

[DESCRIPTION]

[TITLE OF INVENTION]

OPERATION EFFICIENCY ESTIMATION SYSTEM, OPERATION EFFICIENCY
ESTIMATION METHOD, OPERATION EFFICIENCY ESTIMATION DEVICE, AND
5 NON-TRANSITORY STORAGE MEDIUM

[Technical Field]

[0001]

Embodiments of the present invention relate to an operation efficiency
estimation system, an operation efficiency estimation method, an operation efficiency
10 estimation device, and a non-transitory storage medium.

[Background Art]

[0002]

Pumps transporting water in water supply facilities consume a lot of electricity.
The power consumption of pumps accounts for most of the power consumption of the
15 entire water supply facilities. Therefore, reducing the power consumption of pumps is
effective for reducing the power consumption of the entire water supply facilities.
Generally, the operation efficiency of a pump decreases due to age-related deterioration.
The operation efficiency represents the rate at which the pump can convert electric power
into hydraulic energy and is calculated using the discharge flow rate, the discharge
20 pressure, and the power consumption. Therefore, it is possible to reduce power
consumption of pumps by measuring the operation efficiencies of the pumps and using
more efficient pumps.

[0003]

To measure the operation efficiencies of pumps, it is ideal to provide instruments
25 for measuring the discharge flow rate, the discharge pressure, and the power consumption

for each pump. However, in general water supply facilities, the discharge flow rate, the discharge pressure and the power consumption of pumps are measured as total values for the pumps. Installing various instruments for each individual pump is not realistic in terms of cost. Therefore, conventionally it is not easy to determine the operation efficiency of each pump.

[Citation List]

[Patent Literature]

[0004]

[Patent Literature 1]

10 Japanese Unexamined Patent Application, First Publication No. 2008-14230

[Patent Literature 2]

Japanese Unexamined Patent Application, First Publication No. 2012-207546

[Non Patent Literature]

[0005]

15 [Non Patent Literature 1]

Proposal of maintenance management in consideration of the remaining life of pumps installed in a sewage treatment plant, JICA Journal “EICA” Vol. 18, No. 4, 2014

[Summary of Invention]

[Technical Problem]

20 [0006]

An object of the present invention is to provide an operation efficiency estimation system, an operation efficiency estimation method, an operation efficiency estimation device, and a non-transitory storage medium which can estimate the operation efficiency of each individual pump while suppressing an increase in load on the facilities.

25 [Solution to Problem]

[0007]

An operation efficiency estimation system of an embodiment includes fluid transportation devices, an operation information acquirer, an operation period extractor, a power measurer, a pressure measurer, a flow rate measurer, and an operation efficiency estimator. The fluid transportation devices are installed respectively in a plurality of transportation paths merging at a point and are configured to transport fluid flowing through the transportation paths. The operation information acquirer is configured to acquire operation information indicating an active or stop state of each of the fluid transportation devices in time series. The operation period extractor is configured to extract a sole operation period of each of the fluid transportation devices during which the fluid transportation device is active alone on the basis of the operation information. The power measurer is configured to measure total power consumption of the fluid transportation devices and to acquire power information indicating the total power consumption in time series. The pressure measurer is configured to measure a pressure of the fluid and to acquire pressure information indicating the pressure in time series. The flow rate measurer is configured to measure a flow rate of the fluid at the merging point and to acquire flow rate information indicating the flow rate in time series. The operation efficiency estimator is configured to estimate an operation efficiency of the fluid transportation device which was active in the sole operation period on the basis of the power information, the pressure information and the flow rate information in the sole operation period.

[Brief Description of Drawings]

[0008]

Fig. 1 is a diagram showing a specific example of a water supply facility.

Fig. 2 is a functional block diagram showing a functional configuration of a

pump efficiency estimation device 100 according to the first embodiment.

Fig. 3A is a diagram showing a specific example of an operation efficiency estimation method in the first embodiment.

Fig. 3B is a diagram showing a specific example of the operation efficiency estimation method in the first embodiment.

Fig. 3C is a diagram showing a specific example of the operation efficiency estimation method in the first embodiment.

Fig. 3D is a diagram showing a specific example of the operation efficiency estimation method in the first embodiment.

Fig. 4 is a diagram showing a specific example of determining a centroid value of a plurality of operation efficiencies as an estimated operation efficiency value.

Fig. 5 is a flowchart showing a sequence of estimating the operation efficiencies of pumps by the pump efficiency estimation device 100 according to the first embodiment.

Fig. 6 is a functional block diagram showing a functional configuration of a pump efficiency estimation device 100a according to a second embodiment.

Fig. 7A is a diagram showing a specific example of a method for estimating the operation efficiency in the second embodiment.

Fig. 7B is a diagram showing a specific example of the method for estimating the operation efficiency in the second embodiment.

Fig. 7C is a diagram showing a specific example of the method for estimating the operation efficiency in the second embodiment.

Fig. 8 is a flowchart showing a sequence of estimating the operation efficiencies of pumps by the pump efficiency estimation device 100a according to the second embodiment.

Fig. 9 is a functional block diagram showing a functional configuration of a pump efficiency estimation device 100b according to a third embodiment.

Fig. 10 is a functional block diagram showing a functional configuration of a pump efficiency estimation device 100c according to a fourth embodiment.

5 Fig. 11 is a diagram illustrating preconditions to be satisfied by an estimated pressure curve.

Fig. 12 is a diagram illustrating preconditions to be satisfied by an estimated pressure curve.

10 Fig. 13 is a diagram illustrating preconditions to be satisfied by an estimated power curve.

Fig. 14 is a diagram showing an example in the case where the patterns of operating states are limited.

Fig. 15 is a functional block diagram showing a functional configuration of a pump efficiency estimation device 100d according to a fifth embodiment.

15 Fig. 16 is a diagram showing coverage ratios when changing pumps to be thinned out.

Fig. 17 is a functional block diagram showing a functional configuration of a pump efficiency estimation device 100e according to a sixth embodiment.

20 Fig. 18 is a diagram showing a specific example of a first display mode of operation efficiency information.

Fig. 19 is a diagram showing a specific example of a second display mode of operation efficiency information.

Fig. 20 is a diagram showing a specific example of a third display mode of operation efficiency information.

25 Fig. 21 is a diagram showing a first method of deleting unnecessary data.

[Description of Embodiments]

[0009]

Hereinafter, an operation efficiency estimation system, an operation efficiency estimation method, an operation efficiency estimation device, and a non-transitory storage medium according to embodiments will be described with reference to the drawings.

[0010]

(First Embodiment)

Fig. 1 is a diagram showing a specific example of a water supply facility.

10 In Fig. 1, reference numeral 1 denotes transportation paths through which water is transported. Solid arrows in the figure indicate the direction in which water is transported and water flowing through the transportation paths 1 merges at a confluence point denoted by reference numeral 2. Pumps 3-1 to 3-4, a flow rate meter 4, and a pressure meter 5 are installed in the water supply facility having the transportation paths.

15 The pumps 3-1 to 3-4 (fluid transportation devices) are installed respectively in a plurality of transportation paths 1 before merging at the confluence point 2. The flow rate meter 4 is installed at the confluence point 2 or a transportation path 1 after merging. The flow rate meter 4 measures the flow rate of water flowing through the transportation path 1 at the installation position. The pressure meter 5 is installed at the confluence

20 point 2 or the transportation path 1 after merging. The pressure meter 5 measures the pressure of water flowing through the transportation path 1 at the installation position. Hereinafter, for ease of explanation, the pumps 3-1 to 3-4 are collectively referred to as pumps 3 unless otherwise distinguished.

[0011]

25 In Fig. 1, reference numeral 6 denotes switches for controlling power supply to a

power demand facility including the pumps 3. Hereinafter, for ease of explanation, these switches are collectively referred to as switches 6 unless otherwise distinguished. The example in Fig. 1 shows a state in which all the switches are off and, in this state, all the pumps 3 stop operating. Lines between the switches 6 and the pumps 3 represent power transmission lines. The switches 6 are connected to an electric power system 7 that supplies power to the pumps 3. A power meter 8 measures electric power supplied by the electric power system 7.

[0012]

An operation control system 9 (an operation information acquirer) controls the operations of the pumps 3. The operation control system 9 controls the operation of each pump 3 by controlling on/off of one of the switches 6 corresponding to the pump 3.

[0013]

A pump efficiency estimation device 100 estimates the operation efficiency of each pump 3. The pump efficiency estimation device 100 acquires flow rate information, pressure information, power information, and operation information from the flow rate meter 4 (a flow rate measurer), the pressure meter 5 (a pressure measurer), the power meter 8 (a power measurer), and the operation control system 9. The flow rate information is information that is obtained by measurement of the flow rate meter 4 and indicates the flow rate of water flowing through the transportation path 1 in time series. The pressure information is information that is obtained by measurement of the pressure meter 5 and indicates the pressure of water flowing through the transportation path 1 in time series. The power information is information that is obtained by measurement of the power meter 8 and indicates power supplied by the electric power system 7 in time series. The operation information is information indicating the operating state of each pump 3 in time series. Specifically, the operation information is

information indicating on or off of the switches 6 corresponding respectively to the pumps 3. The pump efficiency estimation device 100 estimates the operation efficiency of each pump 3 on the basis of the acquired flow rate information, pressure information, power information, and operation information.

5 [0014]

Hereinafter, the configuration of the pump efficiency estimation device 100 shown in Fig. 1 will be described in detail.

[0015]

Fig. 2 is a functional block diagram showing a functional configuration of the pump efficiency estimation device 100 according to the first embodiment.

The pump efficiency estimation device 100 includes a central processing unit (CPU), a memory, an auxiliary storage device, and the like connected via a bus. The CPU executes a pump efficiency estimation program stored in the memory or the auxiliary storage device. By executing the pump efficiency estimation program, the pump efficiency estimation device 100 functions as a device including an operation information acquirer 101, a flow rate information acquirer 102, a pressure information acquirer 103, a power information acquirer 104, an operation period extractor 105, and an operation efficiency estimator 106. All or a part of the functions of the pump efficiency estimation device 100 may be realized by using hardware such as an application specific integrated circuit (ASIC), a programmable logic device (PLD), or a field programmable gate array (FPGA). The pump efficiency estimation program may be recorded in a computer-readable recording medium. The computer-readable recording medium is, for example, a portable medium such as a flexible disk, a magneto-optical disk, a ROM or a CD-ROM, or a storage device such as a hard disk mounted in a computer system. The pump efficiency estimation program may be

transmitted via an electric communication line.

[0016]

Each of the operation information acquirer 101, the flow rate information acquirer 102, the pressure information acquirer 103, and the power information acquirer 104 includes a communication interface for connecting to a network such as a local area network (LAN) and acquires various types of information through communication with other systems and devices.

[0017]

The operation information acquirer 101 acquires operation information from the operation control system 9. The operation information acquirer 101 outputs the acquired operation information to the operation period extractor 105.

The flow rate information acquirer 102 acquires flow rate information from the flow rate meter 4. The flow rate information acquirer 102 outputs the acquired flow rate information to the operation efficiency estimator 106.

The pressure information acquirer 103 acquires pressure information from the pressure meter 5. The pressure information acquirer 103 outputs the acquired pressure information to the operation efficiency estimator 106.

The power information acquirer 104 acquires power information from the power meter 8. The power information acquirer 104 outputs the acquired power information to the operation efficiency estimator 106.

[0018]

Each of the operation information acquirer 101, the flow rate information acquirer 102, the pressure information acquirer 103, and the power information acquirer 104 may include an interface for connecting thereto a recording medium such as a flexible disk or a flash memory. In this case, the operation information acquirer 101,

the flow rate information acquirer 102, the pressure information acquirer 103, and the power information acquirer 104 may acquire various types of information by reading information from these recording media.

[0019]

5 Figs. 3A to 3D are diagrams showing a specific example of an operation efficiency estimation method according to the first embodiment.

Fig. 3A is a diagram showing a specific example of the operation information.

Fig. 3B is a diagram showing a specific example of the flow rate information. Fig. 3C

is a diagram showing a specific example of the pressure information. Fig. 3D is a

10 diagram showing a specific example of the power information. In Figs. 3A, 3B, 3C and 3D, a horizontal axis represents time and the time axes of the figures indicate the same time periods. A vertical axis in Fig. 3A represents operating states of four pumps 1 to 4. Vertical axes in Figs. 3B, 3C, and 3D represent flow rate, pressure and power, respectively.

15 [0020]

The operating state of each pump is represented by a binary value of ON or OFF, ON indicates that the pump is active, and OFF indicates that the pump is inactive. Figs. 3A to 3D show that only the pump 2 is active in a sole operation period indicated in the figures.

20 [0021]

We now return to the description of Fig. 2.

The operation period extractor 105 acquires the operation information from the operation information acquirer 101. Based on the operating state of each pump

indicated by the operation information, the operation period extractor 105 extracts a

25 period (hereinafter referred to as a “sole operation period”), during which a single pump

is operating alone, from a period indicated by the operation information. The operation period extractor 105 outputs, to the operation efficiency estimator 106, sole operation information indicating the extracted sole operation period and the pump which was operating in the sole operation period.

5 [0022]

The operation efficiency estimator 106 acquires the flow rate information, the pressure information, and the power information from the flow rate information acquirer 102, the pressure information acquirer 103, and the power information acquirer 104, respectively. The operation efficiency estimator 106 also acquires the sole operation
10 information from the operation period extractor 105. The operation efficiency estimator 106 estimates an operation efficiency of each pump on the basis of the acquired flow rate information, pressure information, power information, and sole operation information.

[0023]

Specifically, the operation efficiency estimator 106 extracts corresponding
15 information in the sole operation period from each of the flow rate information, the pressure information, and the power information. Based on the extracted flow rate information, pressure information and power information, the operation efficiency estimator 106 calculates the operation efficiency of the pump corresponding to the sole operation period. The operation efficiency is calculated, for example, by the following
20 equation (1).

[0024]

[Math. 1]

$$\eta(t) = \frac{Q(t) \cdot H(t)}{P(t)} \quad \dots (1)$$

[0025]

In equation (1), $\eta(t)$ represents an operation efficiency at time t . $Q(t)$ and $H(t)$ in the numerator on the right side of equation (1) represent a flow rate and pressure at time t , respectively, and the product thereof corresponds to a hydrodynamic energy into which a part of the supplied power has been converted by the pump. The denominator on the right side of equation (1) represents the power at time t . That is, the operation efficiency $\eta(t)$ is a rate at which the power supplied at time t has been converted into hydrodynamic energy.

[0026]

The operation efficiency estimator 106 can calculate the operation efficiency of the pump 2 by using the flow rate information, the pressure information, and the power information in the sole operation period shown in Figs. 3A to 3D described above. In this manner, the pump efficiency estimation device 100 can calculate the operation efficiency of each pump by extracting the sole operation period of each pump.

[0027]

As shown in Fig. 3A to Fig. 3D, when a plurality of (flow rate, pressure and power) measurement data items are acquired at a plurality of times in the sole operation period, a plurality of operation efficiencies are also calculated. In this case, the operation efficiency estimator 106 determines a representative value of the plurality of operation efficiency values and uses the representative value as an estimated operation efficiency value. For example, as shown in the following Fig. 4, the operation efficiency estimator 106 obtains a centroid value of the plurality of operation efficiencies to determine the estimated operation efficiency value.

[0028]

Fig. 4 is a diagram showing a specific example of determining a centroid value of a plurality of operation efficiencies as an estimated operation efficiency value.

In Fig. 4, a vertical axis represents an operation efficiency value and a horizontal axis represents time. Points plotted in Fig. 4 indicate a plurality of operation efficiency values calculated on the basis of a plurality of measurement data items in the sole operation period. Each operation efficiency value is calculated from measurement data at each time. The example of Fig. 4 shows that the operation efficiency estimator 106 sets a value at the centroid of a point group as an estimated operation efficiency value. The operation efficiency value at the centroid of the point group is represented, for example, by the following equation (2).

[0029]

10 [Math. 2]

$$\bar{\eta} = \frac{\sum_{t=0}^n \eta(t)}{n} \quad \dots (2)$$

[0030]

The operation efficiency estimator 106 may use a statistical value other than a value at the centroid of the points as the estimated operation efficiency value. For example, the operation efficiency estimator 106 may use an average value of the points as the estimated operation efficiency value or may use a value at the midpoint of the sole operation period as the estimated operation efficiency value.

[0031]

Fig. 5 is a flowchart showing a sequence of estimating the operation efficiencies of pumps by the pump efficiency estimation device 100 according to the first embodiment.

First, the pump efficiency estimation device 100 acquires operation information, flow rate information, pressure information, and power information (step S101).

Specifically, the operation information acquirer 101 acquires operation information from the operation control system 9, the flow rate information acquirer 102 acquires flow rate information from the flow rate meter 4, the pressure information acquirer 103 acquires pressure information from the pressure meter, and the power information acquirer 104 acquires power information from the power meter 8. The operation information acquirer 101 outputs the acquired operation information to the operation period extractor 105. The flow rate information acquirer 102, the pressure information acquirer 103, and the power information acquirer 104 output the acquired flow rate information, pressure information, and power information, respectively, to the operation efficiency estimator 106.

[0032]

Based on the operation information output from the operation information acquirer 101, the operation period extractor 105 extracts a sole operation period from a period indicated by the operation information (step S102). The operation period extractor 105 outputs information indicating the extracted sole operation period to the operation efficiency estimator 106.

[0033]

The operation efficiency estimator 106 acquires the flow rate information, the pressure information, and the power information output from the flow rate information acquirer 102, the pressure information acquirer 103, and the power information acquirer 104, respectively. The operation efficiency estimator 106 acquires measurement data of the sole operation period from each of the flow rate information, the pressure information, and the power information on the basis of the information indicating the sole operation period output from the operation period extractor 105 (step S103).

[0034]

The operation efficiency estimator 106 calculates an operation efficiency of a pump which was operating in each sole operation period on the basis of the acquired measurement data of the sole operation period (step S104). Here, a plurality of operation efficiency values are calculated on the basis of a plurality of measurement data items respectively corresponding to a plurality of times at which the plurality of measurement data items were acquired in each sole operation period. The operation efficiency estimator 106 determines a representative value from the plurality of calculated operation efficiency values (step S105). The operation efficiency estimator 106 outputs the determined representative value as an estimated operation efficiency value of each pump (step S106).

[0035]

The pump efficiency estimation device 100 of the first embodiment configured as described above extracts a sole operation period during which each pump was operating alone from the operation information and calculates the pump operation efficiency of each pump on the basis of measurement data of the extracted sole operation period. Therefore, the pump efficiency estimation device 100 can estimate the operation efficiency of each pump from measurement values collectively measured for a plurality of pumps and estimate the operation efficiency of each individual pump while suppressing an increase in load on the facilities.

[0036]

(Second Embodiment)

Hereinafter, a pump efficiency estimation device 100a of a second embodiment will be described. The pump efficiency estimation device 100 of the first embodiment estimates the operation efficiency of each pump by extracting the sole operation period of each pump from the operation information. In the estimation method according to the

first embodiment, it is possible to estimate the operation efficiency in a range of flow rates in which measurement data is present (hereinafter referred to as a “flow rate range”), but it may not be possible to estimate the operation efficiency outside the flow rate range.

In general, it is known that there are correlations between the flow rate and the pressure and between the flow rate and power consumption, and it is not possible to simply compare the operation efficiencies of pumps having different flow rate ranges.

Therefore, in order to make it possible to compare the operation efficiencies of pumps having different flow rate ranges, the pump efficiency estimation device 100a of the second embodiment estimates pressure and power with respect to the flow rate from

measurement data in a sole operation period acquired for a certain pump.

[0037]

Fig. 6 is a functional block diagram showing a functional configuration of the pump efficiency estimation device 100a according to the second embodiment.

In Fig. 6, the same functional units as those in Fig. 2 are denoted by the same reference numerals as those in Fig. 2 to omit descriptions thereof.

The pump efficiency estimation device 100a of the second embodiment is different from the pump efficiency estimation device 100 of the first embodiment in that the pump efficiency estimation device 100a includes an operation efficiency estimator 106a instead of the operation efficiency estimator 106 and further includes a pressure curve estimator 107 and a power curve estimator 108.

[0038]

The pressure curve estimator 107 determines parameters (hereinafter referred to as “pressure parameters”) of a model for estimating a pressure from a flow rate.

Specifically, the pressure curve estimator 107 acquires information indicating the sole operation period of each pump from the operation period extractor 105. The pressure

curve estimator 107 also acquires flow rate information and pressure information from the flow rate information acquirer 102 and the pressure information acquirer 103, respectively. The pressure curve estimator 107 determines the pressure parameters of each pump on the basis of measurement data of the sole operation period in the flow rate
5 information and the pressure information.

[0039]

The power curve estimator 108 determines parameters (hereinafter referred to as “power parameters”) of a model for estimating a power from a flow rate. Specifically, the power curve estimator 108 acquires information indicating the sole operation period
10 of each pump from the operation period extractor 105. The power curve estimator 108 also acquires flow rate information and power information from the flow rate information acquirer 102 and the power information acquirer 104, respectively. The power curve estimator 108 determines power parameters of each pump on the basis of measurement data of the sole operation period in the flow rate information and the power information.

15 [0040]

Here, the correlation between the flow rate and the pressure is expressed, for example, by the following equation (3) and the correlation between the flow rate and the power is expressed, for example, by the following equation (4).

[0041]

20 [Math. 3]

$$H(t) = \alpha Q(t)^2 + \beta Q(t) + \gamma \quad \dots (3)$$

[0042]

[Math. 4]

$$P(t) = \delta Q(t)^3 + \varepsilon Q(t)^2 + \lambda Q(t) + \mu \quad \dots (4)$$

[0043]

In equation (3), α , β and γ are pressure parameters and δ , ε , λ and μ in equation (4) are power parameters. The pressure curve estimator 107 and the power curve estimator 108 estimate pressure parameters and power parameters which optimize equations (3) and (4), respectively, on the basis of measurement data of the sole operation period in the flow rate information, the pressure information, and the power information. Optimization of such parameters can be formulated as linear optimization problems as in the following equations (5) to (8) and can be solved by a method such as a least squares technique.

[0044]

[Math. 5]

$$\min \int (H(t) - \hat{H}(t))^2 dt \quad \dots (5)$$

[0045]

[Math. 6]

$$\hat{H}(t) = \alpha Q(t)^2 + \beta Q(t) + \gamma \quad \dots (6)$$

[0046]

[Math. 7]

$$\hat{P}(t) = \delta Q(t)^3 + \varepsilon Q(t)^2 + \lambda Q(t) + \mu \quad \dots (7)$$

[0047]

[Math. 8]

$$\min \int (P(t) - \hat{P}(t))^2 dt \quad \dots (8)$$

[0048]

A symbol “^” in equations (5) to (8) is hereinafter referred to as a “hat” and a hatted variable means that the variable is an estimated value. Hereinafter, a hatted symbol is described as a “^symbol” in the specification.

[0049]

The pressure curve estimator 107 and the power curve estimator 108 determine the pressure parameters and the power parameters, respectively, by solving the above optimization problems. The pressure curve estimator 107 and the power curve estimator 108 output the determined pressure parameters and power parameters respectively to the operation efficiency estimator 106a.

[0050]

The operation efficiency estimator 106a acquires pressure parameters and power parameters output from the pressure curve estimator 107 and the power curve estimator 108, respectively. Based on the acquired pressure parameters and power parameters, the operation efficiency estimator 106a constructs an operation efficiency estimation model representing the operation efficiency of each pump with respect to an arbitrary flow rate. The operation efficiency estimator 106a estimates the operation efficiency of each pump on the basis of the constructed operation efficiency estimation model. In the case of using equations (3) and (4), the operation efficiency estimation model is expressed by the following equation (9).

[0051]

[Math. 9]

$$\eta = \frac{\alpha Q^3 + \beta Q^2 + \gamma Q}{\delta Q^3 + \varepsilon Q^2 + \lambda Q + \mu} \quad \dots (9)$$

[0052]

Figs. 7A to 7C are diagrams showing a specific example of a method for estimating the operation efficiency in the second embodiment.

5 Fig. 7A is a diagram showing pressure information in a sole operation period of a certain pump. Fig. 7B is a diagram showing power information in the sole operation period of the pump. Fig. 7C is a diagram showing an operation efficiency estimation model estimated on the basis of the pressure information and the power information in the sole operation period of the pump. By constructing the operation efficiency

10 estimation model representing the operation efficiency with respect to an arbitrary flow rate on the basis of the pressure information and power information acquired in an arbitrary flow rate range in this manner, the pump efficiency estimation device 100a of the second embodiment makes it possible to compare the operation efficiencies of pumps having different flow rate regions.

15 [0053]

Fig. 8 is a flowchart showing a sequence of estimating the operation efficiencies of pumps by the pump efficiency estimation device 100a according to the second embodiment.

20 In Fig. 8, the same functional units as those in Fig. 5 are denoted by the same reference numerals as those in Fig. 5 to omit descriptions thereof.

The pressure curve estimator 107 acquires information indicating the sole operation period of each pump from the operation period extractor 105. The pressure curve estimator 107 also acquires the flow rate information and the pressure information from the flow rate information acquirer 102 and the pressure information acquirer 103,

respectively. The pressure curve estimator 107 determines pressure parameters of each pump on the basis of measurement data of the sole operation period in the flow rate information and the pressure information (step S201). The pressure curve estimator 107 outputs the determined pressure parameters of each pump to the operation efficiency estimator 106a.

[0054]

The power curve estimator 108 acquires information indicating the sole operation period of each pump from the operation period extractor 105. The power curve estimator 108 also acquires the flow rate information and the power information from the flow rate information acquirer 102 and the power information acquirer 104, respectively. The power curve estimator 108 determines power parameters of each pump on the basis of measurement data of the sole operation period in the flow rate information and the power information (step S202). The power curve estimator 108 outputs the determined power parameters of each pump to the operation efficiency estimator 106a.

[0055]

The operation efficiency estimator 106a acquires the pressure parameters and power parameters output from the pressure curve estimator 107 and the power curve estimator 108, respectively. Based on the acquired pressure parameters and power parameters, the operation efficiency estimator 106a constructs an operation efficiency estimation model representing the operation efficiency of each pump with respect to an arbitrary flow rate (step S203). The operation efficiency estimator 106a estimates the operation efficiency of each pump on the basis of the constructed operation efficiency estimation model.

[0056]

The pump efficiency estimation device 100a according to the second embodiment configured as described above calculates, for each pump, pressure and power parameters for obtaining models representing the pressure and power in an arbitrary flow rate range of the pump on the basis of measurement data in the sole operation period of the pump and constructs an operation efficiency estimation model for estimating the operation efficiency of each pump in an arbitrary flow rate range using the determined pressure parameters and power parameters. By constructing this operation efficiency estimation model, the pump efficiency estimation device 100a makes it possible to compare the operation efficiencies of pumps having different flow rate ranges.

[0057]

(Third Embodiment)

Hereinafter, a pump efficiency estimation device 100b of a third embodiment will be described. The pump efficiency estimation device 100a of the second embodiment makes it possible to compare operation efficiencies of pumps having different flow rate ranges by constructing an operation efficiency estimation model for estimating the operation efficiency in an arbitrary flow rate range on the basis of measurement data acquired for a certain flow rate range. However, in the estimation method according to the second embodiment, if sufficient measurement data for a sole operation period cannot be obtained for each pump, there is a possibility that pressure parameters and power parameters of the operation efficiency estimation model may not be able to be determined. Therefore, the pump efficiency estimation device 100b of the third embodiment makes it possible to determine pressure parameters and power parameters on the basis of measurement data acquired under a condition that a plurality of pumps operate at the same time.

[0058]

Fig. 9 is a functional block diagram showing a functional configuration of the pump efficiency estimation device 100b according to the third embodiment.

In Fig. 9, the same functional units as those in Fig. 6 are denoted by the same
5 reference numerals as those in Fig. 6 to omit descriptions thereof.

The pump efficiency estimation device 100b of the third embodiment is different from the pump efficiency estimation device 100a of the second embodiment in that the pump efficiency estimation device 100b does not include the operation period extractor 105 and includes a pressure curve estimator 107b instead of the pressure curve estimator 107 and a power curve estimator 108b instead of the power curve estimator 108.
10

[0059]

The pressure curve estimator 107b acquires operation information from the operation information acquirer 101. The operation information can be expressed by the following equation (10) when it is expressed as operation information $d_i(t)$ of each pump
15 at time t (where “ i ” is an identification number of each pump).

[0060]

[Math. 10]

$$d_i(t) = \begin{cases} 1 & \text{(when pump is active)} \\ 0 & \text{(when pump is inactive)} \end{cases} \dots (10)$$

[0061]

20 Here, an optimization problem for obtaining pressure parameters can be formulated as the following equations (11) to (14). Hereinafter, a pump indicated by identification number i will be referred to as pump i .

[0062]

[Math. 11]

$$\min \int (Q(t) - \hat{Q}(t))^2 dt \quad \dots (11)$$

Subject to

[Math. 12]

$$\hat{Q}(t) = \sum_{i=1}^n d_i(t) \hat{q}_i(t) \quad \dots (12)$$

5 [0063]

[Math. 13]

$$\hat{q}_i(t) = \frac{-\beta_i + \sqrt{\beta_i^2 - 4\alpha_i(\gamma_i - H(t))}}{2\alpha_i} \quad \dots (13)$$

[0064]

[Math. 14]

$$10 \quad \alpha_i < 0, \gamma_i > 0, \beta_i^2 - 4\alpha_i(\gamma_i - \max(H(t))) \geq 0 \quad \dots (14)$$

[0065]

In equations (12) and (13), $\hat{q}_i(t)$ represents an estimated value of the flow rate measured at time t for pump i . Also, α_i , β_i and γ_i in equations (13) and (14) represent pressure parameters of the pump i . Since the pressure is constant at any point on the transportation path, $\hat{q}_i(t)$ is expressed by equation (13) using the pressure $H(t)$.

15

[0066]

The power curve estimator 108b acquires operation information from the operation information acquirer 101. As with the pressure parameters, an optimization problem for obtaining power parameters can be formulated as the following equations

20 (15) to (17).

[0067]

[Math. 15]

$$\min \int \left(P(t) - \hat{P}(t) \right)^2 dt \quad \dots (15)$$

Subject to

5 [Math. 16]

$$\hat{P}(t) = \sum_{i=1}^n d_i(t) \hat{p}_i(t) \quad \dots (16)$$

[0068]

[Math. 17]

$$\hat{p}_i(t) = \delta_i \hat{q}_i(t)^3 + \varepsilon_i \hat{q}_i(t)^2 + \lambda_i \hat{q}_i(t) + \mu_i \quad \dots (17)$$

10 [0069]

Since the optimization problems of the equations (12) to (14) formulated as described above are nonlinear optimization problems, the pressure curve estimator 107b and the power curve estimator 108b estimate pressure parameters and power parameters, respectively, by solving the above optimization problems using a metaheuristic technique such as a genetic algorithm, simulated annealing, or particle swarm optimization. The pressure curve estimator 107b and the power curve estimator 108b output the pressure parameters and the power parameters of each pump determined by the above estimation to the operation efficiency estimator 106a.

[0070]

20 Since the method of formulating a nonlinear optimization problem uses a solution formula, complex numbers may appear in the evaluation of the optimization

problem. Although the above formulation prevents the occurrence of complex numbers by constraint conditions, other methods may also be used to prevent the occurrence of complex numbers. For example, a method of setting the value of an evaluation function to infinity when a complex number occurs in the evaluation function may be conceived.

- 5 In this case, the above optimization problems can be formulated as the following equations (18) to (23).

[0071]

[Math. 18]

$$\min f = \begin{cases} \int_0^{\infty} (Q(t) - \hat{Q}(t))^2 dt & \beta_i^2 - 4\alpha_i(\gamma_i - \max(H(t))) \geq 0 \text{ or } \alpha_i < 0 \text{ or } \gamma_i > 0 \\ \text{other} & \end{cases} \quad \dots (18)$$

- 10 Subject to

[Math. 19]

$$\hat{Q}(t) = \sum_{i=1}^n d_i(t) \hat{q}_i(t) \quad \dots (19)$$

[0072]

[Math. 20]

$$\hat{q}_i(t) = \frac{-\beta_i + \sqrt{\beta_i^2 - 4\alpha_i(\gamma_i - H(t))}}{2\alpha_i} \quad \dots (20)$$

15

[0073]

[Math. 21]

$$\min \int \left(P(t) - \hat{P}(t) \right)^2 dt \quad \dots (21)$$

Subject to

- 20 [Math. 22]

$$\hat{P}(t) = \sum_{i=1}^n d_i(t) \hat{p}_i(t) \quad \dots (22)$$

[0074]

[Math. 23]

$$\hat{p}_i(t) = \delta_i \hat{q}_i(t)^3 + \varepsilon_i \hat{q}_i(t)^2 + \lambda_i \hat{q}_i(t) + \mu_i \quad \dots (23)$$

5 [0075]

The pump efficiency estimation device 100b of the third embodiment configured as described above determines pressure parameters and power parameters by solving nonlinear optimization problems formulated on the basis of measurement data acquired under a condition that a plurality of pumps operate at the same time. By determining

10 pressure parameters and power parameters through solving of nonlinear optimization problems, the pump efficiency estimation device 100b can determine the pressure parameters and power parameters of an operation efficiency estimation model even when sufficient measurement data of a sole operation period cannot be obtained for each pump.

[0076]

15 (Fourth Embodiment)

Hereinafter, a pump efficiency estimation device 100c of a fourth embodiment will be described. The pump efficiency estimation device 100b of the third embodiment determines pressure parameters and power parameters by solving nonlinear optimization problems formulated on the basis of measurement data acquired under a condition that a

20 plurality of pumps operate at the same time. However, in the parameter determination method of the third embodiment, the number of parameters to be estimated in the optimization problem is large and thus identifiability is reduced and an optimal solution sometimes cannot be obtained. Therefore, the pump efficiency estimation device 100c

of the fourth embodiment first determines an approximate straight line of measurement data and determines pressure parameters and power parameters through extrapolation in consideration of the characteristics of the pump on the basis of parameters of the determined approximate straight line.

5 [0077]

Fig. 10 is a functional block diagram showing a functional configuration of the pump efficiency estimation device 100c according to the fourth embodiment.

In Fig. 10, the same functional units as those in Fig. 9 are denoted by the same reference numerals as those in Fig. 9 to omit descriptions thereof.

10 The pump efficiency estimation device 100c of the fourth embodiment is different from the pump efficiency estimation device 100b of the third embodiment in that the pump efficiency estimation device 100c includes a pressure curve estimator 107c instead of the pressure curve estimator 107b and a power curve estimator 108c instead of the power curve estimator 108b and further includes a straight line approximator 109.

15 Hereinafter, the configurations of the functional units will be described with regard to each of pressure parameter determination and power parameter determination.

[0078]

[Determination of pressure parameters]

The straight line approximator 109 acquires operation information from the
20 operation information acquirer 101. The straight line approximator 109 also acquires flow rate information and pressure information from the flow rate information acquirer 102 and the pressure information acquirer 103, respectively. Based on the acquired operation information, flow rate information, and pressure information, the straight line approximator 109 determines an approximate straight line representing the pressure
25 according to the flow rate in each pump. When measurement data is acquired for a

narrow flow rate range, an approximate straight line indicating the pressure $H(t)$ is expressed by the following equation (24).

[0079]

[Math. 24]

$$5 \quad H(t) = a_i q_i(t) + b_i \quad \dots (24)$$

[0080]

In this case, parameters a_i and b_i of the approximate straight line represented by equation (24) can be determined by solving an optimization problem formulated as the following equations (25) to (27).

10 [0081]

[Math. 25]

$$\min \int (Q(t) - \hat{Q}(t))^2 dt \quad \dots (25)$$

Subject to

[Math. 26]

$$15 \quad \hat{Q}(t) = \sum_{i=1}^n d_i(t) \hat{q}_i(t) \quad \dots (26)$$

[0082]

[Math. 27]

$$\hat{q}_i(t) = \frac{1}{a_i} H(t) + \frac{b_i}{a_i} \quad \dots (27)$$

[0083]

20 Since the optimization problem formulated as described above is a linear optimization problem, the optimization problem can be solved using a method such as a

least squares technique. The straight line approximator 109 outputs the parameters of the approximate straight line determined by solving the optimization problem to the pressure curve estimator 107c.

[0084]

- 5 The pressure curve estimator 107c determines pressure parameters of each pump on the basis of the parameters of the approximate straight line determined by the straight line approximator 109. Specifically, the pressure curve estimator 107c determines pressure parameters by solving preconditions expressed by the following equations (28) to (30) as simultaneous equations.

10 [0085]

[Math. 28]

$$\gamma = H_{\text{ini_max}} \quad \dots (28)$$

[0086]

[Math. 29]

15
$$2\alpha \frac{Q_1 + Q_2}{2} + \beta = a \quad \dots (29)$$

[0087]

[Math. 30]

$$\alpha Q_2^2 + \beta Q_2 + \gamma = a Q_2 + b \quad \dots (30)$$

[0088]

- 20 Fig. 11 is a diagram illustrating preconditions to be satisfied by an estimated pressure curve.

In Fig. 11, a horizontal axis represents the flow rate and a vertical axis represents the pressure. A point group 20 in Fig. 11 represents a set of points at which

measurement data acquired for a pump of which a pressure curve is to be obtained is plotted. Here, let us assume that the pump which operates alone and corresponds to the measurement data shown as the point group 20 is pump A. A point group 21 represents a set of points at which measurement data acquired when a plurality of pumps, rather
 5 than the pump A alone, operate is plotted.

[0089]

In Fig. 11, H_1 represents a maximum value of the pressure in all measured pressure information. Similarly, H_2 represents a minimum value of the pressure in all measured pressure information. In the case of the example of Fig. 11, H_1 belongs to the
 10 point group 21 and H_2 belongs to the point group 20.

[0090]

Here, the straight line approximator 109 determines parameters (a and b in the figure) representing the approximate straight line for the point group 20 by solving the optimization problem formulated by equations (25) to (27). An approximate straight
 15 line 22 in Fig. 11 is obtained by determining these parameters.

[0091]

The pressure curve estimator 107c determines pressure parameters representing a pressure curve 23 by solving equations (28) to (30) as simultaneous equations using the parameters a and b of the approximate straight line determined by the straight line
 20 approximator 109.

[0092]

H_{ini_max} in equation (28) represents a shut-off pressure. The shut-off pressure refers to the pressure when all pumps do not supply water, in other words, the pressure when all pumps are shut off. That is, H_{ini_max} is the pressure when $Q = 0$, and equation
 25 (28) represents a precondition that the shut-off pressure does not deteriorate regardless of

pump efficiency.

[0093]

In equations (29) and (30), Q_1 corresponds to a point on the pressure curve 23 to be determined and represents a flow rate when the pressure is H_1 . Similarly, Q_2 corresponds to a point on the pressure curve 23 to be determined and represents a flow rate when the pressure is H_2 . That is, a range from Q_1 to Q_2 represents a flow rate range at the time when the measurement data is acquired. That is, equation (29) represents an assumption that the gradient of a tangent line 24 of the pressure curve 23 at the center of the flow rate range (g_Q in the figure) is the same as the gradient of the approximate straight line 22. Also, equation (30) represents a precondition that the pressure curve 23 passes through a point on the approximate straight line 22 at the maximum value of the flow rate range.

[0094]

The pressure curve estimator 107c may determine the pressure parameters by setting the above three preconditions as in the following equations (31) to (33).

[0095]

[Math. 31]

$$\gamma = H_{\text{ini_max}} \quad \dots (31)$$

[0096]

20 [Math. 32]

$$\alpha Q_1^2 + \beta Q_1 + \gamma = a Q_1 + b \quad \dots (32)$$

[0097]

[Math. 33]

$$\alpha Q_2^2 + \beta Q_2 + \gamma = a Q_2 + b \quad \dots (33)$$

[0098]

Fig. 12 is a diagram illustrating preconditions to be satisfied by an estimated pressure curve.

5 The difference between the preconditions shown in Fig. 11 and the preconditions shown in Fig. 12 is that equation (29) is replaced with equation (32). Equation (33) represents a precondition that the pressure curve 23 passes through a point on the approximate straight line 22 at the maximum value of the flow rate range, whereas equation (32) represents a precondition that the pressure curve 23 passes through a point
10 on the approximate straight line 22 at the minimum value of the flow rate range.

[0099]

As described above, the pressure curve estimator 107c solves the preconditions represented by equations (28) to (30) or equations (31) to (33) as simultaneous equations on the basis of the parameters of the approximate straight line determined by the straight
15 line approximator 109 to determine the pressure parameters such that the pressure curve satisfies the above preconditions.

[0100]

[Determination of power parameters]

The straight line approximator 109 acquires operation information from the
20 operation information acquirer 101. The straight line approximator 109 also acquires flow rate information and power information from the flow rate information acquirer 102 and the power information acquirer 104, respectively. Based on the acquired operation information, flow rate information and power information, the straight line approximator 109 determines an approximate straight line representing the power according to the flow

rate of each pump. When measurement data is acquired for a narrow flow rate range, an approximate straight line indicating power $P(t)$ is expressed by the following equation (34).

[0101]

5 [Math. 34]

$$p_i(t) = c_i q_i(t) + e_i \quad \dots (34)$$

[0102]

In this case, parameters c_i and e_i of the approximate straight line represented by equation (34) can be determined by solving an optimization problem formulated as the following equations (35) to (37). In solving this optimization problem, an estimated value of the flow rate obtained by equation (27) through the pressure parameter determination is used for flow rate $q_i(t)$ of each pump.

[0103]

[Math. 35]

$$\min \int \left(P(t) - \hat{P}(t) \right)^2 dt \quad \dots (35)$$

Subject to

[Math. 36]

$$\hat{P}(t) = \sum_{i=1}^n d_i(t) \hat{p}_i(t) \quad \dots (36)$$

[0104]

20 [Math. 37]

$$\hat{p}_i(t) = c_i q_i(t) + e_i \quad \dots (37)$$

[0105]

Since the optimization problem formulated as described above is a linear optimization problem, the optimization problem can be solved using a method such as a least squares technique. The straight line approximator 109 outputs the parameters of the approximate straight line determined by solving the above optimization problem to the power curve estimator 108c.

[0106]

The power curve estimator 108c determines power parameters of each pump on the basis of the parameters of the approximate straight line determined by the straight line approximator 109. Specifically, the power curve estimator 108c determines power parameters by solving preconditions expressed by the following equations (38) to (41) as simultaneous equations.

[0107]

[Math. 38]

$$\mu = P_{\text{ini_max}} \dots (38)$$

[0108]

[Math. 39]

$$\delta Q_1^3 + \varepsilon Q_1^2 + \lambda Q_1 + \mu = aQ_1 + b \dots (39)$$

[0109]

20 [Math. 40]

$$\delta Q_2^3 + \varepsilon Q_2^2 + \lambda Q_2 + \mu = aQ_2 + b \dots (40)$$

[0110]

[Math. 41]

$$3\delta\left(\frac{Q_1 + Q_2}{2}\right)^2 + 2\varepsilon\left(\frac{Q_1 + Q_2}{2}\right) + \lambda = a \quad \dots (41)$$

[0111]

Fig. 13 is a diagram illustrating preconditions to be satisfied by an estimated power curve.

5 In Fig. 13, a horizontal axis represents the flow rate and a vertical axis represents the power. A point group 30 in Fig. 13 represents a set of points at which measurement data acquired for the pump A of which a power curve is to be obtained is plotted. A point group 31-1 and a point group 31-2 represent sets of points at which measurement data acquired at different times for the pump A is plotted. Hereinafter, for
10 ease of explanation, the point group 31-1 and the point group 31-2 are described as point groups 31 unless otherwise distinguished.

[0112]

In Fig. 13, P_1 represents a maximum value of the power indicated by points included in the point group 30. Similarly, P_2 represents a minimum value of the power
15 indicated by the points included in the point group 30.

[0113]

Here, the straight line approximator 109 determines parameters (c and e in the figure) representing an approximate straight line of the point group 30 by solving the optimization problem formulated by equations (35) to (37). An approximate straight
20 line 32 in Fig. 13 is obtained by determining these parameters.

[0114]

The power curve estimator 108c determines power parameters representing a power curve 33 by solving equations (38) to (41) as simultaneous equations using the

parameters c and e of the approximate straight line determined by the straight line approximator 109.

[0115]

In equation (38), P_{ini_max} is the power when $Q = 0$ and equation (38) represents a precondition that the power for a flow rate of zero does not change.

[0116]

In equations (39) to (41), Q_1 corresponds to a point on the power curve 33 to be determined and represents the flow rate when the power is P_1 . Similarly, Q_2 corresponds to a point on the power curve 33 to be determined and represents the flow rate when the pressure is P_2 . That is, a range from Q_1 to Q_2 represents a flow rate range at the time when the measurement data is acquired. That is, equation (39) represents a precondition that the power curve 33 passes through a point on the approximate straight line 32 at the minimum value of the flow rate range. Similarly, equation (40) represents a precondition that the power curve 33 passes through a point on the approximate straight line 32 at the maximum value of the flow rate range. Equation (41) represents a precondition that the gradient of a tangent line 34 of the power curve 33 at the center of the flow rate range (g_Q in the figure) is the same as the gradient of the approximate straight line 32.

[0117]

As described above, the power curve estimator 108c solves the preconditions represented by equations (38) to (41) as simultaneous equations on the basis of the parameters of the approximate straight line determined by the straight line approximator 109 to determine the power parameters such that the power curve satisfies the above preconditions.

[0118]

The pump efficiency estimation device 100c according to the fourth embodiment configured as described above can formulate the determination of pressure parameters and power parameters as linear optimization problems by approximating measurement data acquired for a certain flow rate range as a straight line. Therefore, the pump efficiency estimation device 100c of the fourth embodiment can determine pressure parameters and power parameters more accurately.

[0119]

(Fifth Embodiment)

Hereinafter, a pump efficiency estimation device 100d of a fifth embodiment will be described. In the pump efficiency estimation devices of the second to fourth embodiments described above, the determination of pressure parameters and power parameters for estimating the operation efficiency is formulated as optimization problems. Identifiability of parameters to be determined is important in estimating the operation efficiency by solving the optimization problems. It is operation information of the pump that essentially affects the identifiability of the optimization problems described above.

[0120]

For example, parameters of pump i cannot be determined if operation information $d_i(t)$ indicating the (active or inactive) operating state of the pump i is always zero. Also, even when $d_i(t)$ is not always zero, parameters cannot be determined if patterns of operating states that $d(t)$ can take are limited. Even if parameters can be determined in such a case, the reliability of the parameters is low.

[0121]

Fig. 14 is a diagram showing an example in the case where the patterns of operating states are limited.

Fig. 14 shows the case where $d(t)$ indicating the operating states of three pumps takes only two patterns of values $\{1, 1, 0\}$ or $\{1, 1, 1\}$. In Fig. 14, a total flow rate represents the sum of the flow rates of the pumps and total power consumption represents the sum of the power consumption of the pumps. In this case, it is possible to estimate parameters for the pump 3 since switching between active and inactive states of the pump 3 is included in the operation information. However, it is not possible to estimate parameters for the pump 1 and the pump 2 since switching between active and inactive states of the pump 1 and the pump 2 is not included in the operation information.

[0122]

Therefore, in the present embodiment, a coverage ratio is defined as an index for estimating the operation efficiency more accurately. The coverage ratio is a value indicating how much the operation information covers possible patterns. The pump efficiency estimation device 100d makes it possible to estimate the operation efficiency more accurately by solving the optimization problems using measurement data acquired in periods during which the operation information indicates a higher coverage ratio.

[0123]

Fig. 15 is a functional block diagram showing a functional configuration of the pump efficiency estimation device 100d according to the fifth embodiment.

In Fig. 15, the same functional units as those in Fig. 10 are denoted by the same reference numerals as those in Fig. 10 to omit descriptions thereof.

The pump efficiency estimation device 100d of the fifth embodiment is different from the pump efficiency estimation device 100c of the fourth embodiment in that the pump efficiency estimation device 100d further includes a coverage ratio improver 110.

[0124]

The coverage ratio improver 110 acquires operation information from the

operation information acquirer 101. The coverage ratio improver 110 performs a coverage ratio improvement process for improving the coverage ratio of the acquired operation information to generate operation information with an improved coverage ratio. The coverage ratio improver 110 outputs the generated operation information to the
5 pressure curve estimator 107c and the power curve estimator 108c.

Details of the coverage ratio improvement process performed by the coverage ratio improver 110 will be described below.

[0125]

[Coverage ratio enhancement process]

10 The coverage ratio R is defined, for example, by the following equation (42).

[0126]

[Math. 42]

$$R = \frac{\text{Number of patterns included in } d(t)}{\text{Number of possible patterns} - 1} \quad \dots (42)$$

[0127]

15 Here, 1 which is subtracted from the number of possible patterns as the denominator of equation (42) represents the case where all pumps are inactive. For example, in the example of Fig. 14, the number of possible patterns is $2^3 = 8$ and the number of patterns included in $d(t)$ is 2. Therefore, in this case, the coverage ratio $R = 2/(8-1) \doteq 0.29$.

20 [0128]

The coverage ratio improver 110 improves the coverage ratio of the operation information by thinning out operation information of pumps which is the cause of lowering the coverage ratio from the operation information. For example, the case

where the operation information $d(t)$ of the four pumps before the coverage ratio improvement process is expressed by the following equation (43) will be described below.

[0129]

5 [Math. 43]

$$d = \begin{Bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{Bmatrix} \dots (43)$$

[0130]

Columns on the right side of equation (43) correspond to pumps and rows correspond to patterns of operating states of the pumps. Here, the pumps corresponding to the columns on the right side of equation (43) are described as pump 1, pump 2, pump 3 and pump 4 in this order from the left column. In this case, the coverage ratio for the four pumps is $5 / (2^4 - 1) \doteq 0.33$.

[0131]

In this case, for example, the coverage ratio improver 110 thins out operation information for the pump 1 and the pump 2 which change little in the operating states. Specifically, the coverage ratio improver 110 thins out rows indicating that the pump 1 or the pump 2 is active from the matrix on the right side of equation (43). As a result, the operation information is expressed by the following equation (44).

[0132]

20 [Math. 44]

$$d = \begin{Bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 \end{Bmatrix} \dots (44)$$

[0133]

As a result, the coverage ratio of the operation information represented by equation (44) is $2/(2^2-1) \doteq 0.67$, thus improving the coverage ratio.

5 [0134]

Fig. 16 is a diagram showing coverage ratios when changing pumps to be thinned out.

Fig. 16 shows results of performing the coverage ratio improvement process by changing a combination of pumps to be thinned out for the operation information represented by equation (43). Thinning patterns in Fig. 16 represent combinations of pumps to be thinned out. A pump in which “x” is written in a thinning pattern is a pump to be thinned out. The number of target pumps represents the number of pumps of which parameter estimation becomes possible with the operation information after the coverage ratio improvement process. From Fig. 16, it can be seen that the coverage ratio improves as the number of pumps to be thinned out increases. In Fig. 16, the coverage ratio set to zero when the number of target pumps is one indicates that the operation information expressed by equation (43) does not include a pattern indicating an operating state in which the pump 1, the pump 2, and the pump 3 are all inactive.

[0135]

20 In the pump efficiency estimation device 100d of the fifth embodiment configured as described above, the operation information with the coverage ratio improved by the coverage ratio improver 110 is output to the pressure curve estimator 107c and the power curve estimator 108c. The pressure curve estimator 107c and the

power curve estimator 108c solve the optimization problems on the basis of the operation information output from the coverage ratio improver 110, which allows the pump efficiency estimation device 100d to estimate the operation efficiency more accurately.

[0136]

5 (Sixth Embodiment)

Fig. 17 is a functional block diagram showing a functional configuration of a pump efficiency estimation device 100e according to a sixth embodiment.

In Fig. 17, the same functional units as those in Fig. 15 are denoted by the same reference numerals as those in Fig. 15 to omit descriptions thereof.

10 The pump efficiency estimation device 100e of the sixth embodiment is different from the pump efficiency estimation device 100d of the fifth embodiment in that the pump efficiency estimation device 100e further includes a display 111, a storage 112, and a display controller 113.

[0137]

15 The display 111 is configured using a display device such as a cathode ray tube (CRT) display, a liquid crystal display, an organic electro-luminescence (EL) display, or the like. Alternatively, the display 111 may be configured as an interface for connecting these display devices to the pump efficiency estimation device.

[0138]

20 The storage 112 is configured using a storage device such as a magnetic hard disk device or a semiconductor storage device. The storage 112 stores information (hereinafter referred to as “operation efficiency information”) indicating results of estimation of the operation efficiencies of pumps output by the operation efficiency estimator 106a in association with the times at which the operation efficiencies are
25 estimated.

[0139]

The display controller 113 acquires the operation efficiency information from the storage 112 and causes the display 111 to display the operation efficiency information. For example, the display controller 113 displays a list of curves (hereinafter referred to as “efficiency curves”) representing the operation efficiencies of the pumps on the basis of the operation efficiency information. For example, the display controller 113 displays the efficiency curves in the following three modes shown in Figs. 18 to 20.

[0140]

Fig. 18 is a diagram showing a specific example of the first display mode of the operation efficiency information.

The first display mode of the operation efficiency information is a mode which makes it possible to compare the operation efficiency of each pump with respect to an arbitrary flow rate. In the first display mode, for example, the display controller 113 calculates the operation efficiency of each pump with respect to an arbitrary flow rate designated by the user and causes the display 111 to display the calculated operation efficiency value in association with the efficiency curve.

[0141]

Fig. 19 is a diagram showing a specific example of the second display mode of the operation efficiency information.

The second display mode of the operation efficiency information is a mode which makes it possible to compare the operation efficiency of each pump with the maximum operation efficiency value. In the second display mode, the display controller 113 calculates the maximum operation efficiency value of each pump and causes the display 111 to display the calculated maximum operation efficiency value in association with the efficiency curve.

[0142]

Fig. 20 is a diagram showing a specific example of the third display mode of the operation efficiency information.

The third display mode of the operation efficiency information is a mode in
5 which a time-series change in the operation efficiency of an arbitrary pump is displayed. In the third display mode, the display controller 113 causes the display 111 to display an efficiency curve estimated, for example, in each predetermined period in the past for a pump designated by the user in time series.

[0143]

10 The pump efficiency estimation device 100e of the sixth embodiment configured as described above displays the estimation result of the operation efficiency of each pump for which estimation has been performed in such a manner that the estimation result is comparable between pumps or between estimated times of an arbitrary pump. Providing the pump efficiency estimation device 100e with such a function allows
15 visualization of changes in the operation efficiency of each pump, allowing the user to more flexibly make operation plans such as pump maintenance and updating.

[0144]

Hereinafter, a modified example of the above pump efficiency estimation device will be described.

20 [0145]

The above pump efficiency estimation device may also be configured to estimate the operation efficiency after removing unnecessary data from measurement data. For example, the pump efficiency estimation device may remove unnecessary data by the following first or second method.

25 [0146]

Fig. 21 is a diagram showing the first method of deleting unnecessary data.

The first method is a method of removing transient data, measured when the pump starts or stops, from measurement data. In this case, as shown in Fig. 21, the pump efficiency estimation device deletes from the measurement data, for example, data of a predetermined period including the time when the pump starts or stops.

[0147]

The second method is a method of removing outliers from measurement data.

The outliers are pieces of measurement data acquired differently from values which originally needed to be measured due to sensor abnormality, communication bit errors, or the like. As a method of removing such outliers, there is a method using the median Q_{med} and the median absolute deviation Q_{mad} of measurement data. The median Q_{med} and the median absolute deviation Q_{mad} are expressed by the following equations (45) and (46).

[0148]

15 [Math. 45]

$$Q_{\text{med}} = \text{median}(Q(t)) \quad \dots (45)$$

[0149]

[Math. 46]

$$Q_{\text{mad}} = c \times \text{median}(|Q(t) - Q_{\text{med}}|) \quad \dots (46)$$

20 [0150]

In equation (46), c represents a correction coefficient and $c = 1 / 0.6745$ under the assumption of a normal distribution. By using the median Q_{med} and the median absolute deviation Q_{mad} as described above, it is possible to remove unnecessary data from the measurement data as shown in equation (47).

[0151]

[Math. 47]

$$Q(t) = \begin{cases} Q(t) & Q_{\text{med}} - \kappa Q_{\text{mad}} < Q(t) < Q_{\text{med}} + \kappa Q_{\text{mad}} \\ \infty \text{ (outlier)} & \text{other} \end{cases} \dots (47)$$

[0152]

5 In equation (47), κ represents an adjustment parameter and is usually set to a value in a range of 2 to 3.

[0153]

By deleting unnecessary data from measurement data by the first method or the second method described above, the pump efficiency estimation device can estimate the operation efficiency more accurately.

[0154]

According to at least one of the embodiments described above, a plurality of fluid transportation devices installed respectively in a plurality of transportation paths merging at a point and configured to transport fluid flowing through the transportation paths, an operation information acquirer configured to acquire operation information indicating an active or stop state of each of the plurality of fluid transportation devices in time series, a period extractor configured to extract a sole operation period of each of the plurality of fluid transportation devices during which the fluid transportation device is active alone on the basis of the operation information, a power consumption measurer configured to measure a total power consumption of the plurality of fluid transportation devices and to acquire power information indicating the total power consumption in time series, a pressure measurer configured to measure a pressure of the fluid and to acquire pressure information indicating the pressure in time series, a flow rate acquirer configured to measure a flow rate of the fluid at the merging point and to acquire flow

rate information indicating the flow rate in time series, and an estimator configured to estimate an operation efficiency of each of the fluid transportation devices which was active in the sole operation period on the basis of the power information, the pressure information and the flow rate information in the sole operation period are provided,
5 which makes it possible to estimate the operation efficiency of each individual pump while suppressing an increase in load on the facilities.

[0155]

While several embodiments of the present invention have been described, these embodiments have been presented as examples and are not intended to limit the scope of
10 the invention. These embodiments can be implemented in various other forms, and various omissions, substitutions, and changes can be made without departing from the gist of the invention. These embodiments and modifications thereof are included in the scope or gist of the invention and are also similarly included in the scope of the invention described in the claims and equivalents thereof.

[CLAIMS]

[Claim 1]

An operation efficiency estimation system comprising:

fluid transportation devices installed respectively in a plurality of transportation
5 paths merging at a point and configured to transport fluid flowing through the
transportation paths;

an operation information acquirer configured to acquire operation information
indicating an active or stop state of each of the fluid transportation devices in time series;

an operation period extractor configured to extract a sole operation period of
10 each of the fluid transportation devices during which the fluid transportation device is
active alone on the basis of the operation information;

a power measurer configured to measure a total power consumption of the fluid
transportation devices and to acquire power information indicating the total power
consumption in time series;

15 a pressure measurer configured to measure a pressure of the fluid and to acquire
pressure information indicating the pressure in time series;

a flow rate measurer configured to measure a flow rate of the fluid at the
merging point and to acquire flow rate information indicating the flow rate in time series;
and

20 an operation efficiency estimator configured to estimate an operation efficiency
of the fluid transportation device which was active in the sole operation period on the
basis of the power information, the pressure information and the flow rate information in
the sole operation period.

[Claim 2]

25 The operation efficiency estimation system according to claim 1, further

comprising:

a pressure curve estimator configured to estimate a pressure curve indicating a relationship between a flow rate and pressure for the fluid transportation device that was active in the sole operation period on the basis of the flow rate information and the

5 pressure information in the sole operation period; and

a power curve estimator configured to estimate a power curve indicating a relationship between a flow rate and power for the fluid transportation device that was active in the sole operation period on the basis of the flow rate information and the power information in the sole operation period,

10 wherein the operation efficiency estimator is configured to estimate an operation efficiency for an arbitrary flow rate of the fluid transportation device that was active in the sole operation period on the basis of the pressure curve and the power curve.

[Claim 3]

An operation efficiency estimation system comprising:

15 fluid transportation devices installed respectively in a plurality of transportation paths merging at a point and configured to transport fluid flowing through the transportation paths;

an operation information acquirer configured to acquire operation information indicating an active or inactive state of each of the fluid transportation devices in time
20 series;

a power measurer configured to measure a total power consumption of the fluid transportation devices and to acquire power information indicating the total power consumption in time series;

a pressure measurer configured to measure a pressure of the fluid and to acquire
25 pressure information indicating the pressure in time series;

a flow rate measurer configured to measure a flow rate of the fluid at the merging point and to acquire flow rate information indicating the flow rate in time series;

a pressure curve estimator configured to estimate a pressure curve indicating a relationship between a flow rate and pressure for each of the fluid transportation devices
5 on the basis of the operation information, the flow rate information, and the pressure information;

a power curve estimator configured to estimate a power curve indicating a relationship between a flow rate and power for each of the fluid transportation devices on the basis of the operation information, the flow rate information, and the power
10 information; and

an operation efficiency estimator configured to estimate an operation efficiency of each of the fluid transportation devices on the basis of the pressure curve and the power curve.

[Claim 4]

15 The operation efficiency estimation system according to claim 3, wherein the pressure curve estimator is configured to estimate a parameter representing the pressure curve by solving a nonlinear optimization problem, and

the power curve estimator is configured to estimate a parameter representing the power curve by solving a nonlinear optimization problem.

20 [Claim 5]

The operation efficiency estimation system according to claim 3, wherein the pressure curve estimator is configured to approximate a measurement value indicated by the flow rate information and the pressure information by a straight line and to estimate a parameter representing the pressure curve as a solution of simultaneous equations using a
25 condition that a shut-off pressure of the fluid transportation device is constant, and

the power curve estimator is configured to approximate a measurement value indicated by the flow rate information and the pressure information by a straight line and to estimate a parameter representing the power curve as a solution of simultaneous equations using a condition that power for a flow rate of zero does not change.

5 [Claim 6]

The operation efficiency estimation system according to claim 3, further comprising a coverage ratio improver configured to perform a coverage ratio improvement process for removing operation information of an inactive fluid transportation device from the operation information acquired by the operation
10 information acquirer to increase a ratio of the number of combinations of states of the fluid transportation devices included in the operation information after the removal to the number of combinations of possible states thereof,

wherein the pressure curve estimator is configured to estimate the pressure curve on the basis of the operation information, the flow rate information, and the pressure
15 information for which the coverage ratio improvement process has been performed, and

the power curve estimator is configured to estimate the power curve on the basis of the operation information, the flow rate information, and the power information for which the coverage ratio improvement process has been performed.

[Claim 7]

20 The operation efficiency estimation system according to claim 1, further comprising a removal unit configured to remove information which may reduce estimation accuracy of the operation efficiency from the flow rate information acquired by the flow rate measurer, the pressure information acquired by the pressure measurer, and the power information acquired by the power measurer before any process associated
25 with estimation of the operation efficiency is performed.

[Claim 8]

The operation efficiency estimation system according to claim 1, further comprising:

a display configured to display an estimation result of the operation efficiency;

5 and

a display controller configured to cause the display to display the estimation result in such a manner that the estimation result is comparable between the fluid transportation devices;

[Claim 9]

10 The operation efficiency estimation system according to claim 8, wherein the display controller is configured to cause the display to display the estimation result for at least one fluid transportation device selected from the fluid transportation devices in such a manner that the estimation result is comparable in time series.

[Claim 10]

15 An operation efficiency estimation method comprising:

an operation period extraction step including extracting, for each of fluid transportation devices installed respectively in a plurality of transportation paths merging at a point and configured to transport fluid flowing through the transportation paths, a sole operation period during which the fluid transportation device is active alone on the basis of operation information indicating an active or stop state of each of the fluid transportation devices in time series; and

20

an operation efficiency estimation step including estimating an operation efficiency of the fluid transportation device which was active in the sole operation period on the basis of information of the sole operation period regarding power information indicating a total power consumption of the fluid transportation devices in time series,

25

pressure information indicating pressure of the fluid in time series, and flow rate information indicating a flow rate of the fluid at the merging point in time series.

[Claim 11]

An operation efficiency estimation method comprising:

5 a pressure curve estimation step including estimating a pressure curve representing a relationship between a flow rate and pressure for each of fluid transportation devices, which are installed respectively in a plurality of transportation paths merging at a point and are configured to transport fluid flowing through the transportation paths, on the basis of operation information indicating an active or inactive
10 state of each of the fluid transportation devices in time series, flow rate information indicating a flow rate of the fluid at the merging point in time series, and pressure information indicating pressure of the fluid in time series;

a power curve estimation step including estimating a power curve representing a relationship between a flow rate and power for each of the fluid transportation devices on
15 the basis of the operation information, the flow rate information, and power information indicating a total power consumption of the fluid transportation devices in time series;
and

an operation efficiency estimation step including estimating an operation efficiency of each of the fluid transportation devices on the basis of the pressure curve
20 and the power curve.

[Claim 12]

An operation efficiency estimation device comprising:

an operation period extractor configured to extract, for each of fluid transportation devices installed respectively in a plurality of transportation paths merging
25 at a point and configured to transport fluid flowing through the transportation paths, a

sole operation period during which the fluid transportation device is active alone on the basis of operation information indicating an active or stop state of each of the fluid transportation devices in time series; and

an operation efficiency estimator configured to estimate an operation efficiency
5 of the fluid transportation device which was active in the sole operation period on the basis of information of the sole operation period regarding power information indicating a total power consumption of the fluid transportation devices in time series, pressure information indicating pressure of the fluid in time series, and flow rate information indicating a total flow rate of the fluid in time series.

10 [Claim 13]

A non-transitory storage medium storing a computer program for causing a computer to execute:

an operation period extraction step including extracting, for each of fluid transportation devices installed respectively in a plurality of transportation paths merging
15 at a point and configured to transport fluid flowing through the transportation paths, a sole operation period during which the fluid transportation device is active alone on the basis of operation information indicating an active or stop state of each of the fluid transportation devices in time series; and

an operation efficiency estimation step including estimating an operation
20 efficiency of the fluid transportation device which was active in the sole operation period on the basis of information of the sole operation period regarding power information indicating a total power consumption of the fluid transportation devices in time series, pressure information indicating pressure of the fluid in time series, and flow rate information indicating a total flow rate of the fluid in time series.

25 [Claim 14]

An operation efficiency estimation device comprising:

5 a pressure curve estimator configured to estimate a pressure curve representing a relationship between a flow rate and pressure for each of fluid transportation devices, which are installed respectively in a plurality of transportation paths merging at a point and are configured to transport fluid flowing through the transportation paths, on the basis of operation information indicating an active or inactive state of each of the fluid transportation devices in time series, pressure information indicating pressure of the fluid in time series, and flow rate information indicating a flow rate of the fluid at the merging point in time series;

10 a power curve estimator configured to estimate a power curve representing a relationship between a flow rate and power for each of the fluid transportation devices on the basis of the operation information, the flow rate information, and power information indicating a total power consumption of the fluid transportation devices in time series; and

15 an operation efficiency estimator configured to estimate an operation efficiency of each of the fluid transportation devices on the basis of the pressure curve and the power curve.

[Claim 15]

A non-transitory storage medium storing a computer program for causing a
20 computer to execute:

a pressure curve estimation step including estimating a pressure curve representing a relationship between a flow rate and pressure for each of fluid transportation devices, which are installed respectively in a plurality of transportation paths merging at a point and are configured to transport fluid flowing through the
25 transportation paths, on the basis of operation information indicating an active or inactive

state of each of the fluid transportation devices in time series, pressure information indicating pressure of the fluid in time series, and flow rate information indicating a flow rate of the fluid at the merging point in time series;

5 a power curve estimation step including estimating a power curve representing a relationship between a flow rate and power for each of the fluid transportation devices on the basis of the operation information, the flow rate information, and power information indicating a total power consumption of the fluid transportation devices in time series; and

10 an operation efficiency estimation step including estimating an operation efficiency of each of the fluid transportation devices on the basis of the pressure curve and the power curve.