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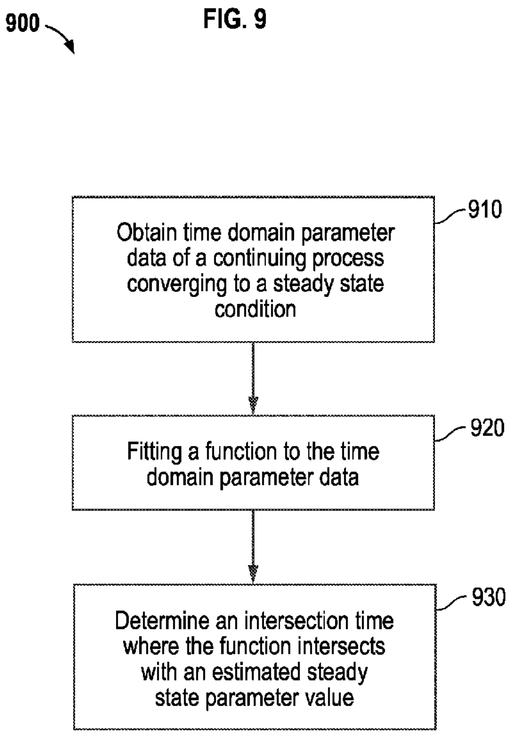
(54) **Title:** ESTIMATING AND DETERMINING A STEADY STATE CONDITION OF A PROCESS

(57) **Abstract:** A method for estimating a time related to a steady state condition of a process is provided. The method comprises obtaining time domain parameter data of a continuing process converging to the steady state condition, fitting a function to the time domain parameter data, and determining an intersection time where the function intersects with an estimated steady state parameter value.

FIG. 9



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ESTIMATING AND DETERMINING A STEADY STATE CONDITION OF A PROCESS

TECHNICAL FIELD

The embodiments described below relate to processes that reach steady state and, more particularly, to estimating and determining the steady state condition of the process.

BACKGROUND

There are numerous mechanical and chemical processes that change state in time, sometimes slowly, as they tend towards a final steady state. One such example is a blending application where two or more components are continuously mixed to achieve a desired concentration of one or more components in the mixture. Most of these processes involve fluid flow and may involve some kind of periodic sampling and off-line (i.e., not in the fluid flow) measurements of physical properties of the fluid to determine if the process has reached its steady state.

Performing periodic sampling of the fluids to measure the physical properties off-line requires prior knowledge of the process to determine the optimum sampling frequency. This requires balancing off-line measurement time and expense against the cost of continuing to run the process not knowing if it has reached its final steady-state. Such off-line measurements may also be used to estimate a time-to-completion of the process. The accuracy of such an estimation will also be determined by the sampling and off-line measurement frequency.

Knowing when the process will be completed, or the time-to-completion, can help determine the timing of all the required steps after the completion of the process, such as packaging or transporting the completed fluid product. The time-to-completion could also be used as feedback to speed up the process, if necessary. It can also be helpful to know when a process is completed. Accordingly, there is a need for estimating and determining a steady state condition of a process.

SUMMARY

A method for estimating a time related to a steady state condition of a process is provided. According to an embodiment, the method comprises obtaining time domain parameter data of a continuing process converging to the steady state condition, fitting a function to the time domain parameter data, and determining an intersection time where the function intersects with an estimated steady state parameter value.

A method of estimating a steady state condition of a process is provided. According to an embodiment, the method comprises obtaining time domain parameter data of a continuing process converging to the steady state condition, fitting a function to the time domain parameter data, and comparing the function to a tolerance to estimate the steady state condition.

A method of determining a steady state condition of a process is provided. According to an embodiment, the method comprises obtaining time domain parameter data of a continuing process converging to the steady state condition and comparing the time domain parameter data to a tolerance to detect the steady state condition.

A device configured to estimate a time related to, and/or estimate and/or determine a steady state condition of a process is provided. According to an embodiment, the device comprises a transducer configured to measure a parameter, and an electronics communicatively coupled to the transducer, the electronics being configured to perform one or more of the foregoing methods.

ASPECTS

According to an aspect, a method for estimating a time related to a steady state condition of a process comprises obtaining time domain parameter data of a continuing process converging to the steady state condition, fitting a function to the time domain parameter data, and determining an intersection time where the function intersects with an estimated steady state parameter value.

Preferably, the estimated steady state parameter value is one of a user input parameter value and a parameter value derived from a prototype process of the continuing process.

Preferably, the parameter value derived from the prototype process is a value of a prototype function fit to the prototype process at a slope of approximately zero.

Preferably, the intersection time is an estimated time-at-completion of the continuing process.

Preferably, the method further comprises determining an estimated time-to-completion of the continuing process based on a time-difference between the intersection time and a current time.

Preferably, obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition.

Preferably, the time domain parameter data comprises a time series of parameter values that relate a time value to a parameter value of the continuing process.

Preferably, obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

According to an aspect, a device configured to estimate a time related to a steady state condition of a process comprises a transducer configured to measure a parameter, and an electronics communicatively coupled to the transducer, the electronics being configured to perform one or more of the foregoing methods.

According to an aspect, a method of estimating a steady state condition of a process, the method comprising obtaining time domain parameter data of a continuing process converging to the steady state condition, fitting a function to the time domain parameter data, and comparing the function to a tolerance to estimate the steady state condition.

Preferably, the tolerance comprises one of a tolerance box and a slope threshold.

Preferably, the tolerance box comprises a tolerance band and a tolerance duration.

Preferably, the steady state condition is estimated when the function is entirely within the tolerance box.

Preferably, the slope threshold is compared to a slope of the function to estimate the steady state condition.

Preferably, the slope of the function is based on a most recent parameter value of the function.

Preferably, obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition.

Preferably, the time domain parameter data of the continuing process is a time series of parameter values that relate a time value to a parameter value of the continuing process.

Preferably, obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

According to an aspect, a device configured to estimate a steady state condition of a process comprises a transducer configured to measure a parameter, and an electronics communicatively coupled to the transducer, the electronics being configured to perform one or more of the foregoing methods.

According to an aspect, a method of determining a steady state condition of a process comprises obtaining time domain parameter data of a continuing process converging to the steady state condition and comparing the time domain parameter data to a tolerance to detect the steady state condition.

Preferably, the tolerance comprises a tolerance band and a tolerance duration.

Preferably, the tolerance duration is a length that extends from a most recent parameter value of the time domain parameter data into a time domain of the time domain parameter data.

Preferably, the method further comprises detecting the steady state condition of the time domain parameter data if the time domain parameter data is entirely within the tolerance band over the tolerance duration.

Preferably, obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition.

Preferably, the time domain parameter data of the continuing process is a time series of parameter values that relate a time value to a parameter value of the continuing process.

Preferably, obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

According to an aspect, a device configured to determine a steady state condition of a process comprises a transducer configured to measure a parameter, and an electronics communicatively coupled to the transducer, the electronics being configured to perform one or more of the foregoing methods.

BRIEF DESCRIPTION OF THE DRAWINGS

The same reference number represents the same element on all drawings. It should be understood that the drawings are not necessarily to scale.

FIG. 1 shows a device 100 configured to estimate and determine a steady state condition of a process.

FIGS. 2 through 5 show graphs 200-500 depicting estimates of a time related to a steady state condition at which the process reaches completion.

FIGS. 6 and 7 show graphs 600, 700 depicting estimates of a steady state condition of a process.

FIG. 8 shows a graph 800 for determining a steady state condition of a process.

FIG. 9 shows a method 900 for estimating a time of a steady state condition of a process.

FIG. 10 shows a method 1000 for estimating a steady state condition of a process.

FIG. 11 shows a method 1100 for determining a steady state condition of a process.

FIG. 12 shows a vibratory meter 5 configured to estimate and determine a steady state condition of a process.

FIG. 13 shows a meter electronics 20 configured to estimate and determine a steady state condition of a process.

FIG. 14 shows an ultrasonic meter 30.

FIG. 15 shows a cross-sectional overhead view of the ultrasonic sensor assembly 31.

DETAILED DESCRIPTION

FIGS. 1 through 15 and the following description depict specific examples to teach those skilled in the art how to make and use the best mode of embodiments of estimating and determining a steady state condition of a process. For the purpose of teaching inventive principles, some conventional aspects have been simplified or omitted. Those skilled in the art will appreciate variations from these examples that fall within the scope of the present description. Those skilled in the art will appreciate that the features described below can be combined in various ways to form multiple variations of estimating and determining a steady state condition of a process. As a result, the embodiments described below are not limited to the specific examples described below, but only by the claims and their equivalents.

FIG. 1 shows a device 100 configured to estimate and determine a steady state condition of a process. As shown in FIG. 1, the device 100 is comprised of a transducer 120 and an electronics 140. The transducer 120 is communicatively coupled to the electronics 140. The device 100 may be configured to measure and/or control one or more parameters of an object and/or an event. Examples of an object include a mechanical device, a fluid flow, etc. An event may be a transitory change in an object that has, for example, event related parameters such as time-duration, intensity, etc. Parameters of the object and/or event may be or include a process that reaches steady state where it is desirable to estimate and determine a steady state condition.

For example, an object may reach a steady state temperature due to an expected and determinable environmental condition. For example, a battery may have a desirable temperature during operation that can reach steady state due to cooling fluid flow. However, a simple control loop based only on contemporaneous differences between a temperature set point and a measured temperature may not be optimal due to, for example, degradation, etc. Accordingly, a temperature sensor may also determine and provide estimates of a steady state condition of the battery temperature so that the cooling system can more effectively control the fluid flow loop. Additionally, or alternatively, the temperature sensor could determine if a steady state condition has actually been reached or if cooling flow should be adjusted in anticipation of, for example, a temperature over or undershoot.

It should be appreciated that many different processes with various parameters can reach steady state. In the example of FIG. 1, a fluid flow is shown as entering and exiting the device 100 with arrows. The device 100 may therefore be a fluid flow device, such as the vibratory meter 5 described with reference to FIGS. 12 and 13 and the ultrasonic meter 30 described with reference to FIGS. 14 and 15, although any suitable device may be employed. For example, an alternative device may be a fork density meter that is immersed in a tank of fluid may be employed where, for example, a reaction, filling, etc., is occurring. As shown in FIG. 1, the device 100 is configured to measure a fluid flow parameter to obtain a time-series of fluid flow parameter values, although any suitable object and/or event having any suitable parameters may be measured and/or controlled.

As shown in FIG. 1, the transducer 120 may be any suitable transducer that senses and/or controls a fluid flow parameter. For example, the transducer 120 may sense a density, pressure, temperature, viscosity, refractive index, flow rate, such as mass or volume flow rate, velocity, salinity, and/or the like, of the fluid flow. Additionally, or alternatively, the transducer 120 may control a pressure, temperature, flow rate, and/or the like, of the fluid flow. Accordingly, the transducer 120 may provide and/or send one or more signals to and/or from the electronics 140. The one or more signals may be indicative, such as proportional to, the sensed and/or controlled fluid flow parameter.

The electronics 140 is configured to send and/or receive the one or more signals to and/or from the transducer 120. Although not shown, the electronics 140 may include one or more processors including and/or coupled to one or more memories. The electronics 140 may also include signal condition circuits configured to convert the one or more signals provided to the electronics 140 into digital data. Additionally, or alternatively, the electronics 140 may include signal generators, amplifiers, and/or the like that convert one or more digital signals, such as a digital set point value, to a signal that is provided to the transducer 120.

The one or more processors may be configured to process the one or more digital signals so as to determine the time-series of fluid flow parameter values. For example, where the transducer 120 is a density transducer, a voltage signal provided by the transducer 120 may be proportional to a density of the fluid flow. The signal conditioning circuit may convert the signal to a digital signal that is, for example, proportional to the density of the fluid flow. The one or more memories may include calibration factors that scale the digital signal to a density value. Accordingly, the electronics 140 may generate a time-series of fluid flow parameter values of the fluid flow parameter.

The electronics 140 may additionally be configured to store, process, and/or transmit the time-series of the fluid flow parameter values. The device 100 may also be configured to receive a time-series of other parameter values or processed parameter values from other devices to, for example, process, compare, aggregate, and/or the like, with the time-series parameter values of the device 100. The time-series of the fluid flow parameter values may be transmitted and/or received via a communications port, which may be any suitable means of communication.

The time-series of fluid flow parameters may be obtained, stored, and/or processed as a series of parameter values in the time-domain. That is, the series of parameter values have a relationship to time due to being measured values obtained and sorted according to a time-domain. Accordingly, the time-series of fluid flow parameters may be, for example, ordered pairs of time-related values and parameter values. The ordered pairs may be expressed as (pv, t), where pv represents a parameter value and t represents a time-related value, although any suitable form may be employed. The time-related value may be, for example, time-index values of integers that correspond to constantly spaced measurements, time-values like seconds, minutes, hours, etc., and/or the like. It should be appreciated that the ordered pairs can be obtained, stored, and/or processed in any form, such as time-indexed data series of parameter values, a matrix relating parameter values to time-values, and/or the like.

As discussed above, fluid flow parameters may reach a steady state. It may be desirable to extrapolate information pertaining to the steady state condition. For example, it may be desirable to estimate and/or detect a steady state condition of the fluid flow. For example, it may be desirable to estimate a time to reach the steady state condition. That is, early in a given process, it may be advantageous to know, even approximately, when a steady state condition may be reached in the future. Additionally, or alternatively, it may be desirable to estimate whether a steady state condition is reached or present and/or to detect a steady state condition.

Estimating a time related to a steady state condition

FIGS. 2 through 5 show graphs 200-500 depicting estimates of a time related to a steady state condition at which the process reaches completion. As shown in FIGS. 2 through 5, the graphs 200-500 include a time axis 210 shown without units, but could be in any suitable unit, such as seconds, hours, days, weeks, etc. As shown in FIGS. 2 through 5, the time axis 210 ranges from 0 to 6. The graphs 200-500 also include a parameter axis 220, which is also not shown with units. The parameter axis 220 could represent any suitable parameter with corresponding suitable units. For example, the parameter axis 220 could be for density in units of grams-per-cubic centimeter, concentration in unitless percentage, viscosity in units of pascal-seconds, etc. As shown in FIGS. 2 through 5, the parameter axis 220 ranges from 0 to 70. For the sake of discussion, the time axis 210 may be in units of days and the parameter axis may be in units of density.

The graphs 200-500 also include parameter data plots 230-530 that represent a common data series, with variations in depiction depending on a current time demarcation. More specifically, the parameter data plots 230-530 are depicted as solid lines from a start time of zero to a current time. After the current time, the parameter data plots 230-530 are depicted as dashed lines to indicate expected, but not yet measured, data. The parameter data plots 230-530 may be measured values of a process. The process may be a continuing process. That is, the process may be ongoing and therefore a current time of the process may be between a start time and a time-at-completion at which a steady state condition of the continuing process may be present.

In the graph 200 of FIG. 2, the parameter data plot 230 includes an expected parameter data plot portion 232 that extends roughly from 0.5 to 6. In the graph 300 of FIG. 3, the parameter data plot 330 includes an expected parameter data plot portion 332 that extends roughly from 1.6 to 6. In the graph 400 shown in FIG. 4, the parameter data plot 430 includes an expected parameter data plot portion 432 that extends from about 0.5 to 6. In the graph 500 shown in FIG. 5, the parameter data plot 530 includes an expected parameter data plot portion 532 that extends from about 1.6 to 6.

The graphs 200-500 also include curves 240-540 fitted to the parameter data plots 230-530. The curves 240-540 are a graphical representation of functions obtained from a curve fit to the parameter data plots 230-530 of the continuing process.

Graphically, the functions are fit to the solid, or non-dashed portions, of the parameter data plots 230-530. The functions are not fitted to the expected parameter data plot portions 232-532 of the parameter data plots 230-530. The functions are continuously updated as the continuing process progresses. Accordingly, the functions are fitted to the parameter data plots 230-530 over a time axis 210 range of zero to a current time.

The curves 240-540 may be considered time-to-completion curves. In FIG. 2, a polynomial curve 240 extends from about 64 on the parameter axis 220 at time 0 to about 1.8 on the time axis 210. In FIG. 3, a polynomial curve 340 extends from about 60 on the parameter axis 220 at time 0 to about 2.7 on the time axis 210. In FIG. 4, an exponential curve 440 extends from about 64 on the parameter axis 220 at time 0 to a coordinate of about 6 on the time axis 210 and 12 on the parameter axis 220. In FIG. 5, an exponential curve 540 extends from about 64 on the parameter axis 220 to a coordinate of 6 on the time axis 210 and 13 on the parameter axis 220.

As to specific equations of the curves 240-530, in FIG. 2, the polynomial curve 240 is defined as $f(t) = 63.7 - 39.8t + 2.1t^2$. In FIG. 3, the polynomial curve 340 is defined as $f(t) = 60.5 - 29.4t + 2.7t^2$. In FIG. 4, the exponential curve 440 is defined as $f(t) = 52.7 + \frac{11.9}{e^{0.95t}}$. In FIG. 5, the exponential curve 540 is defined as $f(t) = 51.0 + \frac{13.3}{e^{0.95t}}$. It should be appreciated that other coefficients and function types (e.g., polynomial, exponential, etc.) may be employed. In the foregoing functions, the dependent variable or output is parameter values of the parameter axis 220 for independent variable t values of the time axis 210.

The graphs 200-500 also include an expected steady state parameter value line 250 of having a parameter axis 220 value of 15.5. The expected steady state parameter value line 250 may be a predetermined value obtained through any suitable means. For example, the expected steady state parameter value line 250 may be obtained based on historical data of multiple runs of a process prototype (e.g., recipe, template, etc.) that is subsequently used to generate the parameter data plot 230-530 shown in FIGS. 2 through 5. The expected steady state parameter value line 250 can therefore be used to estimate an expected completion time, or time-at-completion, for the process, as the following discussion explains.

The graphs 200-500 also include intersection time projection lines 260-560 that extends from an intersection of the curves 240-540 and the expected steady state parameter value line 250 to the time axis 210. Where the intersection time projection lines 260-560 intersect the time axis 210 indicates a time-at-completion, which is an estimated time when the process will reach the expected parameter value of 15.5. In FIG. 2, an intersection time projection line 260 demarcates a time-at-completion of about 1.3 on the time axis 210. In FIG. 3, an intersection time projection line 360 demarcates a time-at-completion of about 1.85 on the time axis 210. In FIG. 4, an intersection time projection line 460 demarcates a time-at-completion of about 2.83 on the time axis 210. In FIG. 5, an intersection projection line 560 demarcates a time-at-completion of about 3.31 on the time axis 210.

As to how long from a current time until a time-at-completion, a time-to-completion may be understood as being the time-at-completion minus the current time. As noted above, the current time is the time at which the expected parameter data plots 232-532 begins in the time-domain. Accordingly, it can be appreciated that the time-at-completion and time-to-completion are estimated values. That is, the time-at-completion and time-to-completion are continuously updated as current time progresses to provide an estimated value related to when a steady state condition of a process may be reached. As can also be appreciated, the accuracy of the estimates depends on a current-time duration of a process.

FIGS. 2 and 4 illustrate curve fitting early in a process. That is, the expected parameter data plot portion 232, 432 of FIGS. 2 and 4 begin relatively early in the process compared to the expected parameter data plot portions 332, 532 of FIGS. 3 and 5. It should also be appreciated that the polynomial curves 240, 340 have a looser fit to their respective parameter data plots 230, 330 than the exponential curves 440, 540 have to their respective parameter data plots 430, 530. Accordingly, the exponential curves 440, 540 may provide more accurate time-at-completion and time-to-completion values. With either the polynomial curves 240, 340 or the exponential curves 440, 540, the curve fitting is progressively improved as the process gets closer to a steady state condition or, in other terms, a current-time duration of the process increases which may be defined as a difference between a current time and a start time.

It should be appreciated that the parameter of a parameter data plot may or may not be a measured parameter of the continuing process. For example, it may be desirable to measure a density of a continuing process for controlling the process itself but estimate and determine a steady state condition based on another parameter that are not of the process. For example, the density of the continuing process may be measured by a vibratory meter where a parameter or parameters used for estimating and/or determining the steady state condition of the continuing process is from other sensor(s) (e.g., temperature, pressure, etc.) that are external to the vibratory meter. These other sensors may essentially be any sensor that, for example, provides data to the vibratory meter, system computer, remote computer, and/or the like.

The foregoing techniques can be used in a variety of conditions. For example, the calculations of time-at-completion and time-to-completion and the estimation and determination of a steady state condition could also be modified depending on the diagnostic parameters provided by the meters. By way of illustration, the Coriolis flow and density meters provide drive gain as a diagnostic parameter. High values of the drive gain could be indicative of process disturbances that might induce larger errors in the measured fluid properties. Parameter data, such as fluid parameter data like density, could be ignored or appropriately weighed down during periods of high drive gain when used to estimate steady-state and time-to-completion using the proposed solution.

In another example, a Coriolis meter, such as the vibratory meter 5 described with reference to FIGS. 12 and 13, may be used to achieve a target mass total (such as in a batch process) for the fluid going through the meter. In this example, the parameter for time-to-completion will be a total mass of fluid that has passed through the sensor. A disturbance here may be the occurrence of relatively low mass flow rate and hence, the mass flow rate itself can be a diagnostic parameter. A Coriolis meter may have poorer accuracy (i.e., higher measurement uncertainty) for mass flow rate measurements at relatively low flow rates. So, when a relatively low flow rate happens, the mass total calculation could be adjusted slightly higher or lower, in more general terms the time-to-completion could be adjusted higher or lower, to account for this higher uncertainty in mass flow rate and hence, in the mass total. Essentially, this disturbance can lead to a higher uncertainty in the time-to-completion and the appropriate adjustment to the time-to-completion (e.g., make it higher or lower) will depend on the process risk of wrongly estimating the time-to-completion.

As discussed above, the expected steady state parameter value line 250 value of 15.5 is based on a characterized process. For example, multiple processes of a prototype or template process may be run and characterized in various conditions. Accordingly, a prototype or template process may be sufficiently well-known such that an expected steady state parameter value line associated with the prototype or template process may be applied to all in-situ processes of the protype or template process. It should be appreciated that alternative methods may be employed that do not require prior knowledge of a prototype or template process or an uncertainty associated with relying on a predetermined value of a characterized prototype or template process, as the following explains.

Estimating a steady state condition of a process

FIGS. 6 and 7 show graphs 600, 700 depicting estimates of a steady state condition of a process. As shown in FIGS. 6 and 7, the graphs 600, 700 include the time axis 210 and the parameter axis 220 described with reference to FIGS. 2 through 5. Also shown in FIGS. 6 and 7 is a parameter data plot 630 similar to the parameter data plots 230-530 described with reference to FIGS. 2 through 5. However, in contrast to the parameter data plots 230-530 shown in FIGS. 2 through 5, the parameter data plot 630 of FIGS. 6 and 7 does not include an expected parameter data plot portion. This is due to the process underlying the parameter data plot 630 reaching completion. The process reaching completion is based on whether or not a steady state condition has been reached. Also shown in FIGS. 6 and 7 is an exponential curve 640 that is fitted to the parameter data plot 630. The exponential curve 640 extends from about 64 on the parameter axis 220 at time 0 of the time axis 210 to a coordinate of 6 on the time axis 210 and about 13 on the parameter axis 220.

Referring to FIG. 6, the most recent parameter value, which may be a most subsequent value of the parameter data plot 630, is indicated by a reference parameter value line 650. The reference parameter value line 650 extends the entire timespan of the time axis 210 and, since it represents a constant parameter value of 13, is perfectly flat or, mathematically, has a parameter/time slope value of zero. As can be appreciated, if a slope of the exponential curve 640 is about zero, then the process can be considered in a steady state condition. Accordingly, a steady state condition can be estimated by determining a slope of the exponential curve 640.

As shown in FIG. 6, the graph 600 includes a slope line 660 of the exponential curve 640. The slope line 660 may be an instantaneous slope of the exponential curve 640 at the time of the most recent parameter value or the most subsequent measured value of the parameter data plot 630, although any suitable slope line may be employed, such as those based on discrete values spaced apart by a discrete span of time, etc. As can be appreciated from comparing the slope line 660 and the reference parameter value line 650, the slope line 660 has a slight slope that could be characterized as having a corresponding angle of less than 1 degree. This slope may indicate that a steady state condition has been reached, depending on a threshold value.

In contrast to the slope line 660 of FIG. 6, FIG. 7 shows a tolerance box 750 about a recent portion of the exponential curve 640. The tolerance box 750 is shown as having a tolerance duration tl_d and a tolerance band tl_b. The tolerance duration tl_d and the tolerance band tl_b may be referred to as dimensions of the tolerance box 750. As can be appreciated, the tolerance box 750 has a substantially narrow profile. That is, the length of the tolerance duration tl_d is substantially greater than the length of the tolerance band tl_b. The dimensions of the tolerance box 750 may be predetermined, based on the conditions of the process, etc.

A position of the tolerance box 750 about the exponential curve 640 may be determined by any suitable means. For example, an algorithm that positions the tolerance box 750 to minimize a deviation from between the exponential curve 640 and the tolerance duration tl_d may be employed. By way of illustration, parameter values of the exponential curve 640 at the ends of the tolerance band tl_b may be compared to proximate values of the tolerance band while “moving” the tolerance box up and down parallel to the parameter axis 220 to minimize any differences. Additionally, or alternatively, a difference of parameter values between the exponential curve 640 at the ends of the tolerance duration tl_d and a value of the tolerance band tl_b may be compared. If the difference of the exponential curve 640 is less than the value of the tolerance band tl_b, then a steady state condition may be indicated. Any suitable method of indicating a steady state condition may be employed, but such an indication may generally be understood to mean something equivalent to the exponential curve 640 lying entirely within the tolerance box 750.

In the above description of FIGS. 6 and 7, the exponential curve 640 is compared to criteria to estimate that a steady state condition has been reached. That is, because the parameter data plot 630 has not been compared to a criterion, a determination of a steady state condition has not been made. As can be appreciated, because the exponential curve 640 may also be used to determine a time-at-completion and/or a time-to-completion, additional computing resources required to estimate a steady state condition may not be significant. Additionally, a true result from an estimate of a steady state condition may, in some cases, be a condition precedent to a determination of a steady state condition of a process.

Determining a steady state condition

FIG. 8 shows a graph 800 for determining a steady state condition of a process. As shown in FIG. 8, the graph 800 includes the time axis 210 and the parameter axis 220 described with reference to FIGS. 2 through 5. Also shown in FIG. 8 is a parameter data plot 830 similar to the parameter data plots 230-530 described with reference to FIGS. 2 through 5. The parameter data plot 830 of FIG. 8 is shown as including an expected parameter data plot portion 832 that extends from a current time of about 5.6 to a time of 6. A curve fit is not shown in FIG. 8, although curve fits may be employed in alternative graphs.

FIG. 8 also shows a tolerance box 850 about a recent portion of the parameter data plot 830. Similar to the tolerance box 750 of FIG. 7, the tolerance box 850 is shown as having a tolerance duration tl_d and a tolerance band tl_b. The tolerance duration tl_d and the tolerance band tl_b may be referred to as dimensions of the tolerance box 850. As can be appreciated, the tolerance box 850 has a substantially narrow profile. That is, the length of the tolerance duration tl_d is substantially greater than the length of the tolerance band tl_b. The dimensions of the tolerance box 850 may be predetermined, based on the conditions of the process, etc.

The tolerance box 850 may be positioned about the parameter data plot 830 in any suitable manner. For example, the tolerance box 850 may be "moved" up and down until a maximum number of parameter values are within the tolerance band tl_b over the tolerance duration tl_d. Additionally, or alternatively, the tolerance box 850 may be "moved" up or down until a minimal number of parameter values are outside the tolerance band tl_b. Additionally, or alternatively, the tolerance band tl_b may be centered on a mean value of the parameter values within the tolerance duration tl_d. However positioned, if the number of parameter values outside the tolerance band tl_b is zero over the tolerance duration tl_d, then a steady state condition may be determined. However, any suitable definition to determine a steady state condition may be employed. It should be understood that any suitable method of indicating a steady state condition may be employed but may generally be understood to mean something equivalent to the parameter data plot 830 lying entirely within the tolerance box 850.

Methods to make and use the above-described estimations and determinations of a steady state condition are addressed in the following.

Methods

FIG. 9 shows a method 900 for estimating a time of a steady state condition of a process. As shown in FIG. 9, the method 900 obtains time domain parameter data of a continuing process converging to the steady state condition in step 910. In step 920, the method 900 fits a function to the time domain parameter data. The method 900, in step 930, determines an intersection time where the function intersects with an estimated steady state parameter value.

The estimated steady state parameter value may be one of a user input parameter value and a parameter value derived from a prototype process of the continuing process. For example, it may be known that a prototype process has a steady state parameter value of 15.5, as an example described above discloses. Other values may be employed. For example, a process may have multiple steady state conditions where, for example, processes are sequential based on a steady state condition being reached in a given process.

The parameter value derived from the prototype process is a value of the function at a slope of approximately zero. The prototype process can be a normalized process that can be scaled to an actual or in situ process depending on process conditions. A function fit to the prototype process could have a portion that approximates a steady state condition of the prototype process where the slope is approximately zero. Such a function may be referred to as a prototypical curve or function. It should be appreciated that adapting a prototypical curve or function to an actual or in situ process may change the dimensions of the prototypical curve due to scaling factors correlated to actual process conditions.

The intersection time may be an estimated time-of-completion of the continuing process. For example, the intersection time may be subsequent to the current time of the continuous process. Accordingly, the intersection time may also be continuously updated as the continuous process progresses. As can be appreciated, the accuracy of the intersection time may also be continuously improved as the continuous process progresses.

The method 900 may further comprise determining an estimated time-to-completion of the continuing process based on a time-difference between a most recent parameter value of the time domain parameter data and the intersection time. The most recent parameter value may be at a current time. However, it should be understood that there may be a time-delay between an actual current time (e.g., as measured by a clock outside the continuing process or device 100) and the current time of the most recent parameter value concatenated in real-time to the time-series of parameter values. The time difference may be comprised of units of time, such as seconds, minutes, hours, days, etc. or may be unitless integers that correspond to some measure of time.

It should be appreciated that the step of obtaining the time domain parameter data of the continuing process converging to the steady state condition may comprise continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition. For example, a given parameter of the continuing process may be measured continuously.

The time domain parameter data may comprise a time series of parameter values that relate a time value to a parameter value of the continuing process. The relationship between the time value and the parameter value may be a relation, such as being on a same row of a table, a quantity relationship, such as ordered pairs of incremented time values that are paired to a parameter value, etc. The format of the time domain parameter data may be in ordered pairs of a parameter value and a time-related value, a matrix that relates time-values to parameter values, and/or the like.

The step of obtaining the time domain parameter data of the continuing process converging to the steady state condition may comprise obtaining time domain parameter data from a fluid flow device measuring a fluid flow process. For example, the device

100 described above may measure a parameter of a fluid flow, such as a concentration, density, mass flow rate, etc. of a fluid flow, although any suitable device that measures parameters of a continuing process may be employed.

FIG. 10 shows a method 1000 for estimating a steady state condition of a process. As shown in FIG. 10, the method 1000 obtains time domain parameter data of a continuing process converging to a steady state condition in step 1010. In step 1020, the method 1000 fits a function to the time domain parameter data. The method 1000, in step 1030, compares the function to a tolerance to estimate the steady state condition. The tolerance may comprise one of a tolerance box and a slope threshold. For example, with reference to FIGS. 6 and 7, the tolerance box and the slope threshold of the method 1000 may respectively be tolerance box 750 and the slope threshold described with reference to FIGS. 7 and 6.

The tolerance box may comprise a tolerance band and a tolerance duration. The tolerance band may be for parameter values and therefore extend parallel to the parameter axis 220. The tolerance duration may be in the time domain and therefore may extend parallel to the time axis 210 described above. The tolerance duration may be a length that extends from a most recent parameter value of the time domain parameter data into a time domain of the time domain parameter data. For example, with reference to FIG. 7, the tolerance duration tl_d of the tolerance box 750 extends from 6 back-in-time to about 5.2, which is a length of about 0.8 as measured against the time axis 210. The steady state condition may be estimated when the function is entirely within the tolerance box. That is, the function is within the tolerance or, more specifically, the tolerance box, if the function has no values that are greater than or less than the parameter values of the tolerance band over the length of the tolerance duration.

The slope threshold may be compared to a slope of the function to estimate the steady state condition. The slope of the function may be based on a most recent parameter value of the function. For example, after curve fitting to the most recent parameter value to obtain a most recent function, a slope of the most recent function may be determined. The slope may be based on a derivative value of the most recent function at the most recent parameter value. Alternatively, the slope may be based on two or more values of the most recent function over a length in the time-domain of the function from the most recent parameter value. The slope of this or other functions may be compared to a threshold slope value to estimate a steady state condition of the continuing process.

The step of obtaining the time domain parameter data of the continuing process converging to the steady state condition may comprise continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition. The time domain parameter data of the continuing process is a time series of parameter values that relate a time value to a parameter value of the continuing process. The step of obtaining the time domain parameter data of the continuing process converging to the steady state condition may comprise obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

FIG. 11 shows a method 1100 for determining a steady state condition of a process. As shown in FIG. 11, the method 1100 obtains time domain parameter data of a continuing process converging to a steady state condition in step 1110. In step 1120, the method 1100 compares the time domain parameter data to a tolerance to detect the steady state condition. The tolerance may be a tolerance box, although any suitable tolerance may be employed. With reference to FIG. 8, the tolerance box of the method 1100 may be the tolerance box 850 of FIG. 8, although any suitable tolerance box may be employed.

The tolerance box may comprise a tolerance band and a tolerance duration. The tolerance duration can extend a length from a most recent parameter value of the time domain parameter data into a time domain of the time domain parameter data. For example, referring to FIG. 8, the tolerance duration extends from about 5.6 back-in-time to about 4.8. The difference between these two values is a length of about 0.8 in the time domain, as measured against the time axis 210, of the parameter data plot 830. The method 1100 may further detect the steady state condition of the time domain parameter data if the time domain parameter data is entirely within the tolerance band over the entire tolerance duration.

Obtaining the time domain parameter data of the continuing process converging to the steady state condition may comprise continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition. The time domain parameter data of the continuing process may be a time series of parameter values that relate a time value to a parameter value of the continuing process. Obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

The methods 900, 1000, and/or 1100 can be performed on the electronics 140 described above, although any suitable electronics, computing resources, including remote computing resources can be employed. For example, the device 100 may be further connected to a remote computing resource that performs the method 900, 1000, and/or 1100. In such a configuration, the device 100 may provide parameter values to the remote computing resource. The remote computing resource and/or the electronics 140 can perform the curve fitting, compare curves/functions and/or the time domain parameter data to tolerances/thresholds. For example, the remote computing resource may be dedicated to curve fitting whereas the electronics 140 performs the comparison of the time domain parameter data to the tolerances/thresholds.

It should be appreciated that the tolerance boxes 750, 850 and thresholds, such as the slope threshold described with reference to FIG. 6, as well as other tolerances and thresholds, could be configured appropriately for the specific parameter and the process. As an example, if an implementation were applied to the volumetric concentration of alcohol in an alcohol-water mixture (typically referred to as ABV or alcohol by volume), a tolerance band could be set to 0.6%, to meet the +/- 0.3% regulatory accuracy requirements.

Additionally, or alternatively, the foregoing methods 900, 1000, 1100 could be applied to more than one parameter. For example, a single or combination of these measured and/or calculated parameters may be used to compute when steady state has been reached. As can be appreciated, the rate of change of these parameters will be used to also estimate time to completion. As the parameters are measured or calculated continuously, the achievement of steady-state and time-to-completion may also be updated at the same or very similar rates.

As can be appreciated, the methods 900-1100, alone or in combination, can be employed in various continuing processes and/or on various devices. The following describes some exemplary devices that may correspond to the device 100 described with reference to FIG. 1.

Exemplary device

FIG. 12 shows a vibratory meter 5 configured to estimate and determine a steady state condition of a process. The vibratory meter 5 is an example of the device 100 described with reference to FIG. 1. As shown in FIG. 12, the vibratory meter 5 is a Coriolis flow meter that comprises a sensor assembly 1 and meter electronics 20. The sensor assembly 1 responds to mass flow rate and density of a process material. The meter electronics 20 is connected to the sensor assembly 1 via leads 10 to provide density, mass flow rate, and temperature information over path 26, as well as other information.

The sensor assembly 1 includes a pair of manifolds 15 and 15', flanges 11 and 11' having flange necks, a pair of parallel conduits 13 and 13', driver 18, resistive temperature detector (RTD) 19, and a pair of pick-off sensors 17l and 17r. Conduits 13 and 13' have two essentially straight inlet legs and outlet legs, which converge towards each other at conduit mounting blocks 12 and 12'. The conduits 13, 13' bend at two symmetrical locations along their length and are essentially parallel throughout their length. Brace bars 14 and 14' serve to define the axis W and W' about which each conduit 13, 13' oscillates. The legs and of the conduits 13, 13' are fixedly attached to conduit mounting blocks 12 and 12' and these blocks, in turn, are fixedly attached to manifolds 15 and 15'. This provides a continuous closed material path through sensor assembly 1.

When flanges 11 and 11' are connected into a process line (not shown) which carries the process material that is being measured, material enters the inlet end of the vibratory meter through an orifice in the flange 11 and is conducted through the manifold 15 to the conduit mounting block 12 having a surface. Within the manifold 15 the material is divided and routed through the conduits 13, 13'. Upon exiting the conduits 13, 13', the process material is recombined in a single stream within the block 12' having a surface and the manifold 15' and is thereafter routed to the outlet end connected by the flange 11' to the process line (not shown).

The conduits 13, 13' are selected and appropriately mounted to the conduit mounting blocks 12, 12' so as to have substantially the same mass distribution, moments of inertia and Young's modulus about bending axes W--W and W'--W', respectively. These bending axes go through the brace bars 14, 14'. Inasmuch as the Young's modulus of the conduits change with temperature, and this change affects the calculation of flow and density, RTD 19 is mounted to conduit 13' to continuously measure the temperature of the conduit 13’. The temperature of the conduit 13’ and hence the voltage appearing across the RTD 19 for a given current passing therethrough is governed by the temperature of the material passing through the conduit 13’. The temperature dependent voltage appearing across the RTD 19 is used in a well-known method by the meter electronics 20 to compensate for the change in elastic modulus of the conduits 13, 13' due to any changes in conduit temperature. The RTD 19 is connected to the meter electronics 20 by a lead.

Both of the conduits 13, 13' are driven by driver 18 in opposite directions about their respective bending axes W and W' and at what is termed the first out-of-phase bending mode of the vibratory meter. This driver 18 may comprise any one of many well-known arrangements, such as a magnet mounted to the conduit 13' and an opposing coil mounted to the conduit 13 and through which an alternating current is passed for vibrating both conduits 13, 13’. A suitable drive signal is applied by the meter electronics 20, via a lead, to the driver 18.

The meter electronics 20 receives the RTD 19, and sensor signals appearing on leads 10 carrying left and right sensor signals, respectively. The meter electronics 20 produces the drive signal appearing on the lead to driver 18 and vibrate conduits 13, 13'. The meter electronics 20 processes the left and right sensor signals and the RTD 19 to compute the mass flow rate and the density of the material passing through sensor assembly 1. This information, along with other information, is applied by meter electronics 20 over path 26 as a signal.

A mass flow rate measurement can be generated according to the equation:

$$\dot{m} = FCF[\Delta t - \Delta t_0]; \qquad \text{Equation [1]}$$

where:

$\dot{m}$ is a measured mass flow rate;

FCF is a flow calibration factor;

Δt is a measured time-difference; and

Δt_0 is a zero-flow time-difference.

The measured time-difference Δt comprises an operationally derived (i.e., measured) time-difference value comprising the time-difference existing between the pickoff sensor signals, such as where the time-difference is due to Coriolis effects related to mass flow rate through the vibratory meter 5. The measured time-difference Δt is a direct measurement of a mass flow rate of the flow material as it flows through the vibratory meter 5. The zero-flow time-difference Δt_0 comprises a time-difference at a zero flow. The zero-flow time-difference Δt_0 is a zero-flow value that may be determined at the factory and programmed into the vibratory meter 5. The zero-flow time-difference Δt_0 is an exemplary zero-flow value. Other zero-flow values may be employed, such as a phase difference, time-difference, or the like, that are determined at zero flow conditions. A value of the zero-flow time-difference Δt_0 may not change, even where flow conditions are changing. A mass flow rate value of the material flowing through the vibratory meter 5 is determined by multiplying a difference between measured time-difference Δt and a reference zero-flow value Δt_0 by the flow calibration factor *FCF*. The flow calibration factor *FCF* is proportional to a physical stiffness of the vibratory meter.

As to density, a resonance frequency at which each conduit 13, 13' vibrates may be a function of the square root of a spring constant of the conduit 13, 13' divided by the total mass of the conduit 13, 13' having a material. The total mass of the conduit 13, 13' having the material may be a mass of the conduit 13, 13' plus a mass of a material inside the conduit 13, 13'. The mass of the material in the conduit 13, 13' is directly proportional to the density of the material. Therefore, the density of this material may be proportional to the square of a period at which the conduit 13, 13' containing the material oscillates multiplied by the spring constant of the conduit 13, 13'. Hence, by determining the period at which the conduit 13, 13' oscillates and by appropriately scaling the result, an accurate measure of the density of the material contained by the conduit 13, 13' can be obtained. The meter electronics 20 can determine the period or resonance frequency using the sensor signals and/or the drive signal. The conduits 13, 13' may oscillate with more than one vibration mode.

The vibratory meter 5 may be calibrated with a factory zero-flow value while the vibratory meter 5 is in a no or zero-flow condition. A user, at any time, may additionally, and optionally, perform a push-button calibration to obtain a push-button zero-flow value. Additionally, or alternatively, the vibratory meter may automatically perform a calibration to obtain an automatic zero-flow value. The zero-flow value used to measure a flow rate of a fluid may be the factory zero-flow value, a push-button zero-flow value, the automatic zero-flow value, or any other suitable zero-flow value.

Measurements, saved values/constants, user settings, saved tables, etc., may be employed during the zero calibration of the vibratory meter 5. The calibration may monitor the vibratory meter 5 for conditions of the vibratory meter 5 and compensate for those conditions. The conditions may include user-input conditions, measured conditions, inferred conditions, or the like, without limitation. The conditions may include temperature, fluid density, flow rate, meter specifications, viscosity, Reynold's number, post calibration compensation, etc. In addition, different constants, such as a flow calibration factor (FCF), for example without limitation, may be applied based on operating conditions or user preference.

An initial zero-flow value may be determined during a calibration conducted as part of the initial factory setup of the vibratory meter 5. This may entail placing the vibratory meter 5 in a no or zero-flow condition and determining a time-difference, phase difference, or the like, between the left and right sensor signals. The determined value is stored in one or more memories as the initial zero-flow value and used as a reference zero-flow value. By way of example, for Equation [1] discussed above, the reference zero-flow value may be the ΔT_0 term, which may be a no or zero-flow time-difference between the left and right sensor signals. Once the reference zero-flow value is determined, the flow calibration factor (FCF) may be established, which, as can be appreciated from above Equation [1], may be a slope of a line that dictates the relationship between the measured time-difference $\Delta t_{measured}$ and the mass flow rate $\dot{m}$. The FCF may be stored in the one or more memories.

FIG. 13 shows a meter electronics 20 configured to estimate and determine a steady state condition of a process. As shown in FIG. 13, the meter electronics 20 includes an interface 21 and a processing system 22. The meter electronics 20 receives a vibrational response from a sensor assembly, such as the sensor assembly 1, for example. The meter electronics 20 processes the vibrational response in order to obtain flow properties of the flow material flowing through the sensor assembly 1. The meter electronics 20 may also perform checks, verifications, calibration routines, or the like, to ensure the flow properties of the flow material are accurately measured.

The interface 21 may receive the sensor signals from one of the pick-off sensors 17l, 17r shown in FIG. 12. The interface 21 can perform any necessary or desired signal conditioning, such as any manner of formatting, amplification, buffering, etc. Alternatively, some or all of the signal conditioning can be performed in the processing system 22. In addition, the interface 21 can enable communications between the meter electronics 20 and external devices. The interface 21 can be capable of any manner of electronic, optical, or wireless communication. The interface 21 can provide information based on the vibrational response. The interface 21 may be coupled with a digitizer, such as a coder/decoder (CODEC), wherein the sensor signal comprises an analog sensor signal. The digitizer samples and digitizes an analog sensor signal and produces a digitized sensor signal.

The processing system 22 conducts operations of the meter electronics 20 and processes flow measurements from the sensor assembly 1. The processing system 22 executes one or more processing routines and thereby processes the flow measurements in order to produce one or more flow properties. The processing system 22 is communicatively coupled to the interface 21 and is configured to receive the information from the interface 21.

The processing system 22 can comprise a general-purpose computer, a micro-processing system, a logic circuit, or some other general purpose or customized processing device. Additionally, or alternatively, the processing system 22 can be distributed among multiple processing devices. The processing system 22 can also include any manner of integral or independent electronic storage medium, such as the storage system 24.

The storage system 24 can store vibratory meter parameters and data, software routines, constant values, and variable values. In one embodiment, the storage system 24 includes routines that are executed by the processing system 22, such as a calibration routine 24a, density routine 24b and mass flow rate routine 24c of the vibratory meter 5. The storage system 24 can store values that are used in the routines, such as temperature correction, calibration, zero offset, etc. The storage system 24 can also store other types of values, such as statistical values, such as a mean, standard deviation, confidence interval, etc., or the like of the various value discussed herein. The storage system 24 can also store values in table format where each row in the table corresponds to a sample of time series, such as a time series of parameter data.

For the vibratory meter 5 described above, the calibration routine 24a may perform a zero verification, a flow calibration factor determination, and/or a mass flow rate error relationship determination and/or correction described above, although any suitable calibration routines may be employed. The density routine 24b may employ the sensor signals received by the interface 21 to calculate a density value. For example, the sensor signals from one of the pick-off sensors 17l, 17r may be employed to determine the resonance frequency at which each conduit 13, 13' vibrates. The resonance frequency can be used to determine a density value 24d.

The mass flow rate routine 24c may determine a mass flow rate value 24e based on the sensor signals received by the interface 21. The mass flow rate value 24e may be determined from the sensor signals, such as a time-difference 24f between a left pickoff sensor signal and a right pickoff sensor signal, and a flow calibration factor (FCF) value 24g.

Also included is the storage system 24 is time domain parameter data 24i, functions 24j, and tolerances/thresholds 24k. As described above, the time domain data 24i can be used to determine the functions 24j. The functions 24j can be used to estimate a time of a steady state condition or estimate the steady state condition. For example, a slope of a function may be compared to a tolerance/threshold 24k. Additionally, or alternatively, the time domain data 24i can be compared to a tolerance box of the tolerance/threshold 24k stored in the storage system 24.

The following discusses another exemplary device that can be used to estimate and determine a steady state condition of a process.

Exemplary ultrasonic meter

FIG. 14 shows an ultrasonic meter 30. The ultrasonic meter 30 includes an ultrasonic sensor assembly 31 and a meter electronics 32. The ultrasonic sensor assembly 31 includes a meter body or spool piece that defines a central passage or bore. The spool piece is designed and constructed to be coupled to a pipeline or other structure carrying fluids (e.g., natural gas) such that the fluids flowing in the pipeline travel through the central bore. While the fluids travel through the central bore, the ultrasonic sensor assembly 31 senses a flow rate of the fluid flow. The spool piece includes flanges that facilitate coupling of the spool piece to another structure.

In order to sense the fluid flow within the spool piece, the ultrasonic sensor assembly 31 includes a plurality of ultrasonic transducer assemblies 31u. As shown in FIG. 14, four such ultrasonic transducer assemblies 31u are shown in full or partial view. The ultrasonic transducer assemblies are paired. Moreover, each ultrasonic transducer assembly 31u electrically couples to a meter electronics 32. More particularly, each ultrasonic transducer assembly 31u is electrically coupled to the meter electronics 32 by way of a respective cable or equivalent signal conducting assembly.

FIG. 15 shows a cross-sectional overhead view of the ultrasonic sensor assembly 31. The spool piece has a predetermined size and defines the central bore through which the measured fluid flows. An illustrative pair of ultrasonic transducer assemblies 31u is located along the length of spool piece. The ultrasonic transducers are acoustic transceivers, and more particularly ultrasonic transceivers. The ultrasonic transducers both generate and receive acoustic signals having frequencies above, for example, about 20 kilohertz. The acoustic signals may be generated and received by a piezoelectric element in each transducer. To generate an ultrasonic signal, the piezoelectric element is stimulated electrically by way of a signal (e.g., a sinusoidal signal), and the element responds by vibrating. The vibration of the piezoelectric element generates the acoustic signal that travels through the measured fluid to the corresponding transducer assembly of the pair. Similarly, upon being struck by an acoustic signal, the receiving piezoelectric element vibrates and generates an electrical signal (e.g., a sinusoidal signal) that is detected, digitized, and analyzed by the meter electronics 32 associated with the ultrasonic sensor assembly 31.

A path, also referred to as a "chord," exists between illustrative ultrasonic transducer assemblies 31u at an angle to a centerline of the ultrasonic sensor assembly 31. The length of chord 33 is the distance between the face of a given ultrasonic transducer assembly 31u and the face of another ultrasonic transducer assembly 31u. A transit time of an ultrasonic signal between the illustrative ultrasonic transducer assemblies 31u depends in part upon whether the ultrasonic signal is traveling upstream or downstream with respect to the fluid flow. The transit time for an ultrasonic signal traveling downstream (i.e., in the same direction as the fluid flow) is less than its transit time when traveling upstream (i.e., against the fluid flow). The upstream and downstream transit times can be used to calculate the average velocity along the signal path, and the speed of sound in the measured fluid. Given the cross-sectional measurements of the ultrasonic sensor assembly 31 carrying the fluid, the average velocity over the area of the central bore may be used to find the volume of fluid flowing through the spool piece.

For a given chord, the chordal flow velocity v is given by:

$$v = \frac{L^2}{2X} \cdot \frac{T_{up} - T_{dn}}{T_{up} T_{dn}}; \qquad \text{Equation [2]}$$

and the chordal speed of sound c is given by:

$$c = \frac{L}{2} \cdot \frac{T_{up} + T_{dn}}{T_{up} T_{dn}}; \qquad \text{Equation [3]}$$

where:

L is the path length (i.e., face-to-face separation between upstream and downstream transducers),

X is the component of *L* within the meter bore in the direction of the flow, and

T_{up} and T_{dn} are the upstream and downstream transit times of sound energy through the fluid.

The average flow velocity through the ultrasonic sensor assembly 31 is given by:

$$v_{avg} = \sum_i w_i v_i; \qquad \text{Equation [4]}$$

where:

w_i is a chordal weighting factor,

v_i is the measured chordal flow velocity, and

the summation i is over all chords.

Accordingly, a pipeline dimension-based time-difference can be determined using the average flow velocity through the ultrasonic sensor assembly 31. Alternatively, a volume flow rate Q can be calculated by multiplying the average flow velocity v_{avg} by the cross-sectional area of the bore in the ultrasonic sensor assembly 31.

The meter electronics 32 may store and/or perform calculations related to some or all of the various equations and/or values described above. For example, the meter electronics 32 can estimate and determine a steady state condition of a process condition according to the above-described methods 900-1100.

The device 100 and methods 900-1100 described above estimate and determine a steady state condition of a process. The process may be a continuing process. That is, the process may be ongoing and therefore a current time of the process may be between a start time and a time-at-completion at which a steady state condition of the continuing process may be present. By continually obtaining time domain parameter data of a continuing process and fitting a function to the time domain parameter data, estimates, such as an estimated time-at-completion and/or an estimated steady state condition, may be increasingly accurate as the current time approaches the steady state condition of the process.

In addition, the steady state condition may be accurately determined by comparing the time domain parameter data to tolerances, such as a tolerance band and a tolerance duration of a tolerance box. By accurately determining the steady state condition of the continuing process, the process may be stopped and/or other processes may be initiated without undue delay or premature initiation. This can significantly improve the reliability of the process and processes that may be dependent on the accurate determination of the steady state condition.

The detailed descriptions of the above embodiments are not exhaustive descriptions of all embodiments contemplated by the inventors to be within the scope of the present description. Indeed, persons skilled in the art will recognize that certain elements of the above-described embodiments may variously be combined or eliminated to create further embodiments, and such further embodiments fall within the scope and teachings of the present description. It will also be apparent to those of ordinary skill in the art that the above-described embodiments may be combined in whole or in part to create additional embodiments within the scope and teachings of the present description.

Thus, although specific embodiments are described herein for illustrative purposes, various equivalent modifications are possible within the scope of the present description, as those skilled in the relevant art will recognize. The teachings provided herein can be applied to other estimation and determination of a steady state condition and not just to the embodiments described above and shown in the accompanying figures. Accordingly, the scope of the embodiments described above should be determined from the following claims.

We claim:

1. A method for estimating a time related to a steady state condition of a process, the method comprising:

obtaining time domain parameter data of a continuing process converging to the steady state condition;

fitting a function to the time domain parameter data; and

determining an intersection time where the function intersects with an estimated steady state parameter value.

2. The method of claim 1, wherein the estimated steady state parameter value is one of a user input parameter value and a parameter value derived from a prototype process of the continuing process.

3. The method of claim 2, wherein the parameter value derived from the prototype process is a value of a prototype function fit to the prototype process at a slope of approximately zero.

4. The method of claim 1, wherein the intersection time is an estimated time-at-completion of the continuing process.

5. The method of claim 1, further comprising determining an estimated time-to-completion of the continuing process based on a time-difference between the intersection time and a current time.

6. The method of claim 1, wherein obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition.

7. The method of claim 1, wherein the time domain parameter data comprises a time series of parameter values that relate a time value to a parameter value of the continuing process.

8. The method of claim 1, wherein obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

9. A device (100) configured to estimate a time related to a steady state condition of a process, the device (100) comprising:

a transducer (120) configured to measure a parameter; and

an electronics (140) communicatively coupled to the transducer (120), the electronics (140) being configured to perform one or more of the foregoing claims 1 through 8.

10. A method of estimating a steady state condition of a process, the method comprising:

obtaining time domain parameter data of a continuing process converging to the steady state condition;

fitting a function to the time domain parameter data; and

comparing the function to a tolerance to estimate the steady state condition.

11. The method of claim 10, wherein the tolerance comprises one of a tolerance box and a slope threshold.

12. The method of claim 11, wherein the tolerance box comprises a tolerance band and a tolerance duration.

13. The method of claim 11, wherein the steady state condition is estimated when the function is entirely within the tolerance box.

14. The method of claim 11, wherein the slope threshold is compared to a slope of the function to estimate the steady state condition.

15. The method of claim 14, wherein the slope of the function is based on a most recent parameter value of the function.

16. The method of claim 10, wherein obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition.

17. The method of claim 10, wherein the time domain parameter data of the continuing process is a time series of parameter values that relate a time value to a parameter value of the continuing process.

18. The method of claim 10, wherein obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

19. A device (100) configured to estimate a steady state condition of a process, the device (100) comprising:

a transducer (120) configured to measure a parameter; and

an electronics (140) communicatively coupled to the transducer (120), the electronics (140) being configured to perform one or more of the foregoing claims 10 through 18.

20. A method of determining a steady state condition of a process, the method comprising:

obtaining time domain parameter data of a continuing process converging to the steady state condition; and

comparing the time domain parameter data to a tolerance to detect the steady state condition.

21. The method of claim 20, wherein the tolerance comprises a tolerance band and a tolerance duration.

22. The method of claim 21, wherein the tolerance duration is a length that extends from a most recent parameter value of the time domain parameter data into a time domain of the time domain parameter data.

23. The method of claim 21, further comprising detecting the steady state condition of the time domain parameter data if the time domain parameter data is entirely within the tolerance band over the tolerance duration.

24. The method of claim 20, wherein obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises continuously obtaining the time domain parameter data of the continuing process converging to the steady state condition.

25. The method of claim 20, wherein the time domain parameter data of the continuing process is a time series of parameter values that relate a time value to a parameter value of the continuing process.

26. The method of claim 20, wherein obtaining the time domain parameter data of the continuing process converging to the steady state condition comprises obtaining the time domain parameter data from a fluid flow device measuring a fluid flow process.

27. A device (100) configured to determine a steady state condition of a process, the device (100) comprising:

a transducer (120) configured to measure a parameter; and

an electronics (140) communicatively coupled to the transducer (120), the electronics (140) being configured to perform one or more of the foregoing claims 20 through 26.

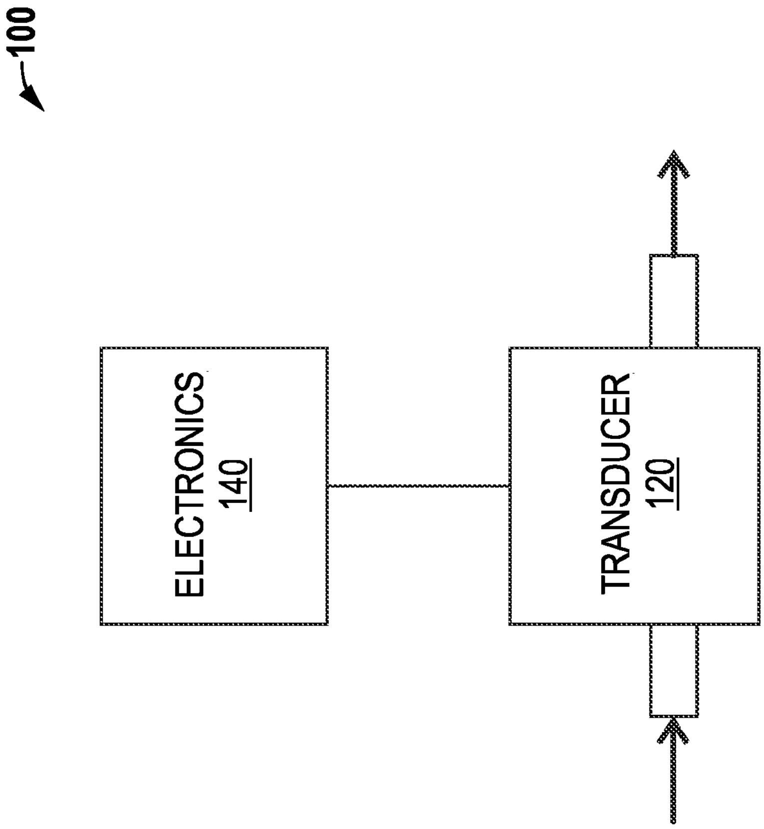


FIG. 1

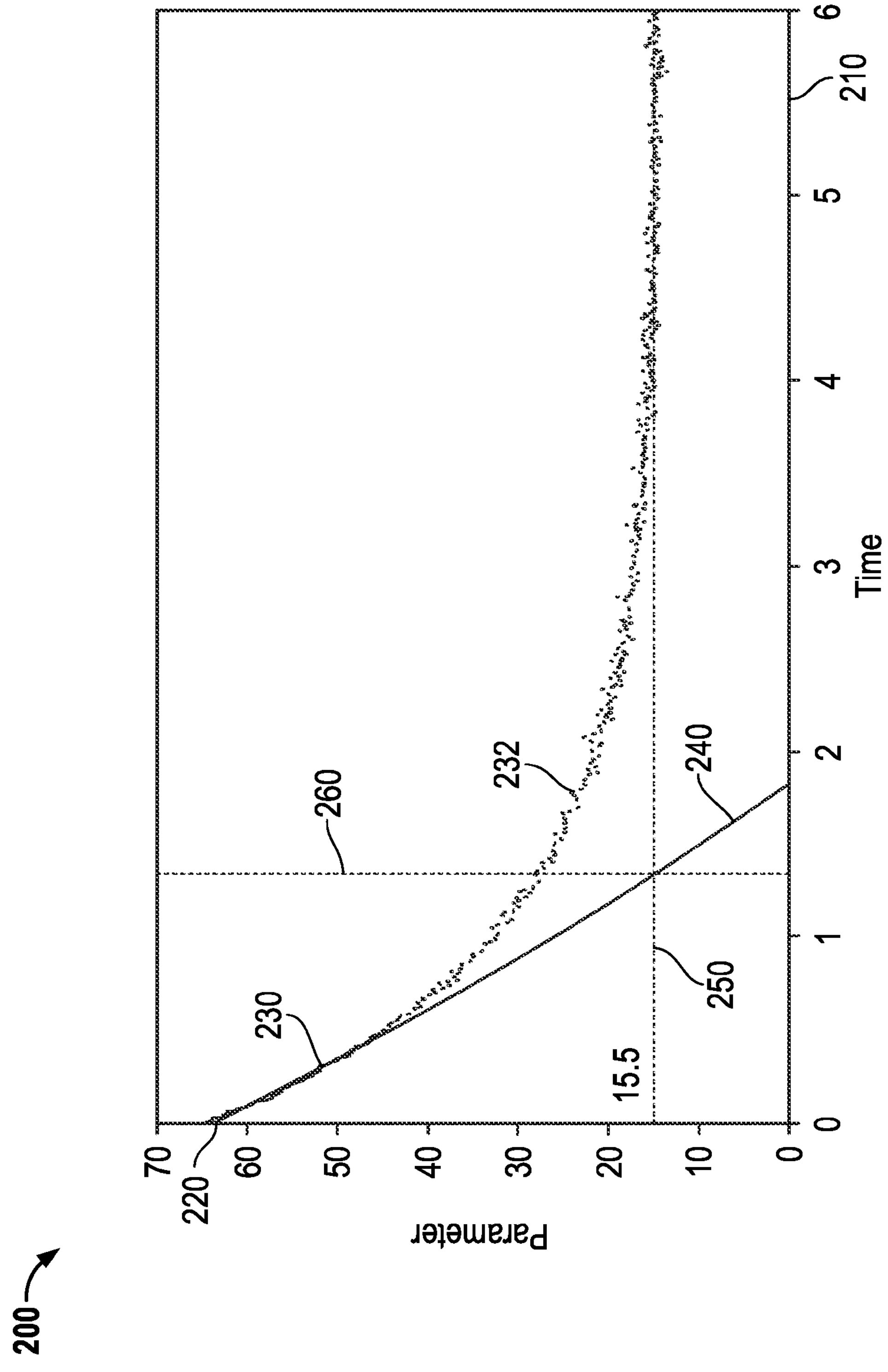

200
Parameter
Time
0
10
20
30
40
50
60
70
1
2
3
4
5
6
15.5
210
220
230
232
240
250
260

FIG. 2

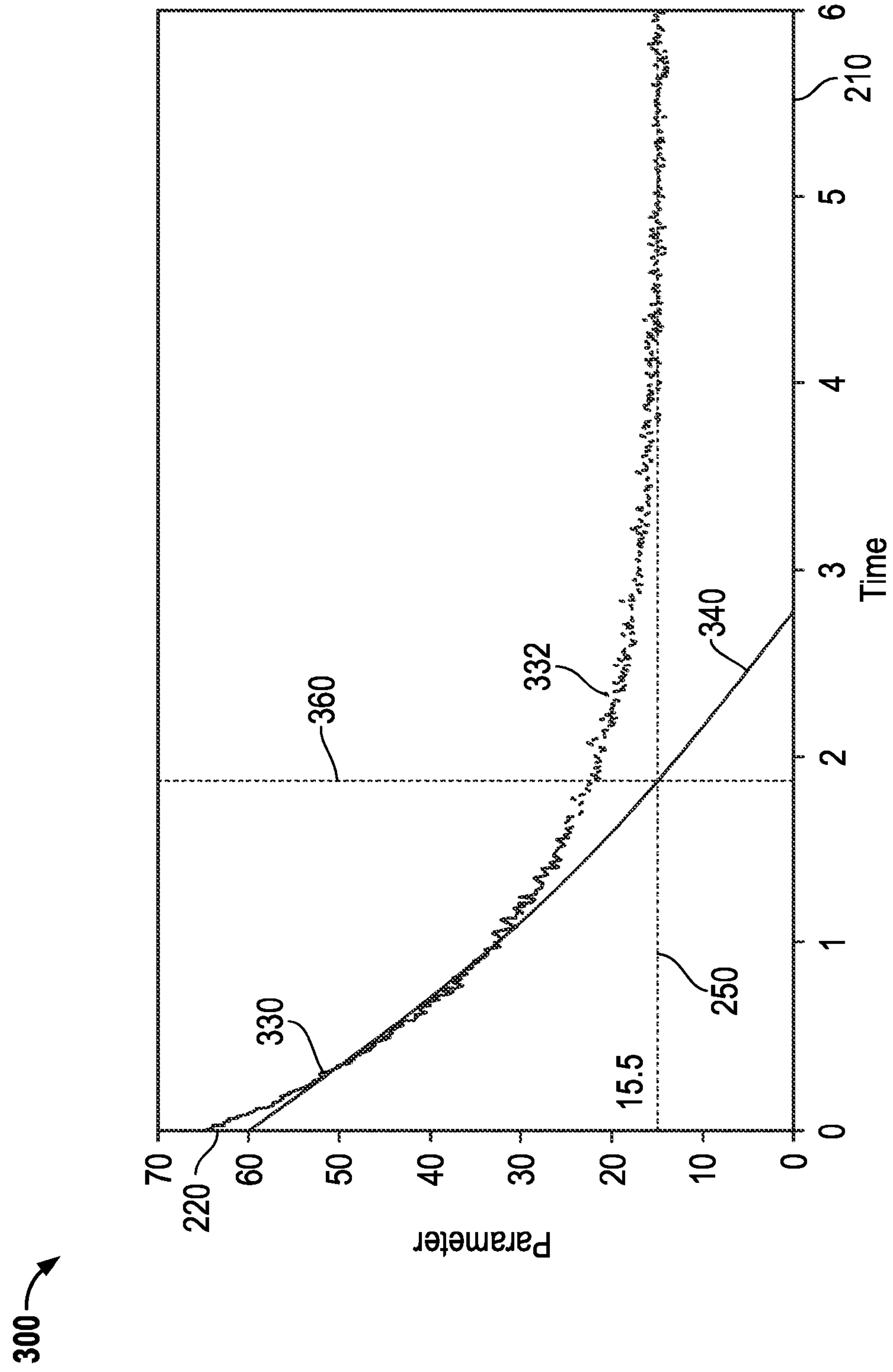

300
Parameter
Time
70
60
50
40
30
20
10
0
1
2
3
4
5
6
220
330
332
340
360
250
210
15.5

FIG. 3

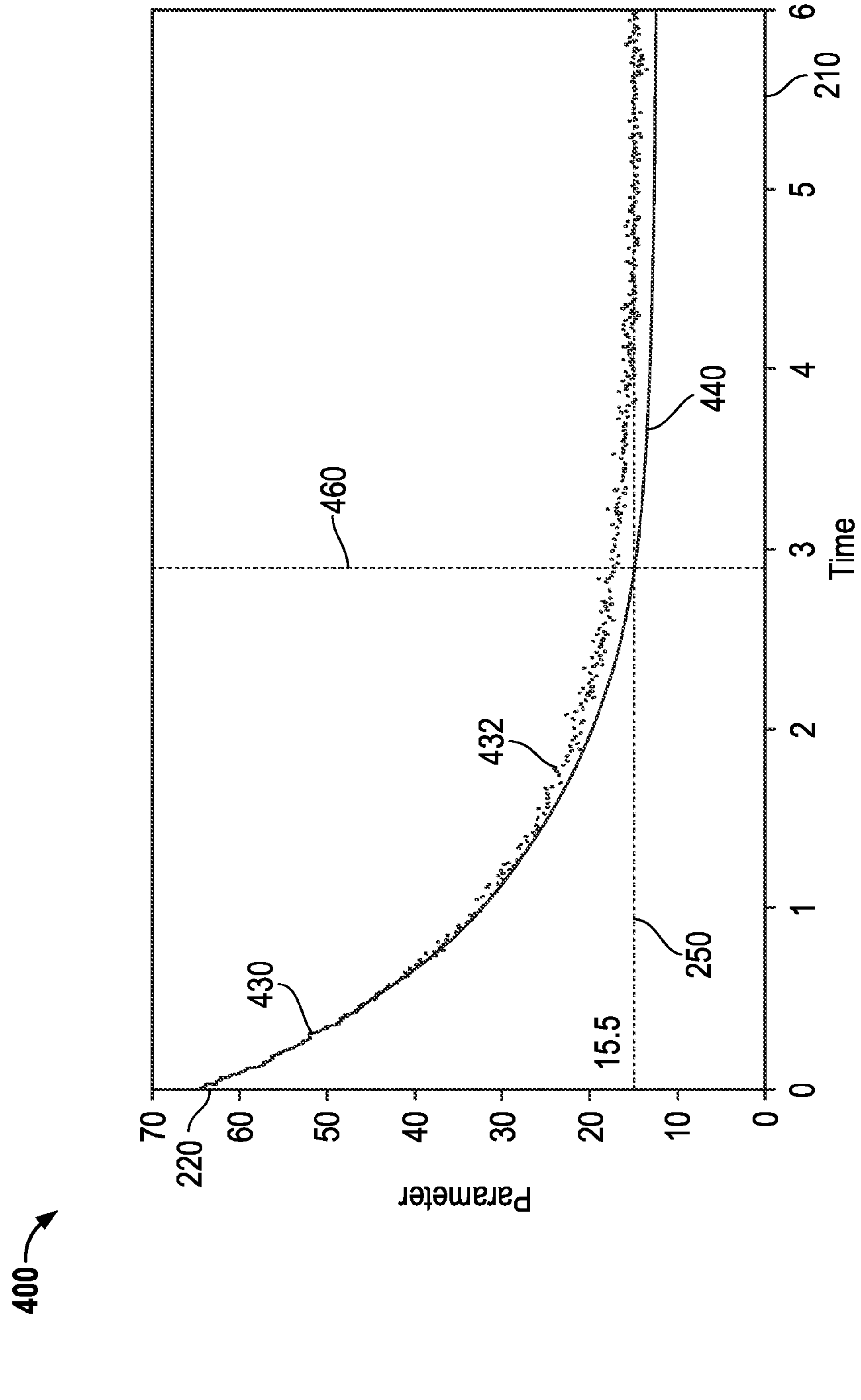

400
Parameter
70
60
50
40
30
20
10
0
220
430
432
460
440
250
15.5
210
0
1
2
3
4
5
6
Time

FIG. 4

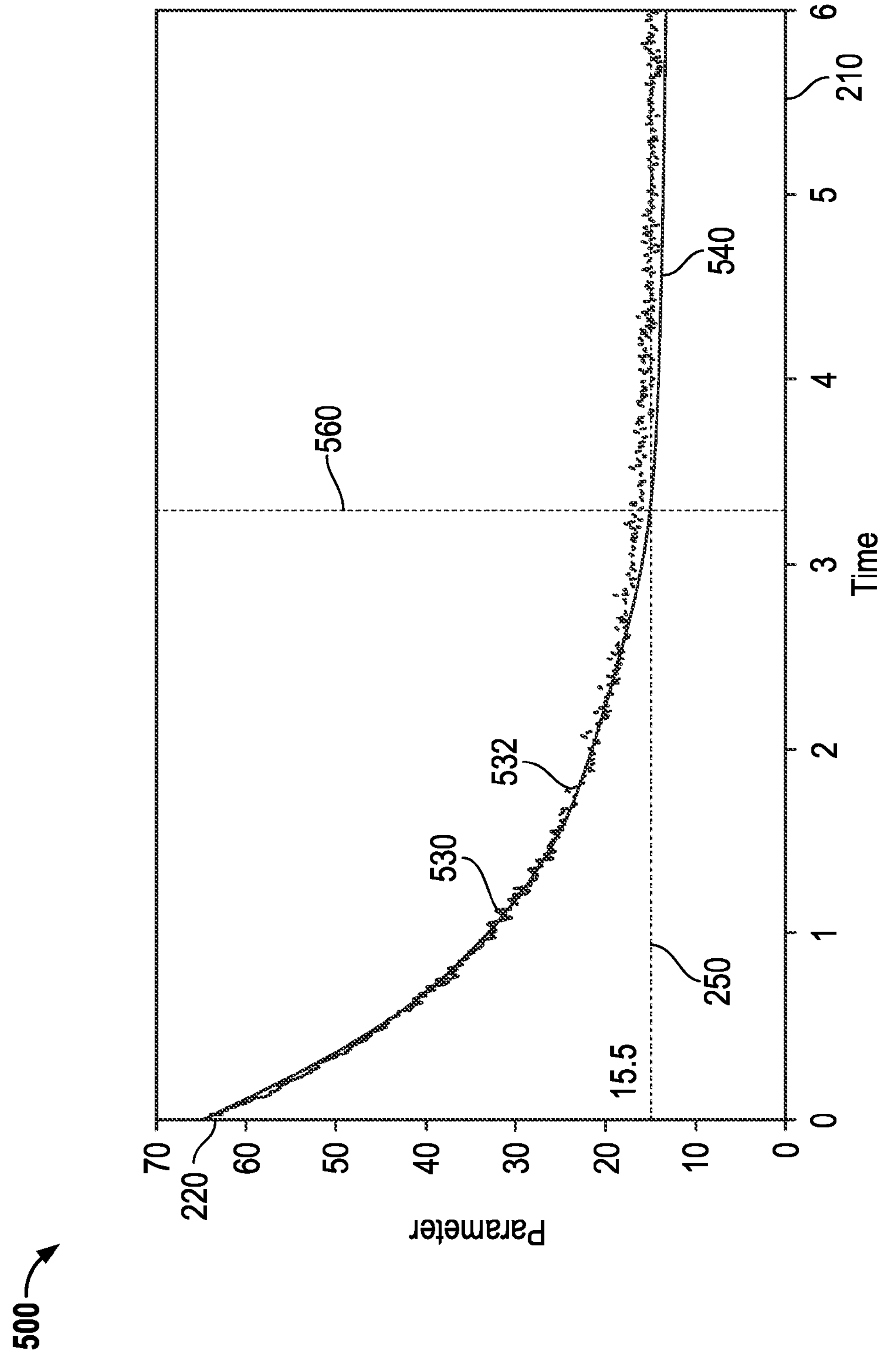

500
Parameter
Time
70
60
50
40
30
20
10
0
1
2
3
4
5
6
15.5
210
220
250
530
532
540
560

FIG. 5

6/15

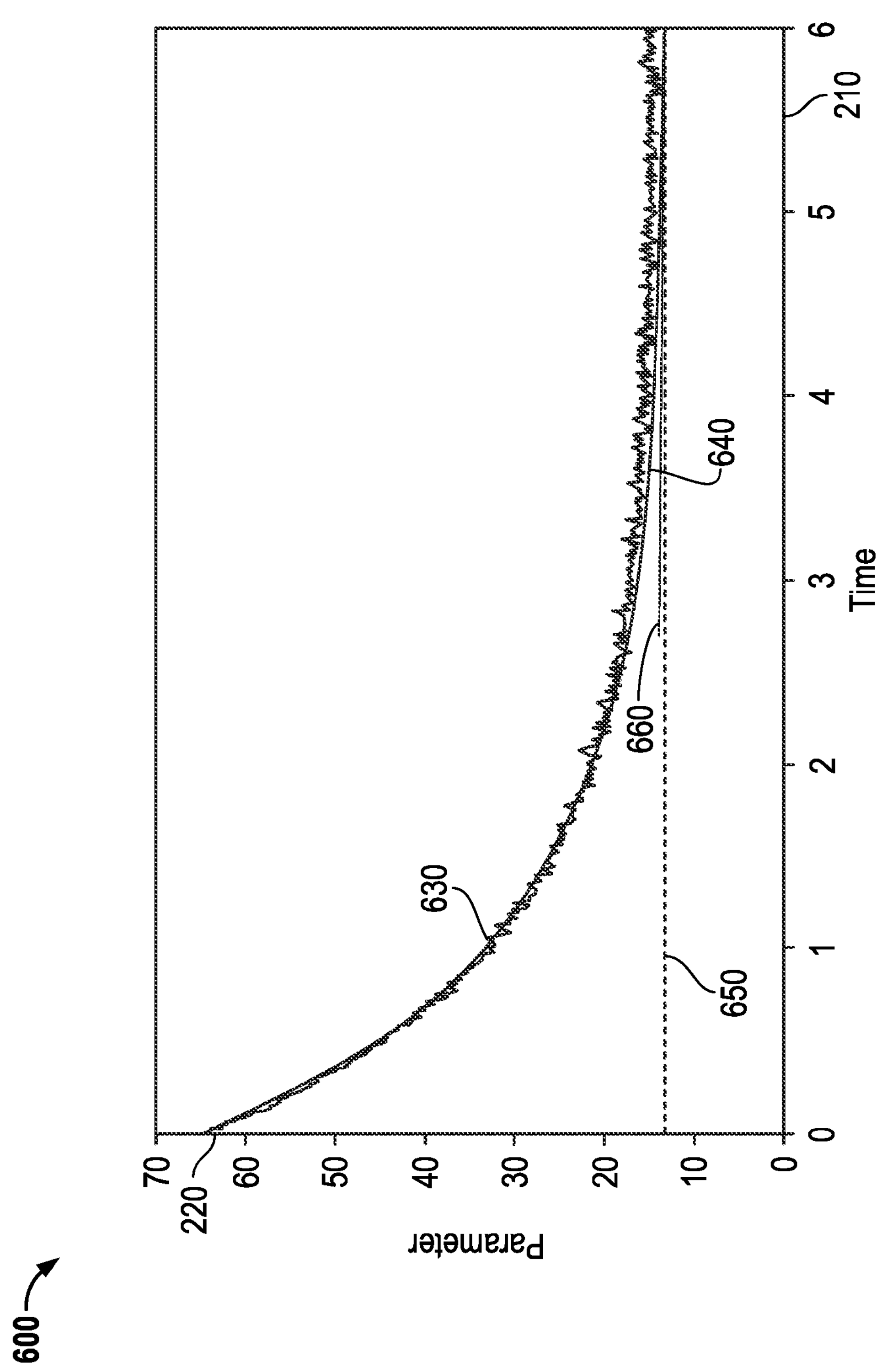

600
Parameter
70
60
50
40
30
20
10
0
220
Time
0
1
2
3
4
5
6
630
650
660
640
210

FIG. 6

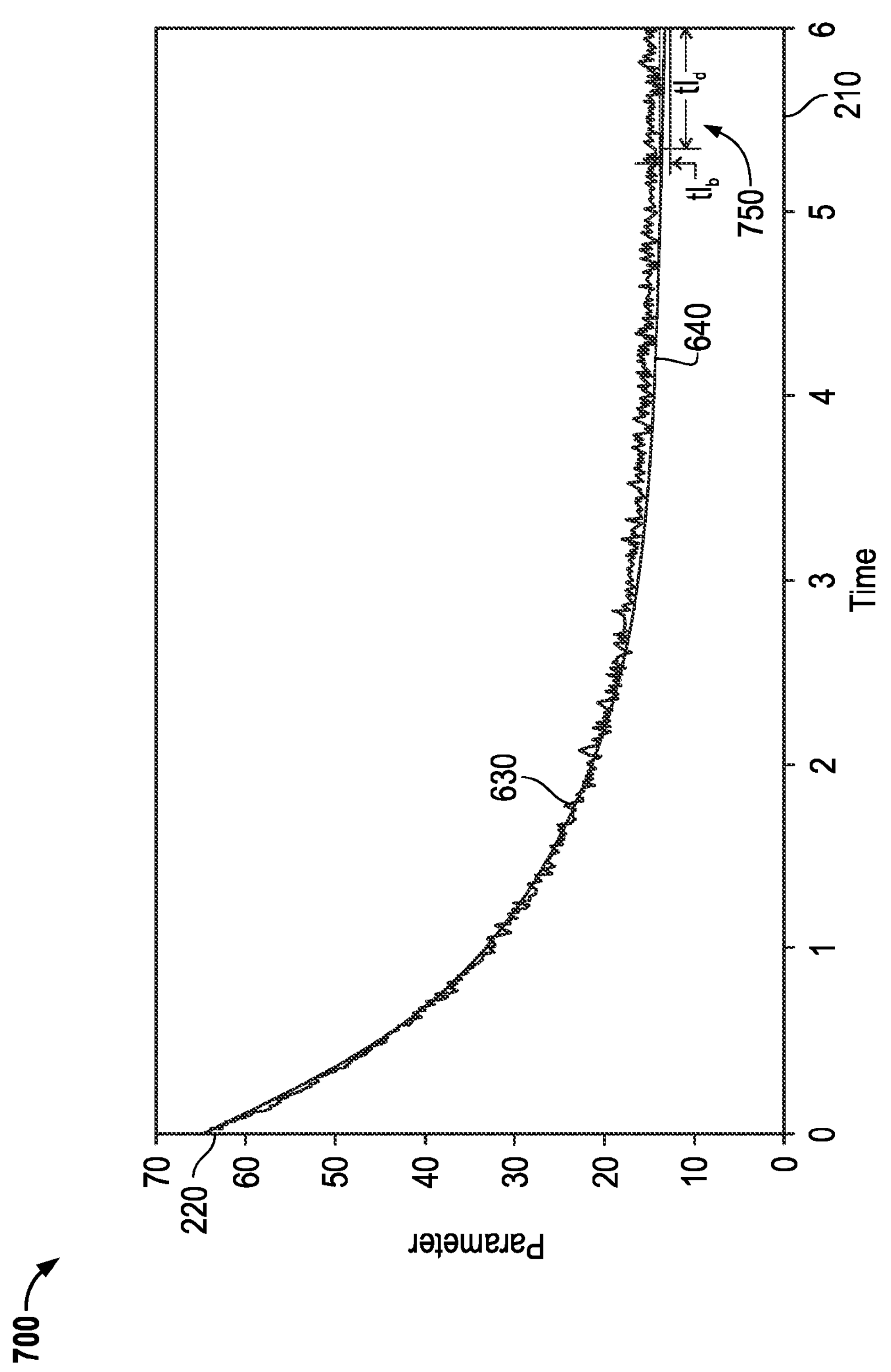

700
Parameter
Time
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
220
630
640
750
210
tl_b
tl_d

FIG. 7

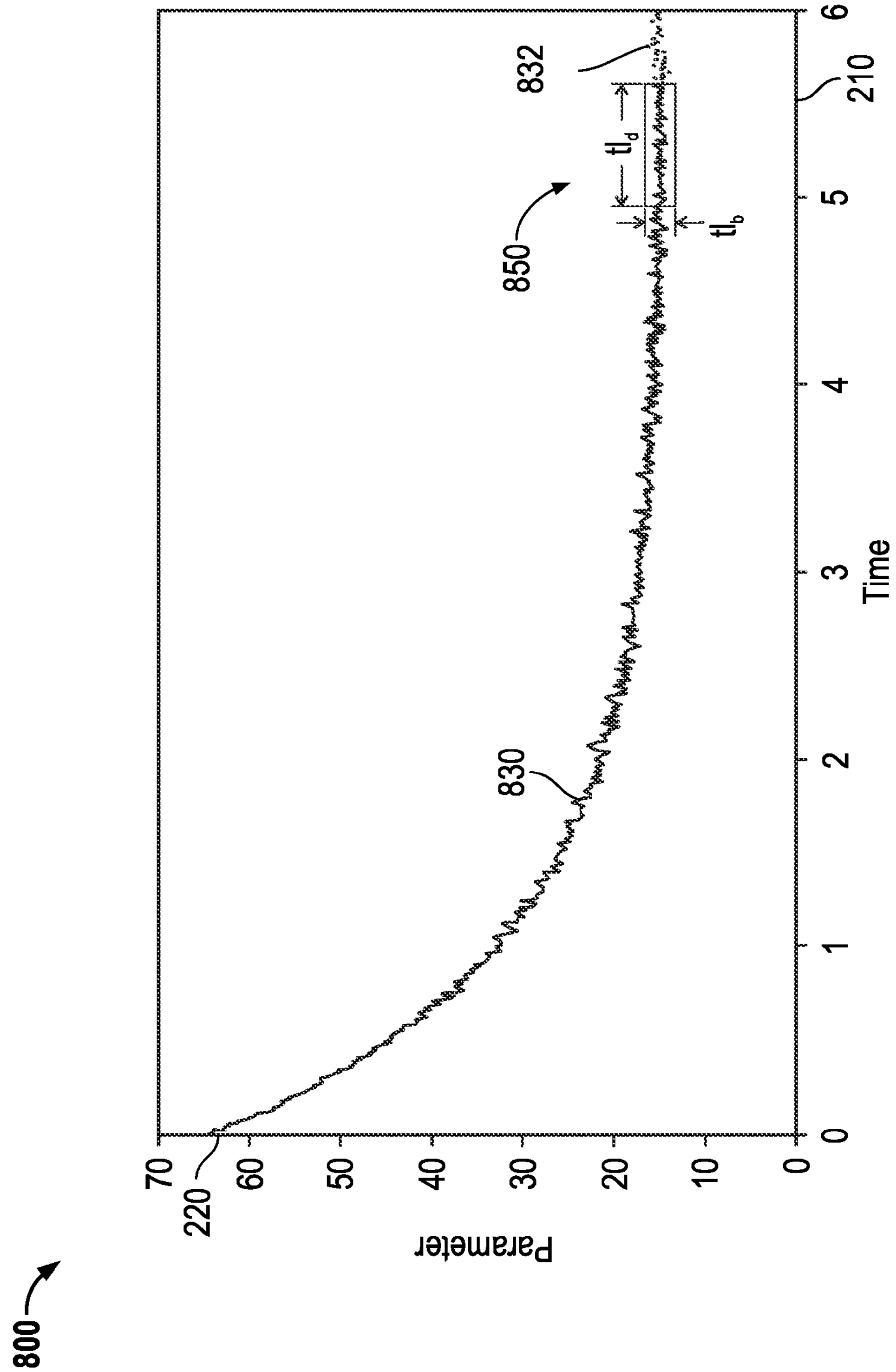

800
Parameter
Time
0
10
20
30
40
50
60
70
1
2
3
4
5
6
220
830
850
832
210
tld
tlb

FIG. 8

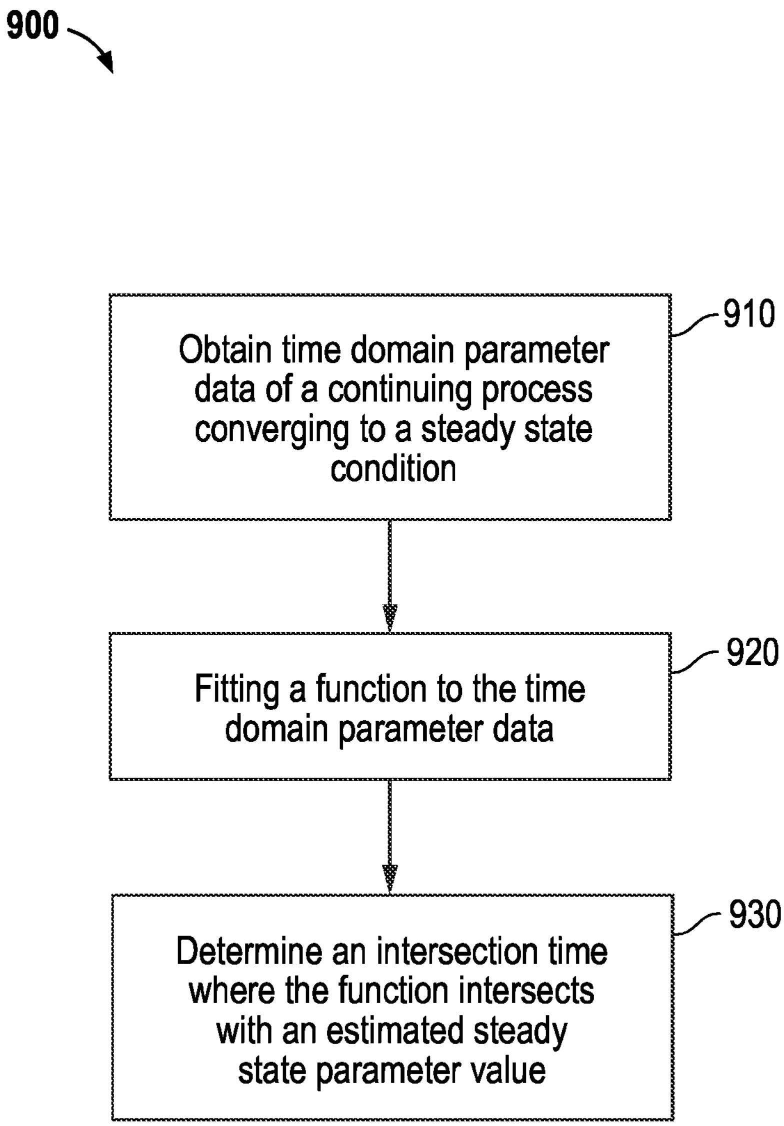

900
Obtain time domain parameter data of a continuing process converging to a steady state condition
910
Fitting a function to the time domain parameter data
920
Determine an intersection time where the function intersects with an estimated steady state parameter value
930

FIG. 9

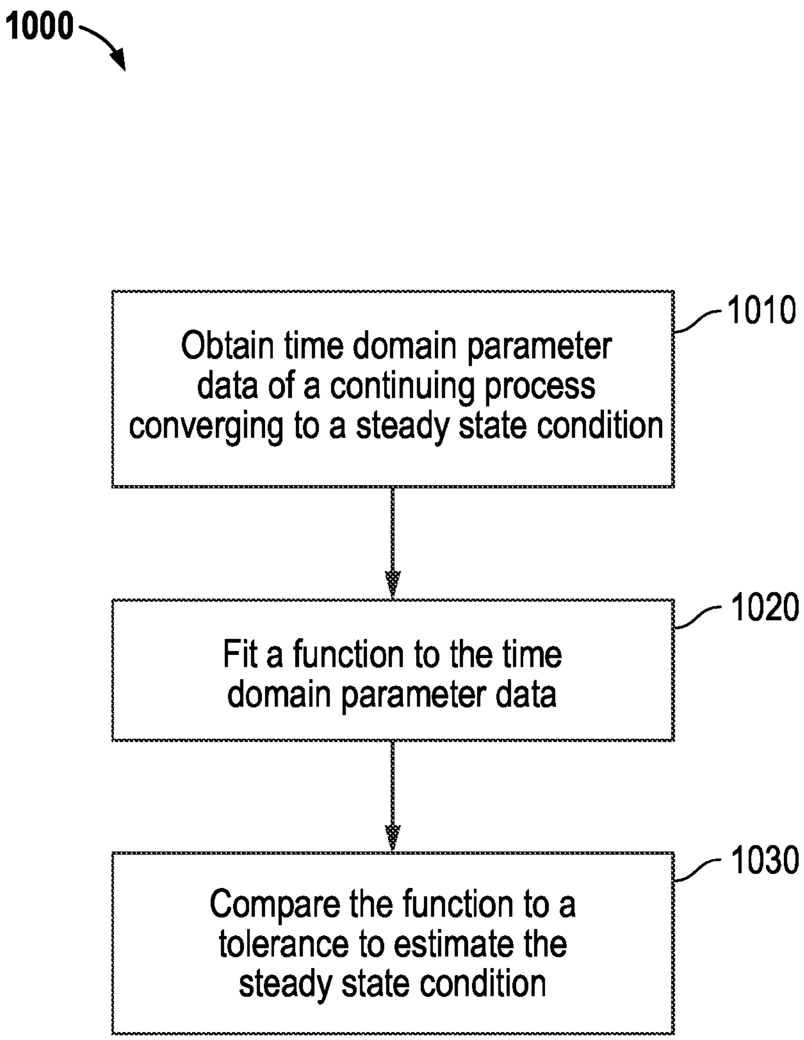

1000
Obtain time domain parameter data of a continuing process converging to a steady state condition
1010
Fit a function to the time domain parameter data
1020
Compare the function to a tolerance to estimate the steady state condition
1030

FIG. 10

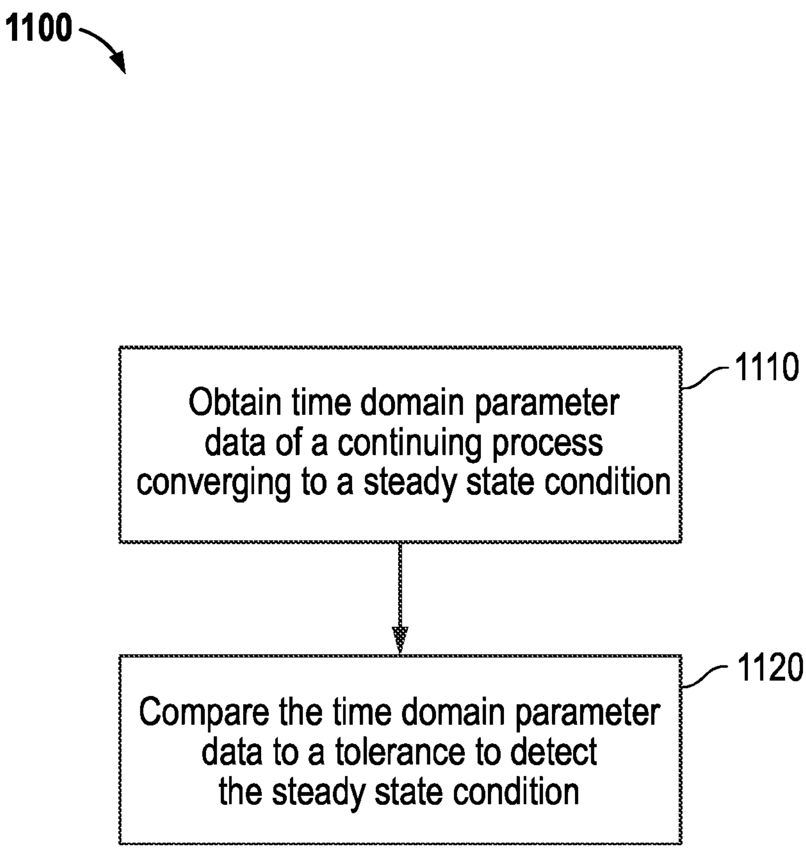
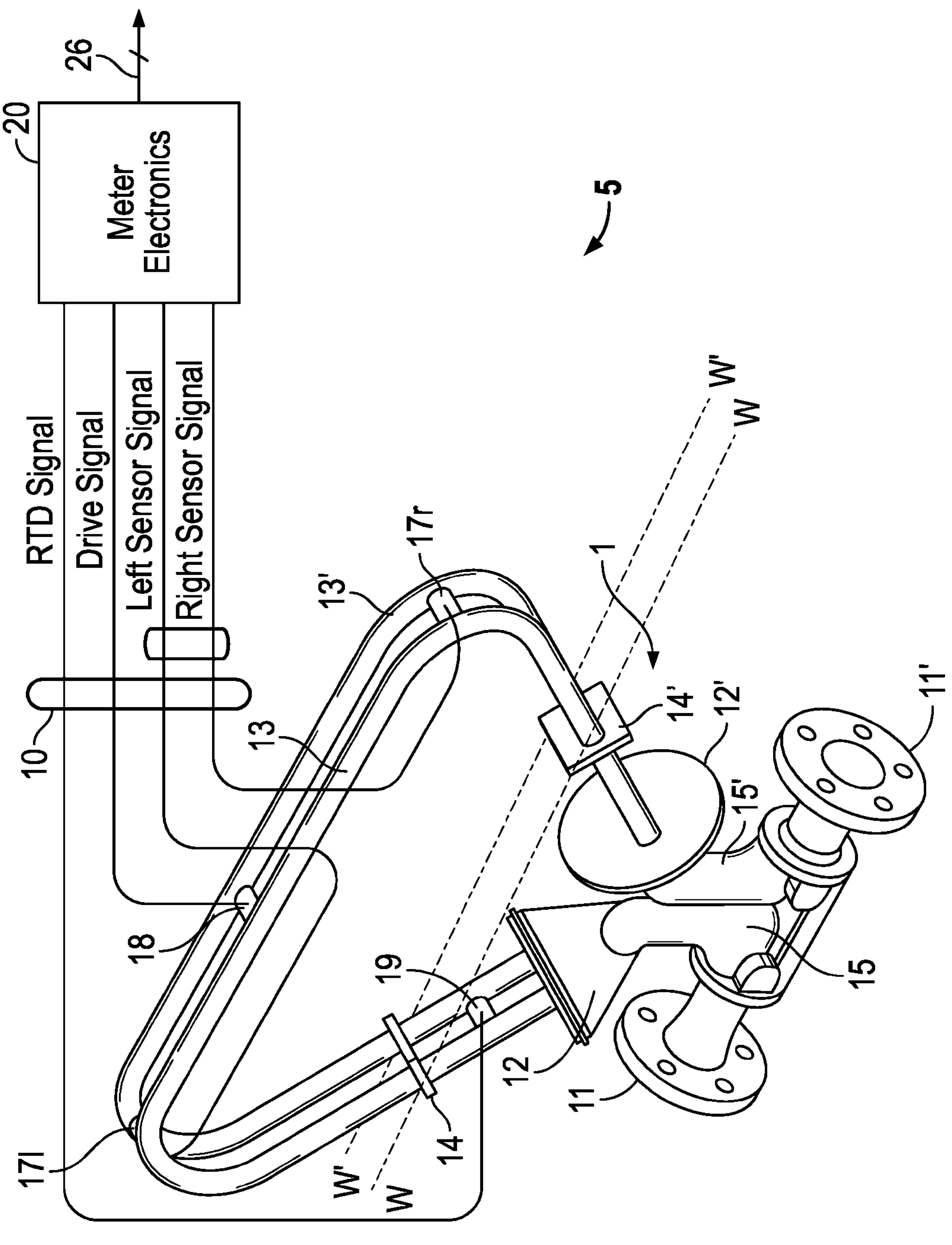

1100
Obtain time domain parameter data of a continuing process converging to a steady state condition
1110
Compare the time domain parameter data to a tolerance to detect the steady state condition
1120

FIG. 11



Meter Electronics
20
26
5
RTD Signal
Drive Signal
Left Sensor Signal
Right Sensor Signal
10
13
13'
17r
17l
18
19
14
14'
1
W'
W
12
12'
11
11'
15
15'

FIG. 12

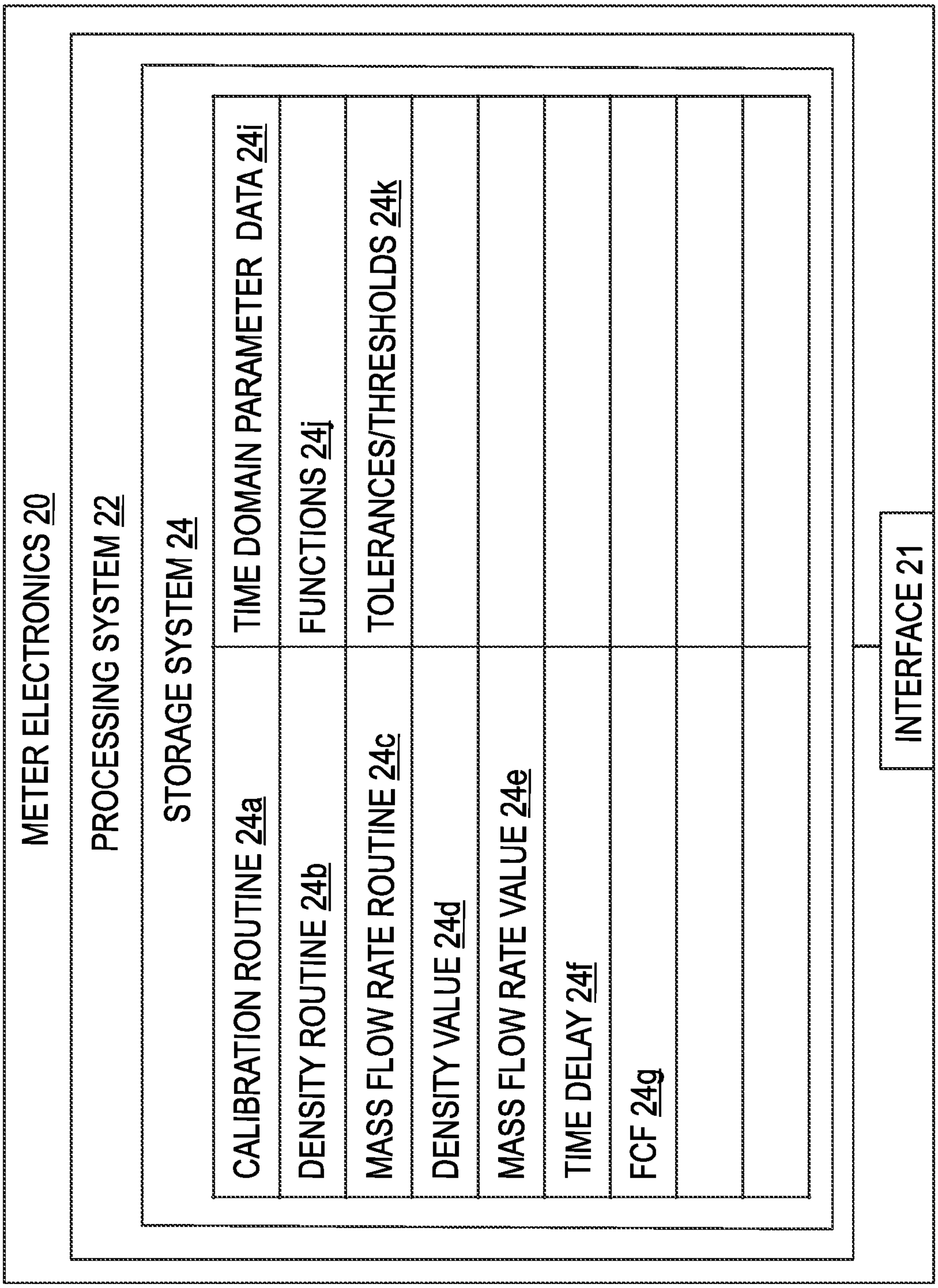

METER ELECTRONICS 20
PROCESSING SYSTEM 22
STORAGE SYSTEM 24
CALIBRATION ROUTINE 24a
DENSITY ROUTINE 24b
MASS FLOW RATE ROUTINE 24c
DENSITY VALUE 24d
MASS FLOW RATE VALUE 24e
TIME DELAY 24f
FCF 24g
TIME DOMAIN PARAMETER DATA 24i
FUNCTIONS 24j
TOLERANCES/THRESHOLDS 24k
INTERFACE 21

FIG. 13

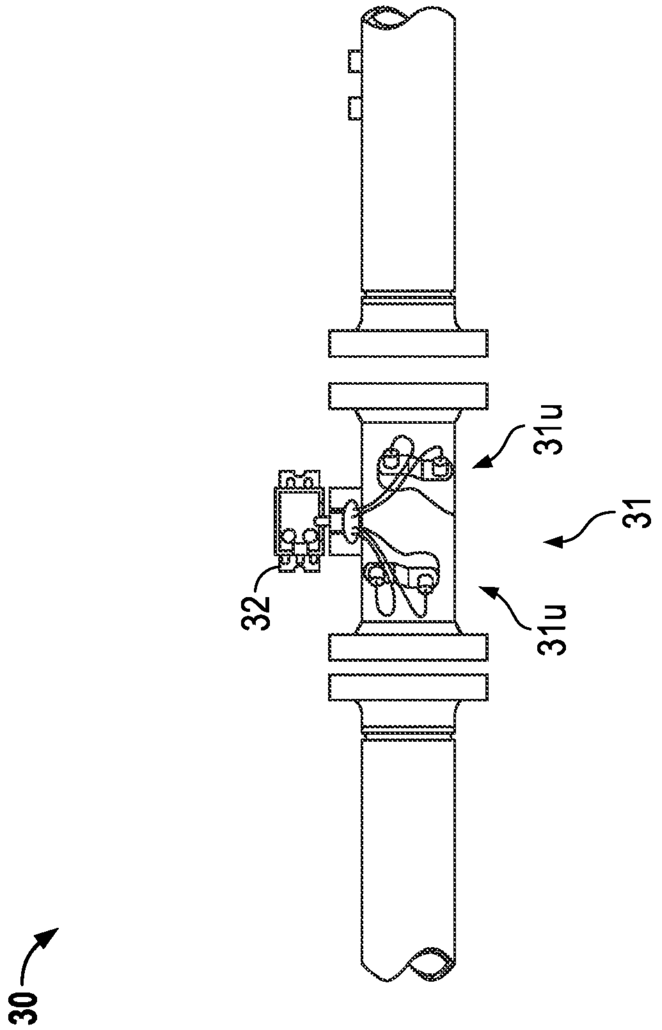


FIG. 14

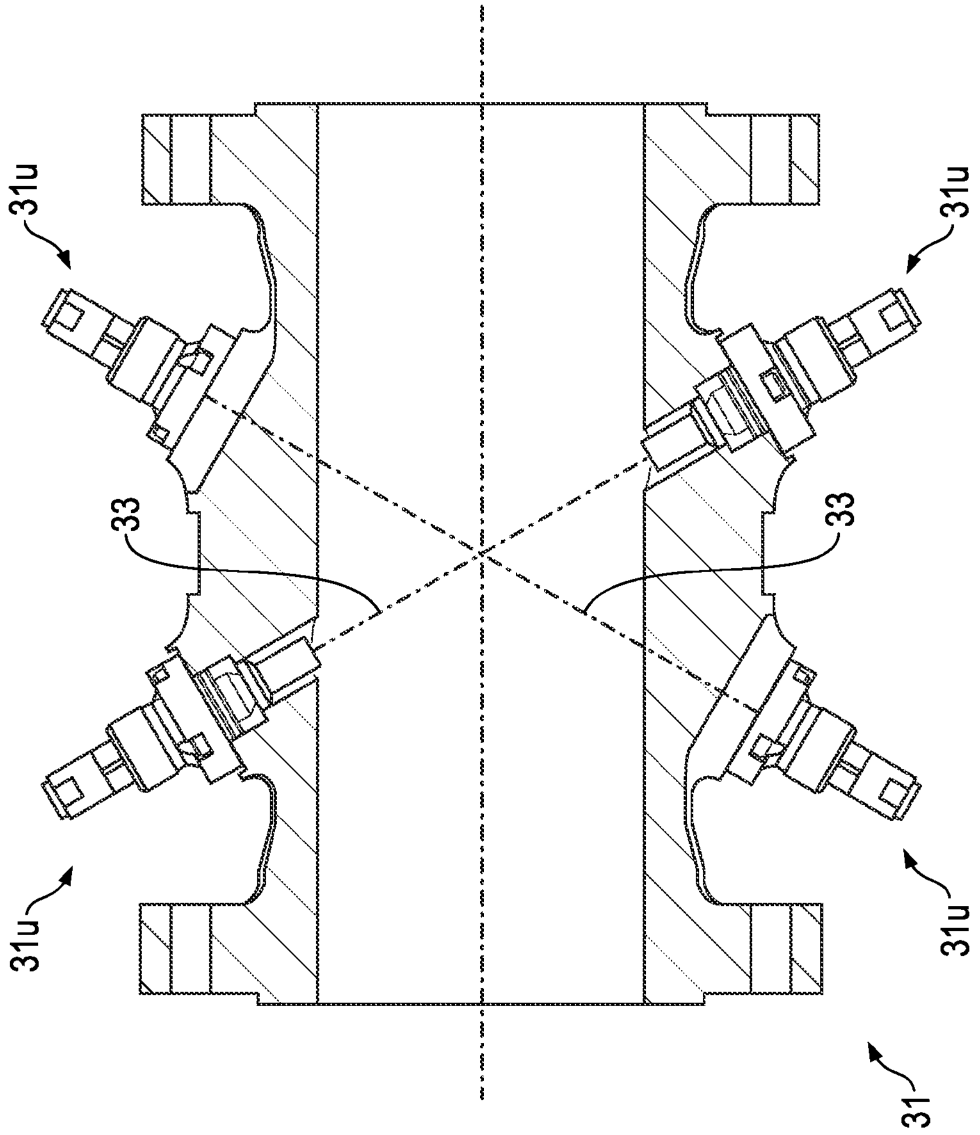


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2023/085089

A. CLASSIFICATION OF SUBJECT MATTER
INV. G05B13/02 G05B17/02 G05B11/06 G05D11/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06F G05B G05D

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

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

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CN 108 491 357 A (CR POWER ENERGY SCIENCE AND TECH CO LTD) 4 September 2018 (2018-09-04) the whole document -----	1-27
X	LECOMPTE STEVEN ET AL: "Experimental results of a small-scale organic Rankine cycle: Steady state identification and application to off-design model validation", APPLIED ENERGY, ELSEVIER SCIENCE PUBLISHERS, GB, vol. 226, 31 May 2018 (2018-05-31), pages 82-106, XP085419892, ISSN: 0306-2619, DOI: 10.1016/J.APENERGY.2018.05.103 the whole document -----	1-27

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"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

"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

"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

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 September 2024	13/09/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Marinica, Raluca

4

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2023/085089

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims;; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☒ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-9

   Determine an intersection time where a fitted function to time domain data intersects an estimated steady-state parameter

   ---

2. claims: 10-19

   Estimate a steady-state condition of a process

   ---

3. claims: 20-27

   Determine a steady-state condition of a process

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2023/085089

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CN 108491357 A	04-09-2018	NONE	