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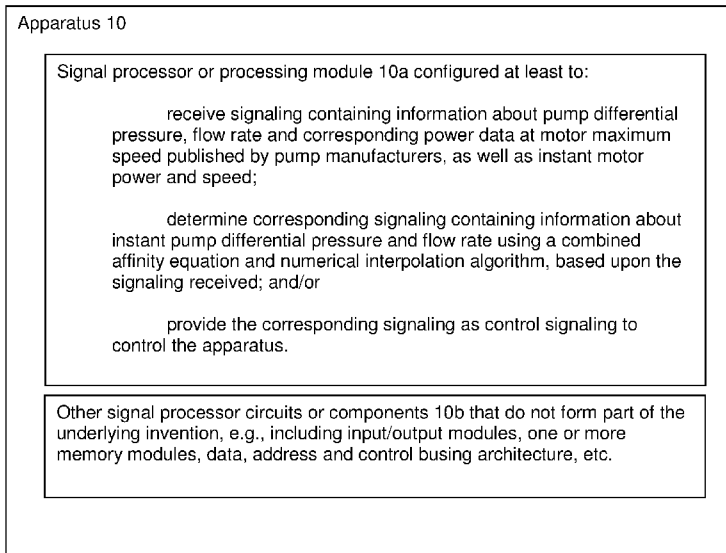


Figure 2B

(57) Abstract: The present invention provides a numerical affinity pump sensorless conversion signal processing technique, e.g. based upon processing the pump differential pressure, flow rate and power at pump maximum speed published by pump manufacturers, as well as the pump affinity law in order to obtain instant pump differential pressures and flow rate directly and numerically. The sensorless converter technique may be applied to any form of pump characteristics distributions simple or complicated, since there is no need to reconstruct and to solve any pump and system characteristics equations. As a result, the computation accuracy is significantly improved.

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DIRECT NUMERIC AFFINITY PUMPS SENSORLESS CONVERTER

CROSS REFERENCE TO RELATED APPLICATION

This application claims benefit to U.S. provisional application no. 62/170,997 (Atty Dckt No. 911-019.020-1/F-B&G-X0020US), filed 4 June 2015, entitled "Direct
5 numeric affinity pumps sensorless converter," which is hereby incorporated by reference in its entirety.

The present invention builds on the family of technologies disclosed in the other related applications identified below.

10 BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a technique for controlling pumping applications; and more particularly, the present invention relates to a method and apparatus for determining instant pump differential pressure and flow rate, and for
15 controlling the pumping applications based upon the determination.

2. Brief Description of Related Art

In previous works by one or more of the inventors of the instant patent application, for hydronic pumping system sensorless control and monitoring, several
20 discrete or numerical sensorless conversion techniques or means were developed and form part of a family of related works set forth in patent documents set forth below, e.g., including that set forth and referenced as documents [3] through [6] below.

For example, following a so-called 3D numerical conversion in the patent
25 document referenced as [3] below, based upon using 3 distribution matrices of pump

pressure, flow rate and power with respect to motor speed and system characteristics coefficients, the system pressure and flow rate were converted from a pair of motor readout values directly. The conversion accuracy was reasonably satisfactory, e.g., with around 5% error in the pump normal operation hydronic region.

5 However, in order to avoid tedious calibration data acquisition when using the 3D conversion method in pumping sensorless control application in field, a mixed discrete and theoretical conversion technique or means was developed and is set forth as well in the patent document referenced as [4] below, e.g., based upon using
10 pump curve and system equations, yielding around 5-8% of the conversion error without the need for instrumentation calibration.

Further, a best-fit affinity sensorless conversion technique was also developed as set forth in patent document referenced as [6] below, e.g., based upon using pump and system characteristics equations together with the empirical power
15 equation. The pump characteristics equation and the empirical power equation are reconstructed by using a polynomial best-fit approach from pump data published by pump manufacturers. System pressures and flow rate were resolved at the steady state equilibrium point of pump and system pressures by using those system and power characteristics equations accordingly, with around a 5% conversion error.
20 However, for slightly more complicated pump pressure and power characteristic distribution curves, it was determined that this technique may pose a slight challenge in order to provide a better representation of the curves and to inverse or resolve those curve equations. The conversion accuracy may not always be satisfactory as well, e.g. for slightly more complicated pump characteristics distributions.

In view of the aforementioned, there remains a need in the pump industry for a better way to determine pump pressure differential and flow rate for sensorless pumping control applications without the need to reconstruct and solve any pump and system characteristics equations.

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SUMMARY OF THE INVENTION

In summary, according to the present invention, a new and unique direct numeric affinity pump sensorless converter is provided herein, e.g., based upon using the pump differential pressure, flow rate and power at pump maximum speed without a need to reconstruct and solve any pump and system characteristics equations. The sensorless converter signal processing technique, or means for implementing the same, provided herein may be applied to any form of pump characteristics distribution, simple or complicated, as long as the monotonic power distribution with respect to flow is preserved. The computation accuracy is significantly improved as well, since there is no need to have the system characteristics coefficient to be inversed from the power to solve pump and system equations, and there is also no extra effort for having the calibrating data as well.

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Specific Embodiments

By way of example, the present invention provides a new and unique technique for a sensorless pumping control application.

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According to some embodiments, the present invention may include, or take the form of, a method or apparatus, e.g., in a hydronic pumping control applications or systems, featuring a signal processor or signal processing module, configured to:

receive signaling containing information about pump differential pressure, flow rate and corresponding power data at motor maximum speed published by pump manufacturers, as well as instant motor power and speed; and

5 determine corresponding signaling containing information about instant pump differential pressure and flow rate using a combined affinity equation and numerical interpolation algorithm, based upon the signaling received.

According to some embodiments, the present invention may include one or more of the following features:

10 The signal processor or processing module may be configured to provide the corresponding signaling as control signaling to control a pump in a pumping system, e.g., including a hydronic pumping system.

 The signal processor or processing module may be configured to determine the corresponding signaling, e.g., by implementing the combined affinity equation
15 and numerical interpolation algorithm as follows:

 obtaining a corresponding maximum power at the pump's maximum speed with respect to the instant motor power and speed parameters using a power affinity equation;

 obtaining corresponding pump differential pressure and flow rate with
20 respect to the corresponding maximum power at the pump's maximum speed using direct numerical interpolation; and

 determining the instant pump differential pressure and flow rate with respect to the instant motor speed and power by using pressure and flow affinity equations.

The signal processor or processing module may be configured to determine the instant pump differential pressure and flow rate by implementing the combined affinity equation and numerical interpolation algorithm and using numerical computation procedures as follows:

5

$$Q(n, w) = \left(\frac{n}{n_{max}}\right) \cdot \bar{q}(n_{max}, W_i, Q_i, \hat{w}(n, w)), \quad (1)$$

$$P(n, w) = \left(\frac{n}{n_{max}}\right)^2 \cdot \bar{p}(n_{max}, W_i, P_i, \hat{w}(n, w)), \quad (2)$$

10 where $\bar{q}(n_{max}, W_i, Q_i, \hat{w})$ and $\bar{p}(n_{max}, W_i, P_i, \hat{w})$ are pump differential pressure and flow rate distribution functions with respect to power and formulated numerically based upon discrete pump data of (P_i, Q_i, W_i) at motor full speed, and \hat{w} is a corresponding power function at pump full speed by the power affinity equation of

15

$$\hat{w}(n, w) = (n/n_{max})^{-3} \cdot w. \quad (3)$$

The apparatus may include, or take the form of, a pump controller for controlling a pump, e.g., in such a hydronic pumping system.

20 The apparatus may include, or take the form of, a hydronic pumping system having a pump and a pump controller, including where the pump controller is configured with the signal processor or processing module for controlling the pump

By way of example, the signal processor or processing module may include, or take the form of, at least one signal processor and at least one memory including computer program code, and the at least one memory and computer program code
25 are configured to, with at least one signal processor, to cause the signal processor at

least to receive the signaling (or, for example, the associated signaling) and determine the corresponding signaling, based upon the signaling received. The signal processor or processing module may be configured with suitable computer program code in order to implement suitable signal processing algorithms and/or
5 functionality, consistent with that set forth herein.

According to some embodiments, the present invention may also take the form of a method including steps for:

receiving in a signal processor or processing module signaling containing information about pump differential pressure, flow rate and
10 corresponding power data at motor maximum speed published by pump manufacturers, as well as instant motor power and speed; and

determining in the signal processor or processing module corresponding signaling containing information about instant pump differential pressure and flow rate using a combined affinity equation and numerical
15 interpolation algorithm, based upon the signaling received.

The method may also include one or more of the features set forth herein, including providing from the signal processor or processing module corresponding signaling as control signaling to control a pump in a pumping system, e.g., including a hydronic pumping system.

20 The instant application provides a new technique that is a further development of, and builds upon, the aforementioned family of technologies set forth herein.

BRIEF DESCRIPTION OF THE DRAWING

The drawing includes the following Figures, which are not necessarily drawn
25 to scale:

Figure 1 includes Figs. 1A, 1B and 1C that show examples of sensorless multistage pumping control systems, e.g., in which the present invention may be implemented, or form part of, according to some embodiments of the present invention.

5 Figure 2A is a schematic diagram of a pump sensorless converter for providing pump pressure (ft) and flow rate (GPM) from motor power (hp) and speed (RPM), e.g., in which the present invention may be implemented, or form part of, according to some embodiments of the present invention.

10 Figure 2B is a block diagram of apparatus, e.g., having a signal processor or processing module, configured for implementing the signal processing functionality, according to some embodiments of the present invention.

Figure 3 shows a graph of pump pressure (Ft) vs. flow rate (gpm) showing pump, system and power characteristic curves with a pressure equilibrium point at a flow steady state.

15 Figure 4 shows a graph of pump pressure (Ft), motor power (hp) and flow rate (gpm) showing a pump sensorless pressure and flow rate conversion by using a affinity and numerical signal processing technique, e.g., according to implementations of some embodiments of the present invention.

20 Figure 5 shows a graph of motor power (hp) vs. normalized system characteristics (Cv/Cv^{Duty}), e.g. according to implementations of some embodiments of the present invention.

25 Figure 6 includes Figs. 6A, 6B and 6C, which show comparisons of pump differential pressure and system flow rate from the sensorless converter, e.g., each having six (6) respective solid lines for 30 Hz, 36 Hz, 42 Hz, 48 HZ, 54 Hz, 60 Hz, and each also having measured data from sensors indicated by symbols, e.g.,

including: for 30 Hz, diamond symbols; 36 Hz, plus ("+") signs; 42 Hz, solid circle symbols; 48 Hz, minus ("-") signs, 54 Hz, triangle symbols; and 60 Hz, "x" symbols; where Fig. 6A shows a graph of flow rate (gpm) vs. power (kw); Fig. 6B shows a graph of pressure (psi) vs. power (kw); and Fig. 6C shows a graph of pressure (ft) vs. flow rate (gpm).

DETAILED DESCRIPTION OF THE INVENTION

Figures 2A and 2B: Implementation of Signal Processing Functionality

In summary, the present invention provides a new and unique direct numerical affinity pump sensorless conversion signal processing technique, or means for implementing the same, e.g. based upon processing the pump differential pressure, flow rate and power at pump maximum speed published by pump manufacturers, as well as the pump affinity law in order to obtain instant pump differential pressures and flow rate directly and numerically. The sensorless converter signal processing technique, or means for implementing the same, set forth herein may be applied to any form of pump characteristics distributions simple or complicated, since there is no need to reconstruct and to solve any pump and system characteristics equations. As a result, the computation accuracy is significantly improved.

Figure 1 show examples of sensorless multistage pumping control systems, e.g., in which the present invention may be implement, or form part of, according to some embodiments of the present invention. For example, Fig. 1A shows a hydronic pumping and variable speed control system, while Figs. 1B and 1C show a pump sensorless converter for pump differential pressure and flow rate associated with the

hydraulic system coefficient at the discharge of a pump and the motor power and speed at the other end of a motor drive.

By way of example, the direct numerical affinity pump sensorless conversion signal processing technique, or means for implementing the same, may include, or form part of, a pump sensorless converter shown in Figure 2A, which processes signaling containing information about motor power (hp) and speed (RPM) and determines suitable processed signaling containing information about pump pressure (ft) and flow rate (GPM). The pump sensorless converter shown in Figure 2A may be implemented, or form part of apparatus, e.g., consistent with that set forth herein.

By way of further example, Figure 2B shows apparatus 10 according to some embodiments of the present invention, e.g., featuring a signal processor or processing module 10a configured at least to:

receive signaling containing information about pump differential pressure, flow rate and corresponding power data at motor maximum speed published by pump manufacturers, as well as instant motor power and speed; and

determine corresponding signaling containing information about instant pump differential pressure and flow rate using a combined affinity equation and numerical interpolation algorithm, based upon the signaling received.

In operation, the signal processor or processing module may be configured to provide corresponding signaling as control signaling to control a pump in a pumping system, e.g., such as a hydraulic pumping system. The corresponding signaling may contain information used to control the pumping hydraulic system.

The signal processor or processing module 10a may be configured in, or form part of, a pump and/or a pump control, e.g., which may include or be implemented in conjunction with a pump control or controller configured therein. By way of example, embodiments are envisioned in which the apparatus is a pump having the signal processor or processing module 10a, and embodiments are envisioned in which the apparatus is a pump control or controller having the signal processor or processing module 10a.

As one skilled in the art would appreciate and understand, the present invention may be implemented using system characteristics and associated equations, e.g., consistent with that set forth herein, as well as by using other types or kinds of system characteristics and associated equations that are either now known or later developed in the future.

By way of example, the functionality of the apparatus 10 may be implemented using hardware, software, firmware, or a combination thereof. In a typical software implementation, the apparatus 10 would include one or more microprocessor-based architectures having, e. g., at least one signal processor or microprocessor like element 10a. One skilled in the art would be able to program with suitable program code such a microcontroller-based, or microprocessor-based, implementation to perform the functionality described herein without undue experimentation. For example, the signal processor or processing module 10a may be configured, e.g., by one skilled in the art without undue experimentation, to receive the signaling containing information about pump differential pressure, flow rate and corresponding power data at motor maximum speed published by pump manufacturers, as well as instant motor power and speed, consistent with that disclosed herein.

Moreover, the signal processor or processing module 10a may be configured, e.g., by one skilled in the art without undue experimentation, to determine the corresponding signaling containing information about instant pump differential pressure and flow rate using a combined affinity equation and numerical interpolation
5 algorithm, consistent with that disclosed herein.

The scope of the invention is not intended to be limited to any particular implementation using technology either now known or later developed in the future. The scope of the invention is intended to include implementing the functionality of the processors 10a as stand-alone processor, signal processor, or signal processor
10 module, as well as separate processor or processor modules, as well as some combination thereof.

The apparatus 10 may also include, e.g., other signal processor circuits or components 10b, including random access memory or memory module (RAM) and/or read only memory (ROM), input/output devices and control, and data and
15 address buses connecting the same, and/or at least one input processor and at least one output processor, e.g., which would be appreciate by one skilled in the art.

Figures 3-6: Detailed Implementation

The following is a detailed description of an implementation of the present
20 invention, e.g., consistent with that set forth in relation to Figures 3 to 6.

Considering a close loop system, pump flow rate and differential pressure at a motor speed for a system position given may be resolved at a steady equilibrium state of pump and system pressures, e.g., which is the intersection of the pump and system curves functions shown schematically in Figure 3. Here, the instant pump
25 characteristic curve, or pump curve, represents the pump differential pressure P with

respect to flow rate Q at a motor speed of n . The instant system curve represents the system flow equation of $C_v = Q/\sqrt{P}$ accordingly. The pump affinity law, represented by the equations for pump flow, differential pressure and motor power, i.e., $Q/Q_{max} = n/n_{max}$, $P/P_{max} = (n/n_{max})^2$ and $w/w_{max} = (n/n_{max})^3$, may be used to compute and determine the pump differential pressure, flow rate and power with respect to an instant motor speed of n at a system position, respectively. Instead of resolving the pump and system curves equations to obtain the steady equilibrium state solution of pressure and flow at any pump speed in the patent document referenced as [6] below, a direct numerical affinity sensorless conversion approach is set forth herein, e.g., consistent with that shown schematically in Fig 4. Here, the pump differential pressure, flow rate and their corresponding power data at motor maximum speed, together with the pump affinity law, may be used to resolve the instant pressure and flow rate of P and Q with respect to instant motor speed and power of n and w directly and numerically.

The numerical determination, computational and signal processing procedures to obtain instant pump differential pressure and flow rate of P and Q are as following. First, the corresponding maximum power of \hat{w} at pump maximum speed of n_{max} with respect to a pair of instant motor power and speed of n and w may be obtained by using the power affinity equation. The corresponding pump differential pressure and flow rate of \hat{P} and \hat{Q} with respect to the power of \hat{w} at n_{max} can then be obtained by using numerical interpolation directly. Finally, the instant pressure and flow rate of P and Q with respect to instant motor speed and power of n and w may be achieved by the pressure and flow affinity equations based upon the pump differential pressure and flow rate of \hat{P} and \hat{Q} , respectively. Note that the

affinity law implies that the sensorless parameter conversion is along the system characteristics curve shown in Figure. 3.

The pump differential pressure and flow rate by following the numerical determination, computation and signal processing procedures described above may
5 be written in form of equations (1) and (2), as follows:

$$Q(n, w) = \left(\frac{n}{n_{max}}\right) \cdot \bar{q}(n_{max}, W_i, Q_i, \hat{w}(n, w)), \text{ and} \quad (1)$$

$$P(n, w) = \left(\frac{n}{n_{max}}\right)^2 \cdot \bar{p}(n_{max}, W_i, P_i, \hat{w}(n, w)), \quad (2)$$

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where $\bar{q}(n_{max}, W_i, Q_i, \hat{w})$ and $\bar{p}(n_{max}, W_i, P_i, \hat{w})$ are the pump differential pressure and flow rate distribution functions with respect to power and formulated numerically based upon the discrete pump data of (P_i, Q_i, W_i) at motor full speed of n_{max} (or at any speed given), and \hat{w} is the corresponding power function at pump full
15 speed of n_{max} by the power affinity equation (3) of:

$$\hat{w}(n, w) = (n/n_{max})^{-3} \cdot w. \quad (3)$$

The distribution functions of \bar{q} and \bar{p} may be formulated directly through the
20 numerical signal processing technique or means, for instance, by implementing interpolation or curve fitting, based upon their discrete pump testing data of (P_i, Q_i, w_i) at motor full speed of n_{max} . However, for slightly more complicated distributions, a piecewise numeric interpolation may be implemented to achieve a

better functional representation and desired accuracy. Note that the monotonic distribution on power with respect to flow may be required here as well.

In case, e.g., if there may be the accuracy requirement at low speed region with system nearly shut down, the pump power affinity law of Eq. 3 may not be sufficient to represent the relation of motor power and speed well due to motor speed slip in low speed as indicated in the patent document referenced as [6] below. A modified form of the power affinity law representation may, therefore, be formulated similarly using the equation (4) as follows:

$$\hat{w}(n, w) = \bar{w}_{norm}(n_i, W_i, n) \cdot w, \quad (4)$$

where $\bar{w}_{norm}(n_i, W_i, n)$ is the power distribution function calibrated based upon an array of the discrete and normalized motor power data of (n_i, W_i) at any system position, which may be obtained numerically by interpolation or fitting as well. Note that the system position can be any position from shut off to fully open, since the normalized power distribution of \bar{w}_{norm} with respect to speed of n is nearly identical at any system position.

For a varying hydronic system with flow regulated by valves or other flow regulators, one may also want to know the instant system characteristic coefficient for a system position at an instant time. By following the similar approach, the normalized system characteristics coefficient with respect to the power data at motor full speed n_{max} , presented in Figure 5, may be formulated directly as that set forth in equation (5):

$$C_v^{norm}(w, n) = \bar{C}_v^{norm}(n_{max}, W_i, \bar{C}_v^{norm}_i, \hat{w}(n, w)), \quad (5)$$

where $\bar{C}_v^{norm}(n_{max}, W_L, \bar{C}_{vi}^{norm}, \hat{w}(n, w))$ is the system coefficient distribution function with respect to the normalized motor power data and instant reversed maximum power of $\hat{w}(n, w)$ at pump maximum speed. Note that the instant system coefficient is the same value along the instant system characteristics curve, shown in Figure. 3.

By using the direct numeric affinity sensorless converter defined in Equations 1-4, the pressure and flow rate values may be determined and computed for a pumping system and compared with the measured data, which are shown in Fig. 6, respectively. The conversion accuracy is reasonably satisfactory with around 5% error in the pump normal operation hydronic region.

The direct numerical affinity pump sensorless converter set forth herein may be used for most hydronic pumping control and monitoring applications, since it is formulated directly and numerically from pump, power characteristics data published by pump manufacturers testing data as well as affinity law, without the need of resolving any characteristic equations reversely as set forth in the patent documents referenced as [3] through [6] below. The technique may be applied to any form of pump characteristics distribution pump simple or complicated, as long as the monotonic power distribution with respect to flow is preserved. Moreover, the direct numerical pump sensorless converter developed herein is much easier to be set up while providing reasonably satisfactory accuracy.

Various Points of Novelty

The present invention may also include, or take the form of, one or more of the following embodiments/implementations:

According to some embodiments, the present invention may include, or take the form of, implementations where the direct numeric affinity pump sensorless converter includes a pump sensorless converter which yields the pump differential pressure and system flow rate with respect to a given pair of motor speed and power readouts, based on the pump differential pressure, flow rate and power at pump maximum speed published by pump manufacturers as well as the pump affinity law. The direct numerical computation procedures to obtain the instant pump differential pressures and flow rate directly and numerically are presented schematically in Figures 3 and 4 as well. The signal processing technique, or means for implementing the same, may be applied to any form of pump characteristics distributions, as long as the monotonic power distribution with respect to flow is preserved.

According to some embodiments, the present invention may include, or take the form of, implementations where the direct numeric affinity pump sensorless converter mentioned above includes the numerical expression of pump differential pressure and flow rate of $P(n, w)$ and $Q(n, w)$ of Equations 1 and 2, at the steady state equilibrium point of the pump differential pressure and system pressure, which is the intersection of the pump and system curves schematically, based upon the pump differential pressure and flow rate numerical distribution data of (P_D, Q_D, W_D) at motor full speed and the pump affinity law.

According to some embodiments, the present invention may include, or take the form of, implementations where the direct numeric distribution functions in the direct numeric affinity pump sensorless converter mentioned above includes the signal processing technique, or means for implementing the same, to formulate the pump pressure and flow rate distribution function in terms of power at maximum

speed directly and numerically, as shown in Figure 4. For that, there is no need to have the system characteristics coefficient to be inversed from the power, prior to obtaining pump pressure and flow rate. The computation accuracy is significantly improved.

5 According to some embodiments, the present invention may include, or take the form of, implementations where the direct numeric procedures in the direct numeric affinity pump sensorless converter mentioned above includes:

- 1) the corresponding maximum power of \hat{w} at pump maximum speed of n_{max} with respect to a pair of instant motor power and speed of n and w is
 10 obtained by using power affinity equation;
- 2) the corresponding pump differential pressure and flow rate of \hat{P} and \hat{Q} with respect to the power of \hat{w} at n_{max} are obtained by using numerical interpolation directly;
- 3) the instant pressure and flow rate of P and Q with respect to instant
 15 motor speed and power of n and w are achieved finally by the pressure and flow affinity equations based upon the pump differential pressure and flow rate of \hat{P} and \hat{Q} , respectively.

Note that the affinity law implies that the sensorless parameter conversion is along the system characteristics curve shown in Figure 3.

20 According to some embodiments, the present invention may include, or take the form of, implementations where the steady state pressure equilibrium point in the direct numeric affinity pump sensorless converter mentioned above includes the intersection point of the pump and system curves functions, as shown in Figure 3. The system pressure or pump differential pressure and flow rate may be resolved by

Equations 1 and 2, at the pressures equilibrium point for a pair of motor readout values given.

According to some embodiments, the present invention may include, or take the form of, implementations where the numeric methods in the direct numeric affinity pump sensorless converter mentioned above may include any kinds of numerical interpolation and fitting algorithms to obtain the pump differential pressure and flow rate of \hat{P} and \hat{Q} at pump maximum speed. However, it is note that, for slightly complicated distributions, the piecewise numeric interpolation may be recommended to achieve better functional representation and accuracy.

According to some embodiments, the present invention may include, or take the form of, implementations using use the pump power affinity function in Equation 3, e.g., in order to obtain the power of \hat{w} at maximum pump speed in the direct numeric affinity pump sensorless converter mentioned above. A preferred version of the modified power affinity function may be formulated similarly with a numerical distribution expression of $\bar{w}_{norm}(n_i, W_i, n)$ in Equation 4, e.g., calibrated based upon an array of the discrete and normalized motor power data of (n_i, W_i) at any system position, which may again be obtained numerically by interpolation or fitting. The modified power affinity function calibrated may be introduced to compensate the power loss due to motor speed slip at low speed region.

According to some embodiments, the present invention may include, or take the form of, implementations where the system characteristics coefficient numeric conversion in the direct numeric affinity pump sensorless converter includes the system characteristics coefficient numeric function in form of

$\bar{c}_v^{norm}(n_{max}, W_i, \bar{c}_{vi}^{norm}, \hat{w}(n, w))$ in Equation 5, which is the system coefficient

distribution with respect to the normalized motor power. For an instant reversed

maximum power of $\hat{w}(n, w)$ at pump maximum speed obtained from Equations 3 or 4, the instant system coefficient of may be obtained by Equation 5 directly and numerically by interpolation or fitting. Note that the instant system coefficient may be the same value along the instant system characteristics curve shown in Figure 3.

5 According to some embodiments, the present invention may include, or take the form of, implementations where the pump and power curves data at motor maximum speed in the direct numeric affinity pump sensorless converter for converting pump differential pressure and flow from pump power and speed includes the pump and power curves data published by pump manufacturers or a few points
10 of pump data acquired at motor full speed in field. Here, the motor power curve data may also be replaced by any potential motor electrical or mechanical readout signals, such as motor current or torque, and so forth.

 According to some embodiments, the present invention may include, or take the form of, implementations where the pumping hydronic system in the direct
15 numeric affinity pump sensorless converter includes all close loop or open loop hydronic pumping systems, such as primary pumping systems, secondary pumping systems, water circulating systems, and pressure booster systems. The systems mentioned here may consist of a single zone or multiple zones as well.

 According to some embodiments, the present invention may include, or take
20 the form of, implementations where the hydronic signals for in the direct numeric affinity pump sensorless converter may include pump differential pressure, system pressure or zone pressure, system or zone flow rate, and so forth.

 According to some embodiments, the present invention may include, or take the form of, implementations where control signals transmitting and wiring
25 technologies may include all conventional sensing and transmitting techniques or

means that are used currently and known in the art. Preferably, wireless sensor signal transmission technologies would be optimal and favorable.

According to some embodiments, the present invention may include, or take the form of, implementations where the pumps mentioned above for the hydronic pumping systems may include a single pump, a circulator, a group of parallel ganged pumps or circulators, a group of serial ganged pumps or circulators, or their combinations.

According to some embodiments, the present invention may include, or take the form of, implementations where systems flow regulation may include manual or automatic control valves, manual or automatic control circulators, or their combinations.

Hydronic Characteristics and Discrete Distribution Functions

Techniques for determining a hydronic characteristics, and techniques for plotting distributions of such hydronic characteristics, e.g., like that shown in Figures 3-6, are also known in the art; and the scope of the invention is not intended to be limited to any particular type or kind thereof that is either now known or later developed in the future.

Moreover, one person skilled in the art would be able to implement the underlying invention without undue experimentation based upon that disclosed herein, including determining hydronic characteristics, and plotting distributions of such hydronic characteristics like that shown herein.

Computer Program Product

The present invention may also, e. g., take the form of a computer program product having a computer readable medium with a computer executable code embedded therein for implementing the method, e.g., when run on a signal processing device that forms part of such a pump or valve controller. By way of example, the computer program product may, e. g., take the form of a CD, a floppy disk, a memory stick, a memory card, as well as other types or kind of memory devices that may store such a computer executable code on such a computer readable medium either now known or later developed in the future.

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Other Related Applications

The application is related to other patent applications that form part of the overall family of technologies developed by one or more of the inventors herein, and disclosed in the following applications:

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[1] U.S. application serial no. 12/982,286 (Atty Dckt No. 911-019.001-1//F-B&G-1001), filed 30 December 2010, entitled "Method and apparatus for pump control using varying equivalent system characteristic curve, AKA an adaptive control curve," which issued as U.S. Patent No. 8,700,221 on 15 April 2014; and

20

[2] U.S. application serial no. 13/717,086 (Atty Dckt No. 911-019.004-2//F-B&G-X0001), filed 17 December 2012, entitled "Dynamic linear control methods and apparatus for variable speed pump control," which claims benefit to U.S. provisional application no. 61/576,737, filed 16 December 2011, now abandoned;

[3] U.S. application serial no. 14/091,795 (Atty Dckt No. 911-019.009-2//F-B&G-X0005), filed 27 November 2013, entitled "3D sensorless conversion method and apparatus," which claims benefit to U.S. provisional application no. 61/771,375, filed 1 March 2013, now abandoned;

5 [4] U.S. application serial no. 14/187,817 (Atty Dckt No. 911-019.010-2//F-B&G-X0008), filed 24 February 2014, entitled "A Mixed Theoretical And Discrete Sensorless Converter For Pump Differential Pressure And Flow Monitoring," which claims benefit to U.S. provisional application no. 61/803,258, filed 19 March 2013, now abandoned;

10 [5] U.S. application serial no. 14/339,594 (Atty Dckt No. 911-019.012-2//F-B&G-X0010US01), filed 24 July 2014, entitled "Sensorless Adaptive Pump Control with Self-Calibration Apparatus for Hydronic Pumping System," which claims benefit to U.S. provisional application serial no. 14/339,594, filed 24 July 2014, now abandoned;

15 [6] U.S. application serial no. 14/680,667 (Atty Dckt No. 911-019.014-2//F-B&G-X0012US01), filed 7 April 2015, entitled " A Best-fit affinity sensorless conversion means for pump differential pressure and flow monitoring," which claims benefit to provisional patent application serial no. 61/976,749, filed 8 April 2014, now abandoned; and

20 [7] U.S. application serial no. 14/730,871 (Atty Dckt No. 911-019.015-2//F-B&G-X0013US01), filed 4 June 2015, entitled "System and flow adaptive sensorless pumping control apparatus energy saving pumping applications," which claims benefit to provisional patent application serial no. 62/007,474, filed 4 June 2014, now abandoned; and

[8] U.S. application no. 14/969,723 (Atty Dckt No. 911-019.017-2//F-B&G-X0015US01), filed 15 December 2015, entitled "Discrete valves flow rate converter," which claims benefit to U.S. provisional application no. 62/091,965, filed 15 December 2014;

5 [9] U.S. application no. 15/044,670, filed 16 February 2016 (Atty Dckt No. 911-019.019-2/F-B&G-X0016US), entitled "Detection means for sensorless pumping control applications," which claims benefit to U.S. provisional application no. 62/116,031, filed 13 February 2015, entitled "No flow detection means for sensorless pumping control applications;"

10 [10] U.S. provisional application no. 62/196,355, filed 24 July 2015, entitled "Advanced real time graphic sensorless energy saving pump control system;"

[11] U.S. provisional application no. 62/341,767, filed 26 May 2016, entitled "Direct numeric affinity multistage pumps sensorless converter;"

15 [12] U.S. provisional application no. 62/343,352, filed 31 May 2016, entitled "Pump control design toolbox means for variable speed pumping application;"

which are all assigned to the assignee of the instant patent application, and which are all incorporated by reference in their entirety.

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The Scope of the Invention

It should be understood that, unless stated otherwise herein, any of the features, characteristics, alternatives or modifications described regarding a particular embodiment herein may also be applied, used, or incorporated with any other embodiment described herein. Also, the drawing herein is not drawn to scale.

Although the present invention is described by way of example in relation to a centrifugal pump, the scope of the invention is intended to include using the same in relation to other types or kinds of pumps either now known or later developed in the future.

Although the invention has been described and illustrated with respect to exemplary embodiments thereof, the foregoing and various other additions and omissions may be made therein and thereto without departing from the spirit and scope of the present invention.

WHAT WE CLAIM IS:

1. Apparatus comprising:

a signal processor or processing module configured at least to:

receive signaling containing information about pump differential

5 pressure, flow rate and corresponding power data at motor maximum speed

published by pump manufacturers, as well as instant motor power and speed;

and

determine corresponding signaling containing information about instant

10 pump differential pressure and flow rate using a combined affinity equation

and numerical interpolation algorithm, based upon the signaling received.

2. Apparatus according to claim 1, wherein the signal processor or processing
module is configured to provide the corresponding signaling to control a pump in a
pumping system, e.g., such as a hydronic pumping system.

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3. Apparatus according to claim 1, wherein the signal processor or processing
module is configured to determine the corresponding signaling by implementing the
combined affinity equation and numerical interpolation algorithm as follows:

obtaining a corresponding maximum power at the pump's maximum

20 speed with respect to the instant motor power and speed parameters using a
power affinity equation;

obtaining corresponding pump differential pressure and flow rate with
respect to the corresponding maximum power at the pump's maximum speed
using direct numerical interpolation; and

determining the instant pump differential pressure and flow rate with respect to the instant motor speed and power by using pressure and flow affinity equations.

- 5 4. Apparatus according to claim 3, wherein the signal processor or processing module is configured to determine the instant pump differential pressure and flow rate by implementing the combined affinity equation and numerical interpolation algorithm and using numerical computation procedures as follows:

10
$$Q(n, w) = \left(\frac{n}{n_{max}}\right) \cdot \bar{q}(n_{max}, W_i, Q_i, \hat{w}(n, w)), \quad (1)$$

$$P(n, w) = \left(\frac{n}{n_{max}}\right)^2 \cdot \bar{p}(n_{max}, W_i, P_i, \hat{w}(n, w)), \quad (2)$$

where $\bar{q}(n_{max}, W_i, Q_i, \hat{w})$ and $\bar{p}(n_{max}, W_i, P_i, \hat{w})$ are pump differential pressure and flow rate distribution functions with respect to power and formulated numerically based upon discrete pump data of (P_i, Q_i, W_i) at motor full speed, and \hat{w} is a corresponding power function at pump full speed by the power affinity equation of

15

$$\hat{w}(n, w) = (n/n_{max})^{-3} \cdot w. \quad (3)$$

20

5. Apparatus according to claim 1, wherein the apparatus comprises a pump controller configured with the signal processor or processing module.

6. Apparatus according to claim 1, wherein the apparatus comprises a hydronic pumping system having a pump and a pump controller, the pump controller configured with the signal processor or processing module for controlling the pump.

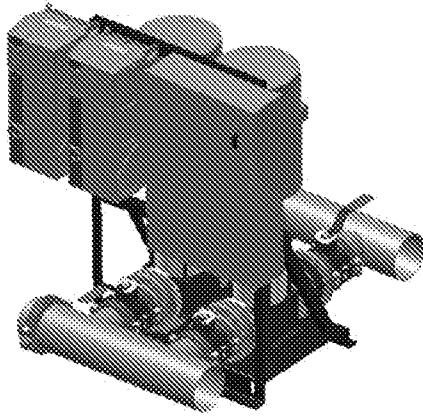


Fig. 1A

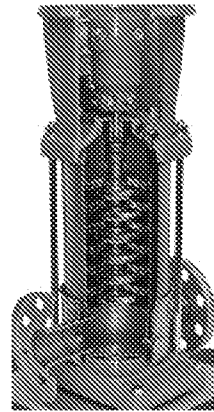


Fig. 1B

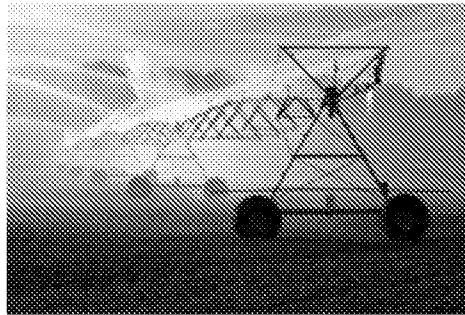


Fig. 1C: For agriculture applications

Figure 1. Examples of sensorless multistage pumping control systems

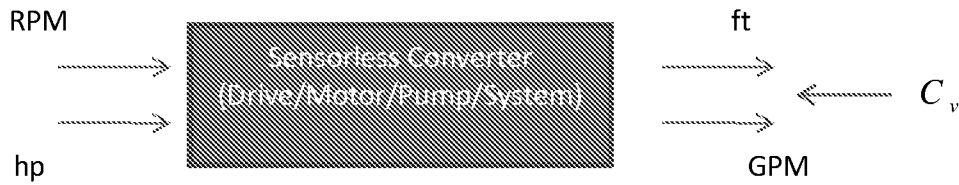


Figure 2A. Pump sensorless converter for pump pressure and flow rate from motor power and speed.

Apparatus 10

Signal processor or processing module 10a configured at least to:

receive signaling containing information about pump differential pressure, flow rate and corresponding power data at motor maximum speed published by pump manufacturers, as well as instant motor power and speed;

determine corresponding signaling containing information about instant pump differential pressure and flow rate using a combined affinity equation and numerical interpolation algorithm, based upon the signaling received; and/or

provide the corresponding signaling as control signaling to control the apparatus.

Other signal processor circuits or components 10b that do not form part of the underlying invention, e.g., including input/output modules, one or more memory modules, data, address and control busing architecture, etc.

Figure 2B

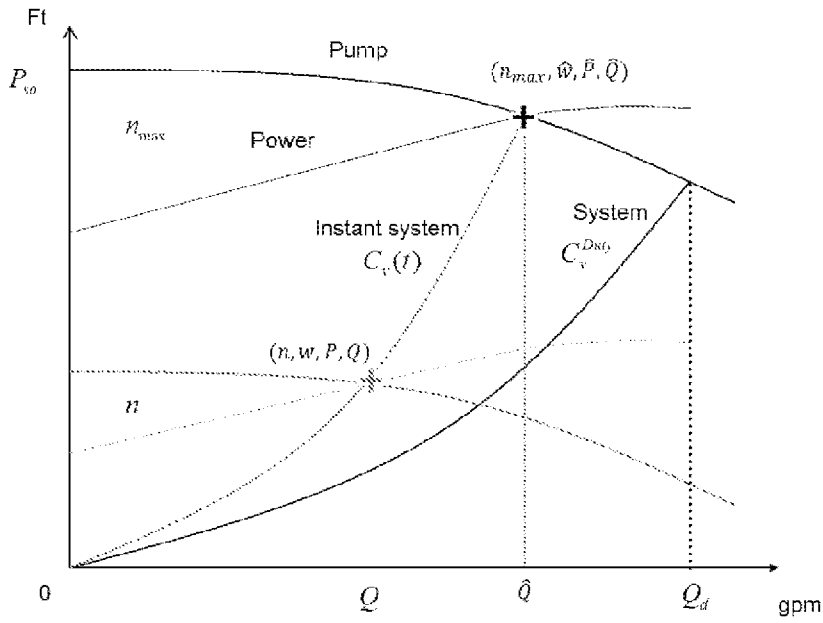


Figure 3. Pump, system and power characteristics curves with the pressure equilibrium point at a flow steady state.

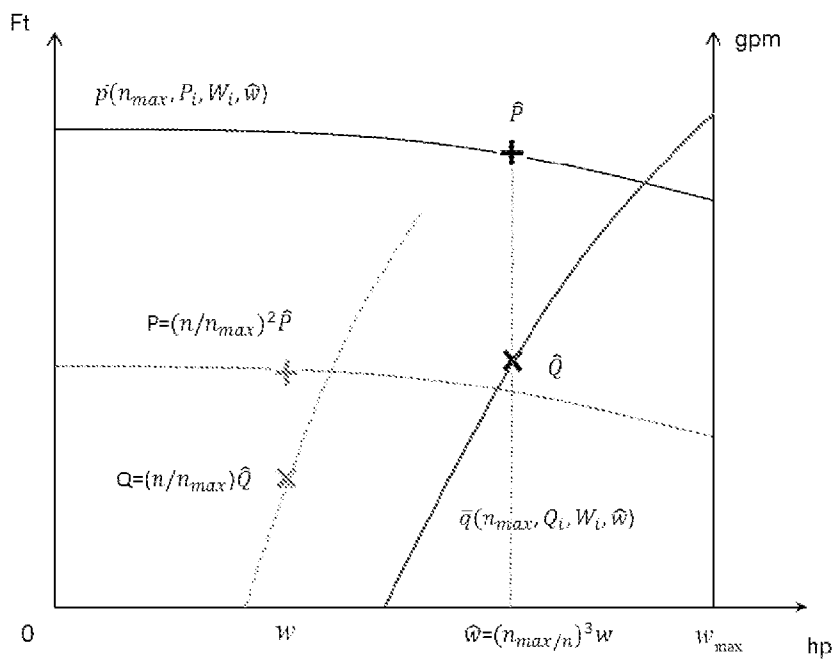


Figure 4. Pump sensorless pressure and flow rate conversion by affinity law and numerical means.

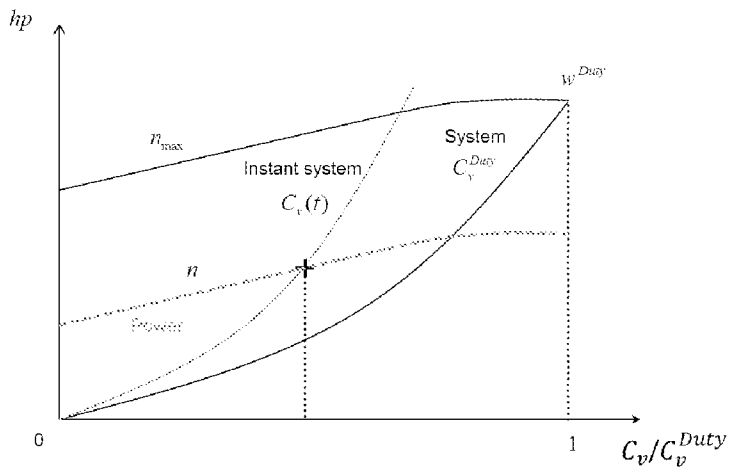


Figure 5: Motor power vs. normalized system characteristics.

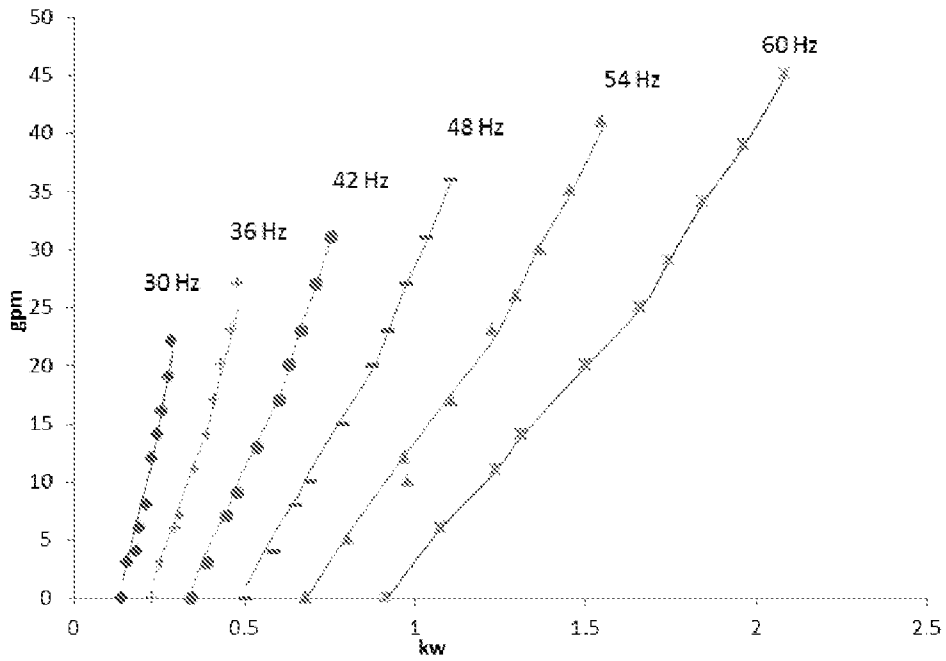


Fig. 6A: Flow rate (gpm) vs. power (kw)

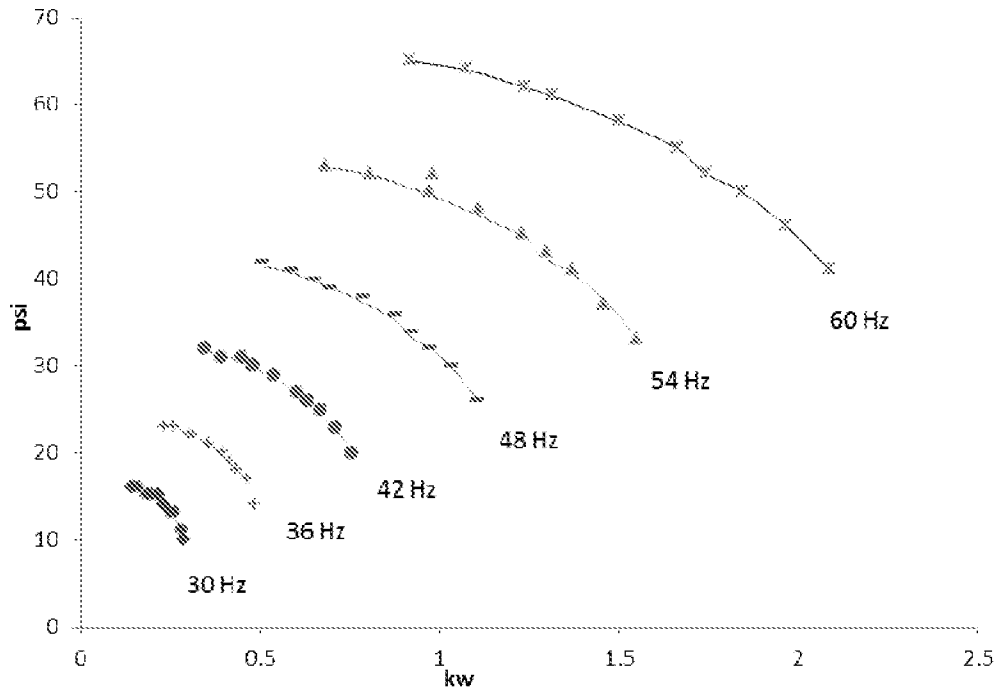


Fig. 6B: Pressure (psi) vs. power (kw)

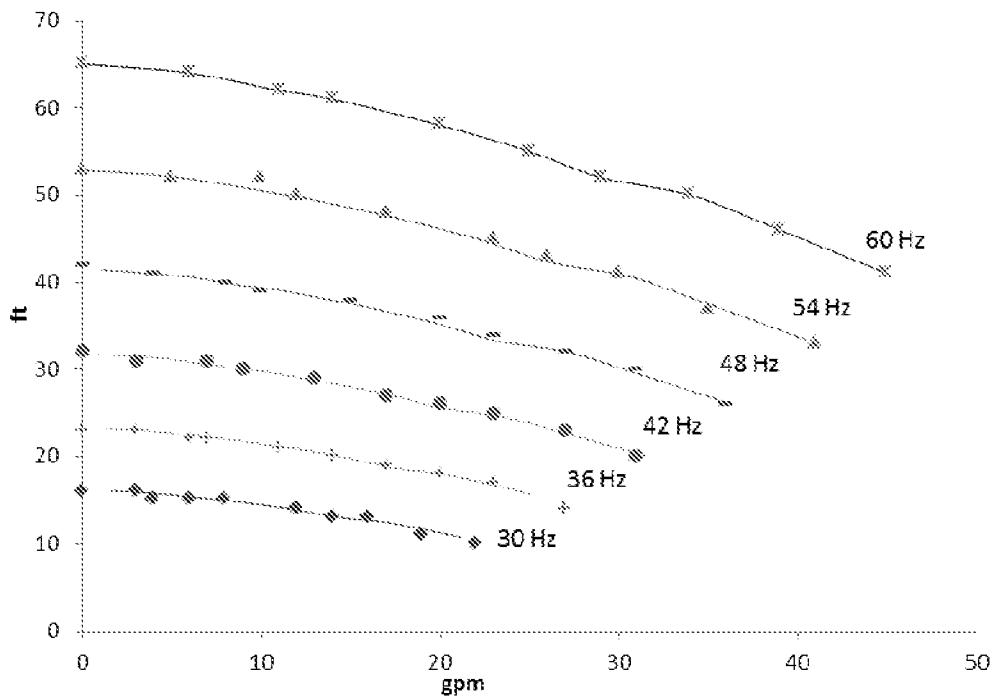


Fig. 6C: Pressure (ft) vs. flow rate (gpm)

Figure 6: Comparisons of pump differential pressure and system flow rate from the sensorless converter (e.g., see the six (6) respective solid lines for 30 Hz, 36 Hz, 42 Hz, 48 Hz, 54 Hz, 60 Hz) and the measured data from sensors (symbols, e.g., including: 30 Hz, diamond symbols; 36 Hz, plus ("+") signs; 42 Hz, solid circle symbols; 48 Hz, minus ("-") signs, 54 Hz, triangle symbols; and 60 Hz, "x" symbols).

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US16/35962

A. CLASSIFICATION OF SUBJECT MATTER
 IPC(8) - F04B 17/03, 49/00, 49/06; G05D 16/20, 7/06 (2016.01)
 CPC - F04B 49/065, 49/103; F04D 15/0088, 15/0066; G05D 7/0617
 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)
 IPC(8): F04B 17/03, 9/00, 49/06; G05D 16/20, 7/06 (2016.01)
 CPC: F04B 49/065, 49/103; F04D 15/0088, 15/0066; G05D 7/0617, 7/0623

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)
 PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, RU, AT, CH, TH, BR, PH, SE, NO, DK, FI, BE, NL, LU, MX, Other Countries (INPADOC)); Google, Google Patent, Google Scholar, EBSCO; Keywords: differential pump pressure motor speed affinity law sensor flow rate calculate estimate interpolate curve RPM variable equation impeller graph plot characteristic hydronic power draw load

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- A	US 2014/0288716 A1 (FLUID HANDLING LLC) 25 September 2014, Fig. 1-6, para. [0019] through [0052], para. [0060] through [0087]	1, 2, 3, 5 & 6 --- 4
A	US 2003/0091443 A1 (SABINI, E et al.) 15 May 2003, para. [0055], [0056], [0057]	1-6
A	US 2013/0204546 A1 (GHD Pty Ltd.) 08 August 2013, entire document	1-6
A	US 2011/0200454 A1 (AHONEN, T et al.) 18 August 2011, para. [0031], [0032]	1-6

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	"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
"E" earlier application or patent but published on or after the international filing date	"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
"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)	"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
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"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 08 August 2016 (08.08.2016)	Date of mailing of the international search report 13 SEP 2016
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Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774
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