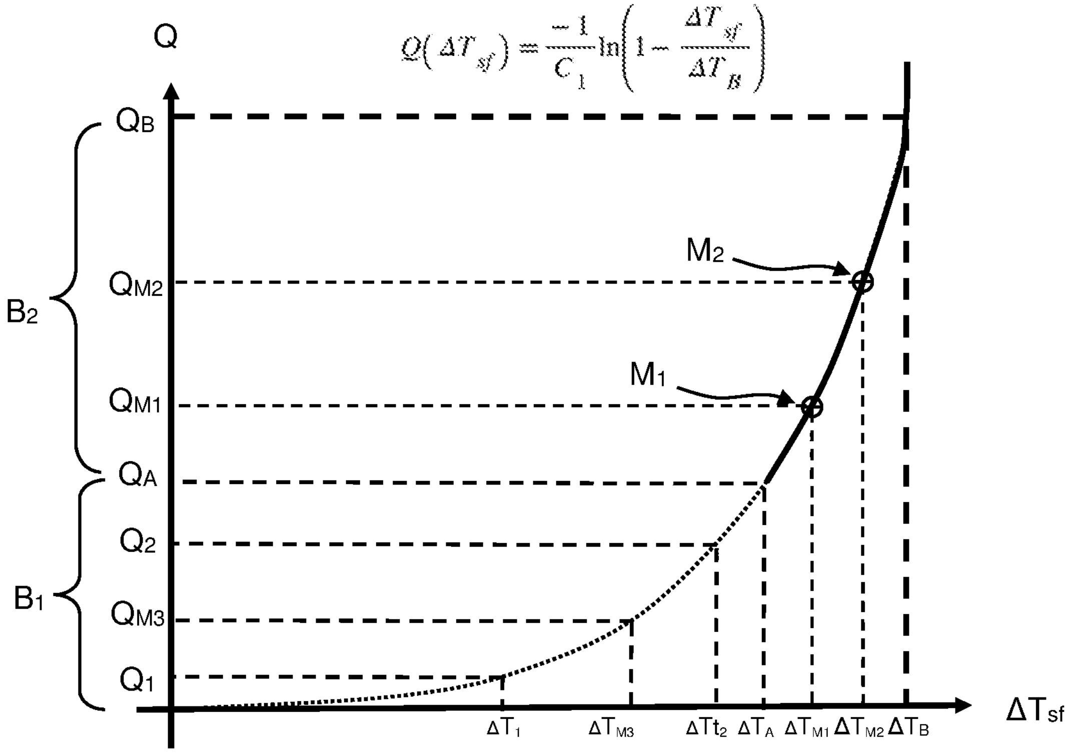


Fig. 8



$$Q(\Delta T_{sf}) = \frac{-1}{C_1}\ln\left(1 - \frac{\Delta T_{sf}}{\Delta T_B}\right)$$

INTERNATIONAL SEARCH REPORT

International application No.

PCT/DK2022/050136

A. CLASSIFICATION OF SUBJECT MATTER

G01F 1/66 (2022.01)i; G01F 1/68 (2006.01)i; G01P 13/00 (2006.01)i

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)

G01D; G01F; G01P
CPC: G01D, G01F, G01P

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

DK, NO, SE, FI: Classes as above.

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

Epodoc, WPI, English full-text

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	GB 2289760 A (BAUMOEL JOSEPH [US]) 29 November 1995 (1995-11-29) e.g. from page 15 line 25 to page 21 line 19, from page 29 line 25 to page 32 line 25, page 35 line 7–22 and from page 45 line 28 to page 46 line 17 and figures	1-33
A	US 2018010978 A1 (HOMESERVE PLC [GB]) 11 January 2018 (2018-01-11) e.g. paragraphs 0019–0024	1-33
A	JP H08304135 A (MATSUSHITA ELECTRIC IND CO LTD) 22 November 1996 (1996-11-22) e.g. paragraphs 0006, 0008, 0010, 0012–0014 and 0022	1-33
A	US 2013081477 A1 (GOTOU HIROKAZU [JP]) 04 April 2013 (2013-04-04) e.g. paragraphs 0012–0018, 0029–0034, 0040–0045, 0050, 0053, 0054, 0058, 0060, 0067, 0069, 0073, 0074, 0083, 0088–0096, 0109 and 0127 and figures 1–7	1-33

☑ Further documents are listed in the continuation of Box C. ☑ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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"E" earlier application or patent but published on or after the international filing date	"&" document member of the same patent family
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search **29 August 2022**	Date of mailing of the international search report **29 August 2022**
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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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International application No.
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