Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25162

181 (2020) 141–150
March

Case study of pump scheduling using sensor-based real-time pump efficiency monitoring

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Received 1 July 2019; Accepted 18 November 2019

ABSTRACT

The issue of carbon emission and energy consumption is one of the major problems all over the country. Most of the energy used in a water supply system is related to the process of water transport from raw water intake to a reservoir using pumps. Energy loss was caused by low pump efficiency which was due to incorrect design, degradation, and operation outside of the best efficiency point. The performance of the pump installed in the water purification plant cannot be the same as that of the factory. Therefore, the technology to operate the pump efficiently under the installation and operating conditions is important. This study focuses on pump scheduling optimization using sensors of water temperature and real-time pump efficiency monitoring. The hybrid hydraulic and thermodynamic calculation approach could provide flow rate and pump efficiency for individual pumps. Energy consumption could be saved by up to 3% when applying the optimized pump scheduling to the test pump station for 4 months.

Keywords: Energy consumption; Real-time monitoring; Pump performance; Pump efficiency; Sensor; Thermodynamic analysis

1. Introduction

As the performance of waterworks gradually becomes sufficient to produce the quantity and quality required for water service, the water supply business is shifting to cost and energy savings through optimization of the operation and management of existing waterworks facilities [1,2]. The Korean waterworks design standards also recently focus on the systematic management and economic operation of the interconnected facilities and the climate change adaptation in the step of design basis. Waterworks facilities are considered to keep pace with the trend of automation and unmanned technology to minimize mechanical and human errors which have significant impacts on waterworks performance [3,4]. The standards describe the importance of asset management for water supply facilities and efficient energy usage [5].

Most of the energy used in a water supply system is related to the process of water transport from raw water intake to a reservoir using pumps. Therefore, the water service provider operates its pumps based on the economical tariff schedule at peak and off-peak periods that can reduce the energy cost [6,7]. About 80% of the power consumption is by a motor, and about 40% of the motor is loaded by pumps. The margin factors for pump capacity are considered in both steps of facility design and pump manufacture. That has resulted that the utility operates pumps outside of the best efficiency point of the pump performance curve with the varied flow-head conditions. It would be causing vibration, noise and shorter pump life.

There are generally three approaches to efficient and economical management of the pumps in waterworks; efficiency and performance improvement of the individual

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pump, the optimum combination of pumps under the best operation point, and pump operation schedule. The efficiency of individual pumps is related to design contents, such as the flow rate, head, and motor that are suitable for the application site [8]. Hydraulic losses due to the structure and shape of the pump, frictional losses due to the pump material and fluid properties, and recycling losses due to wear gaps are considered in the pump efficiency. The other consideration of the pump efficiency problem is how several pumps are operated in combination at the pump station and at which operating point. The efficient combination in pump operation requires a variable speed system, proper capacity distribution of each pump and accurate analysis of a pump characteristic curve.

Another consideration is the pump operation schedule. The pump operation schedule predicts changes in water demand of distribution networks in advance and actively adjusts each reservoir water level and pipeline pressure. The objectives are to minimize pump head, pipeline pressure, reservoir operating levels and power peaks. Besides, it can maximize midnight power utilization, and pump operating efficiency. This ultimately leads to energy savings and pipeline leaks minimizing.

Recently a pump schedule optimization is studied for minimizing an energy-cost operation for the pumps of a water supply network. Then water energy can be controlled by pumps whose energy level is obtained within the pump characteristic curve [2,9–12].

Pump efficiency can be measured by the hydraulic method and thermodynamic method. The traditional hydraulic method is still generally used in waterworks and can calculate pump efficiency from the pump equation, flow rate, head, and electrical power. Most of the pump could not have own information of individual flow rate because individual flow meters are not accurate, expensive and need some space of the installation. It is uneconomical to install a flow meter for each pump to evaluate the operating conditions when several pumps are operated in parallel or series. Thus flow meters are generally installed at the position of the combined pipeline to measure the total flow rate delivered by the combined pumps [13–15].

The thermodynamic method can determine pump efficiency using the water temperature and pressure which are based on the principle of energy conservation. The temperature sensor can monitor the change of water temperature which transfers energy between water and pump motor [16]. When the fluid temperature is raised by the pump, the loss of the pump is directly evaluated as the pump efficiency. This method only needs a sensitive sensor of water temperature and calculation algorithm without using individual flow meter.

In the case of pumps that consume a large amount of energy, it is important to match the machine and system so that the installed machine is operated at the designed flow rate (the best efficiency point). Since pumps are operated for a minimum of ten years, the pipeline condition changes during operation and the performance of the pump itself changes, so that the pump is operated out of the best efficiency point. In this case, it is very important from an energy-saving that the operating state is evaluated in real-time or at regular intervals.

Therefore, this study focused on a fixed-speed pump scheduling using the sensors of water temperature, pressure, and electricity in real-time which were installed at the test water supply pumps or motor control center. The hybrid hydraulic and thermodynamic calculation method was applied to calculate the individual pump flow rate and pump efficiency. Also, this could provide optimum pump scheduling to fit the demand of water supply toward the reservoir and to reduce power consumption.

2. Material and methods

2.1. Experimental instruments of testbed

Fig. 1 shows a picture of a water supply pump station for delivering the final water to the highland reservoir. This pump station is located at the Y water purification plant. The water supply pump station was designed to supply water to 3 reservoirs and capacity was 182,000~232,000 m^3/d using water supply pumps (Fig. 2). In this study, sensors and instruments were installed and tested at this testbed pump station to optimize the pump operating conditions.

Pump operation data for one year before testing were analyzed to understand the pump operation efficiency under the existing pump scheduling condition. The water supply pumps consisted of a total of six with a fixed-speed. As shown in Table 1, four main pumps had a flow rate of 4,200 m^3/h and two auxiliary pumps were half of the main pump capacity. The three combination modes of pump operation were selected by the operator in terms of water reservoirs level, pump operation time, electricity tariff, etc.

2.2. Test instruments and system

It is difficult to measure the individual flow rate of a large water supply pump. Because of the large amount of space required for the flowmeter and the inaccurate readings, the total flow rate is usually measured in an integrated effluent pipeline. In this study, the flow rate of the individual pump was measured by Eq. (2) by real-time measurement of fluid temperature at the suction and discharge of each pump.

Hydraulic instrumentation (TT-G2, Riventa) was attached to each pump. Pressure and water temperature were measured in the suction and discharge of each pump. Both transducers were inserted through one ½" BSP tapping. The pressure transducer connected through a hydraulic quick release coupling in the side port and the temperature transducer through a resealable compression gland (Fig. 3). The temperature probe was inserted 50 mm into the pipework at which time the gate valve was gently tightened onto the probe shaft adding a second point of contact to limit vibration due to the passing fluid.

The pressure and temperature transducers were connected to a data acquisition unit (DAU) next to the pump which processed the signals. Electrical power to the motor was measured at the motor control center through observations on voltage and current on each phase and power factor which yields true power (kW). Connections were made to the secondary side of the potential transformer and current transformer (Fig. 4).

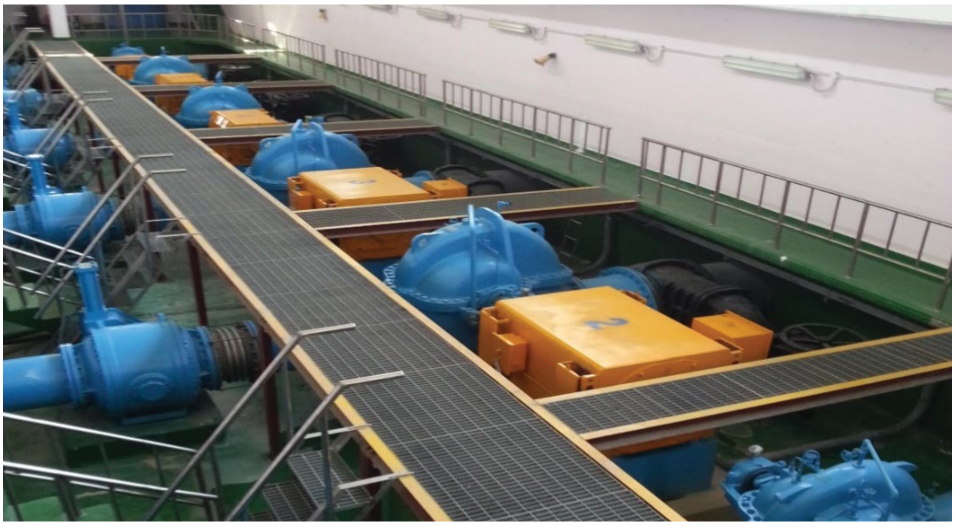

Fig. 1. Testbed of a water supply pump station.

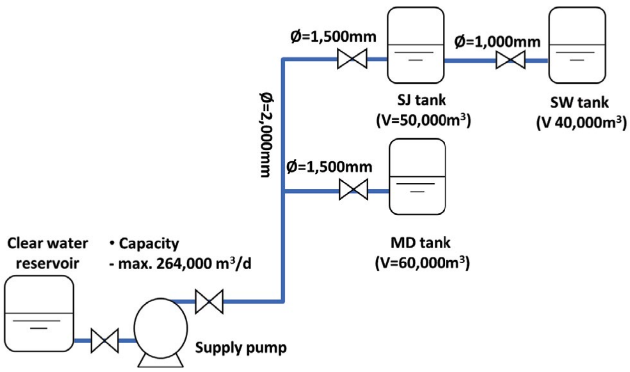

Fig. 2. Overview of water supply network from the pump station to reservoirs.

The human-machine interface was designed for the site-specific information as shown in Fig. 5. Users could monitor the pump combinations, current total head and current specific power in real-time. Besides, the individual pump on duty could show the information of flow rate, efficiency and differential head. Further information could provide the recommendation of pump combination according to the variation of flow rate.

2.3. Thermodynamic pump efficiency measurement

Testing the pumps thermodynamically requires the use of the testing standard ISO5198:1999 (centrifugal, mixed flow, and axial pumps: code for hydraulic performance tests, precision class). For this method, the following is measured and calculated as shown in Table 2.

For the thermodynamic method, the pump efficiency is calculated with only the measurement of temperature and pressure. The flow is then derived from the other parameters. The flow measurement uncertainty is a product of all the others, of which the pump efficiency provides the greatest bearing. In both the thermodynamic and the conventional methods for hydraulic work done is used by Eq. (1).

Table 1
Specification of applied pumps at Y water purification plant

No	Power (kW)	Flow rate (m³/h)	Head (m)	Function
1	450	2,100	58	Auxiliary
2	900	4,200	58	Main
3	900	4,200	58	Main
4	900	4,200	58	Main
5	900	4,200	58	Main
6	450	2,100	58	Auxiliary

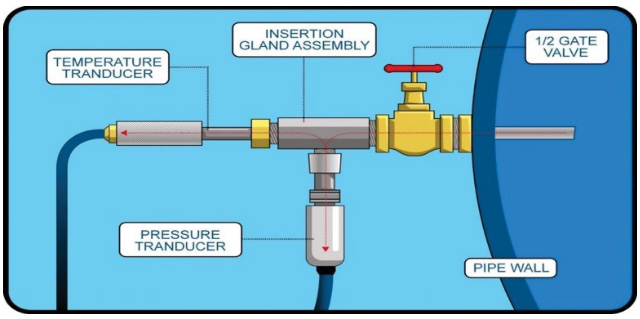

Fig. 3. Installation of temperature and pressure sensor.

$$P_e \cdot \eta_m \cdot \eta_p = \dot{m} \cdot g \cdot \Delta H = \bar{\rho} \cdot g \cdot \dot{Q} \cdot \Delta H \quad (1)$$

where η_m is the motor efficiency respectively; η_p is the pump efficiency; P_e is the electrical power input (W), $\dot{m}$ is the mass flow rate (kg/s), ρ is the average density of the working fluid (kg/m³), g is gravitational acceleration, 9.807 m/s², Q is the volume flow rate (m³/s), and ΔH is the head rise across the pump (m).

For the thermodynamic method, the pump efficiency is calculated with only the measurement of temperature and pressure. The flow of a pump is then derived from the other parameters. The flow measurement uncertainty is a product

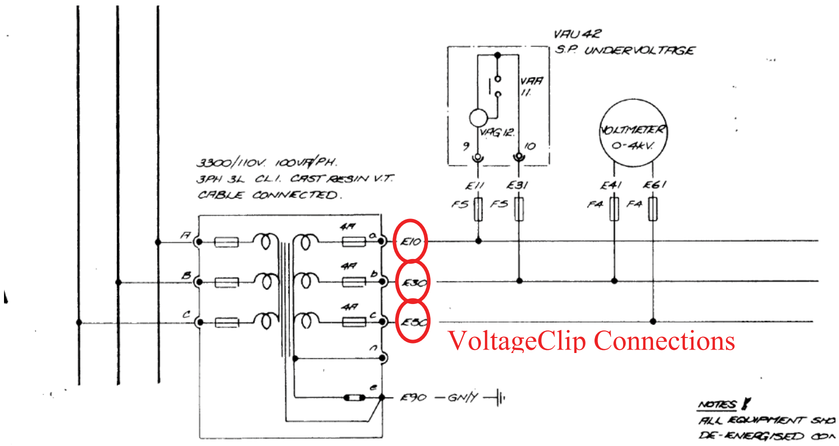

Fig. 4. Typical site electrical drawing with the voltage measurement points.

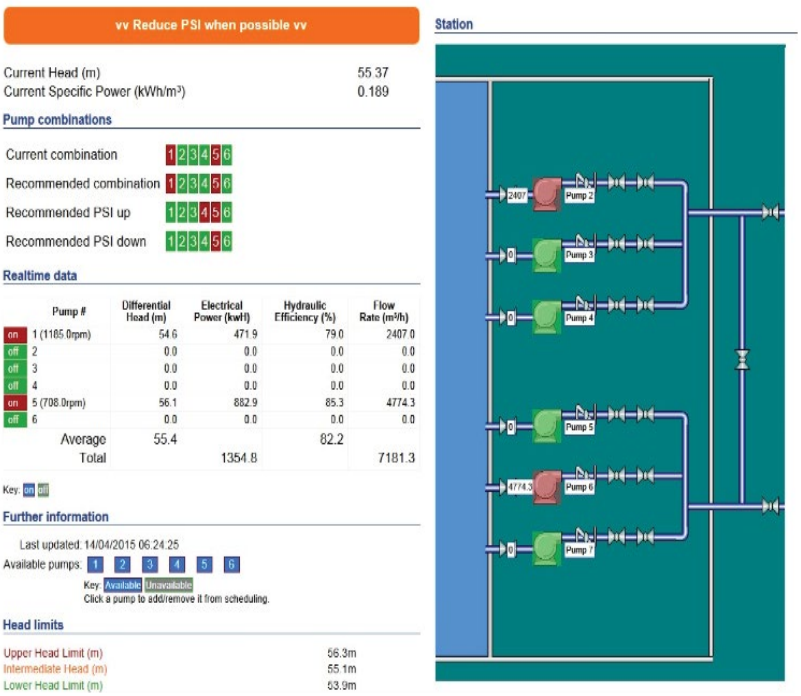

Fig. 5. HMI customized for user practical usage at the pump station.

Table 2
Measurement and calculation requirements for the standard ISO5198

Parameters	Measured	Calculated
Suction and discharge pressure (Pa)	X	
Suction and discharge temperature (°C)	X	
Electrical input power (kW)	X	
Mass flow rate (kg/s)		X
Volume flow rate (m³/h)		X
Drive efficiency (%)		X
Pump head (m)		X
Pump efficiency (%)	X	

of all the others, of which the pump efficiency provides the greatest bearing.

The shaft power (P_s) applied to the pump was computed by electrical input power to the motor (measured by a three-phase power analyzer connected to DAU (FREEFLOW™ DAU, Riventa) and then deducing an estimate for the drive and motor efficiency, η_m, from the original equipment manufacturer (OEM) datasheet, and applying Eq. (2)

$$P_s = P_e \cdot \eta_m H \tag{2}$$

The pump efficiency is measured directly using thermodynamic measurements of temperature and pressure immediately upstream and downstream of the pump, using Eq. (3).

$$\eta_p = \frac{1}{1+\dfrac{Cp\cdot\Delta T}{g\cdot\Delta H}} \quad (3)$$

where Cp is the specific heat capacity (J/kg K) of the working fluid and ΔT is the temperature rise across the pump (°K).

All pressure transducers used are calibrated to the transfer standards outlined in ISO17025. The static pressures were measured by digital transducers, each connected to the pipework either side of the pump. The internal diameters of the suction and discharge pipework, d_1 and d_2, respectively, were measured to provide the necessary inputs for the calculation of the dynamic head.

Total differential head, ΔH, is thus calculated in accordance with the method outlined in ISO 9906:2012 substantially summarized by Eq. (4).

$$\Delta H = \text{Potential Head} + \text{Hydrostatic Head} + \text{Velocity Head}$$

$$\Rightarrow \Delta H = \left[Z_2 - Z_1\right] + \left[\frac{p_2 - p_1}{\bar{\rho}\cdot g}\right] + \left[\frac{U_2^2 - U_1^2}{2\cdot g}\right] \quad (4)$$

where the density, ρ, is accurately known for all pressures and temperatures, and the velocity head term is calculated iteratively using the flow rate and the inlet and outlet pipework diameters (d_1 and d_2) as Eq. (5). Total differential head, ΔH, is thus calculated in accordance with the method outlined in ISO 9906:2012 substantially summarized by Eq. (4). The first term of Eq. (4) is the potential head term and is equivalent to the difference in height between the pressure transducers.

$$\text{If}, U = \frac{4\cdot Q}{\pi\cdot d^2} \Rightarrow \text{Velocity Head} = \frac{16\cdot Q^2}{\pi\cdot 2\cdot g}\left[\frac{1}{d_2^4} - \frac{1}{d_1^4}\right] \quad (5)$$

3. Results and discussion

3.1. Analysis of existing pump operation data

Fig. 6 shows the possible pump combination scenarios that meet the water supply trend for 24 h at the test pump station. Purified water at the water supply pump station was transported to the highland reservoir by combining six pumps which consisted of four main pumps (number 2, 3, 4, 5) and two auxiliary pumps (number 1, 6). The green-colored combination scenarios were mainly used at the testbed. A total of 52 pump combinations were available based on the capabilities of the six pumps, but 21 of them were selected to supply the required flow rate at the field. Besides, the combination of two pumps and three pumps accounted for nearly 80% to meet the reservoir level. The five or six combinations were used to sequentially turn on and off the pumps in pump alternating steps. It was impossible to analyze the characteristics of the pump combination condition that occurred when operating and recording the pump by manual. However, if the operating data of the minute unit is recorded in a computer by real-time sensor, analysis, and diagnosis of pump performance will be possible. As a result, the real-time operation data can be used for real-time optimization program to recommend reasonable pump scheduling to the operator.

Fig. 7 shows the pattern of annual water supply flow rate according to the existing pump combination conditions. The combination condition with more than four pumps was used to supply the high flow rate during summer (from July

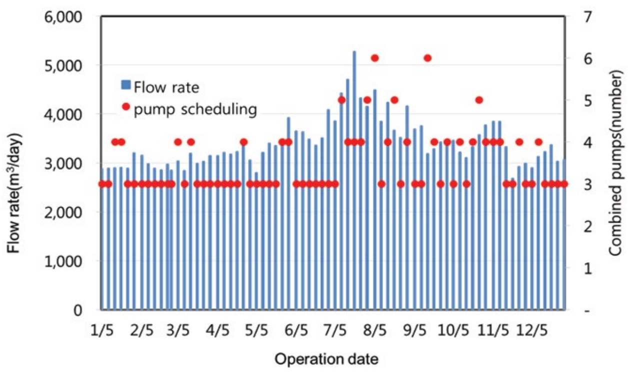

Fig. 7. Pattern of annual flow rate according to pump combination conditions.

1. Scenario to combine two pumps

1	1	1	1	1	2	2	2	2	3	3	3	4	4	5
2	3	4	5	6	3	4	5	6	4	5	6	5	6	6

2. Scenario to combine three pumps

1	1	1	1	1	1	1	1	1	2	2	2	2	2	3	3	3	4
2	2	2	2	3	3	3	4	4	3	3	3	4	4	4	4	5	5
3	4	5	6	4	5	6	5	6	4	5	6	5	6	5	6	6	6

3. Scenario to combine four pumps

1	1	1	1	1	1	1	1	1	2	2	3
2	2	2	2	2	3	3	3	4	3	3	4
3	3	3	4	4	4	4	5	5	4	4	5
4	5	6	5	6	5	6	6	6	5	6	6

4. Scenario to combine five and six pumps

1	1	1	1	1	2
2	2	2	2	3	3
3	3	3	4	4	4
4	4	5	5	5	5
5	6	6	6	6	6

5. Scenario to combine six pumps

1	2	3	4	5	6

Fig. 6. Analysis of possible pump combination scenarios.

to August). It was confirmed that four and five pump combination conditions were used to increase the water flow, but it was impossible to characterize the flow rate in the alternating pump stage.

The pump station delivered the final water to the reservoir from 5,671 to 10,576 m^3/h and the head was measured from 40 to 60 m at this period (Fig. 8). The analysis of pump operation efficiency applying using the hydraulic pump diagnosis system is shown in Fig. 9. The difference in pump efficiency was from a maximum of 83% to a minimum of 57% at the same flow rate. The average pump efficiency was 78% which was less than 80% of the OEM datasheet. Therefore, the optimum combination of the pump should be suggested based on the individual pump flow rate and pump efficiency to correspond to the required flow rate or the water level of the reservoir.

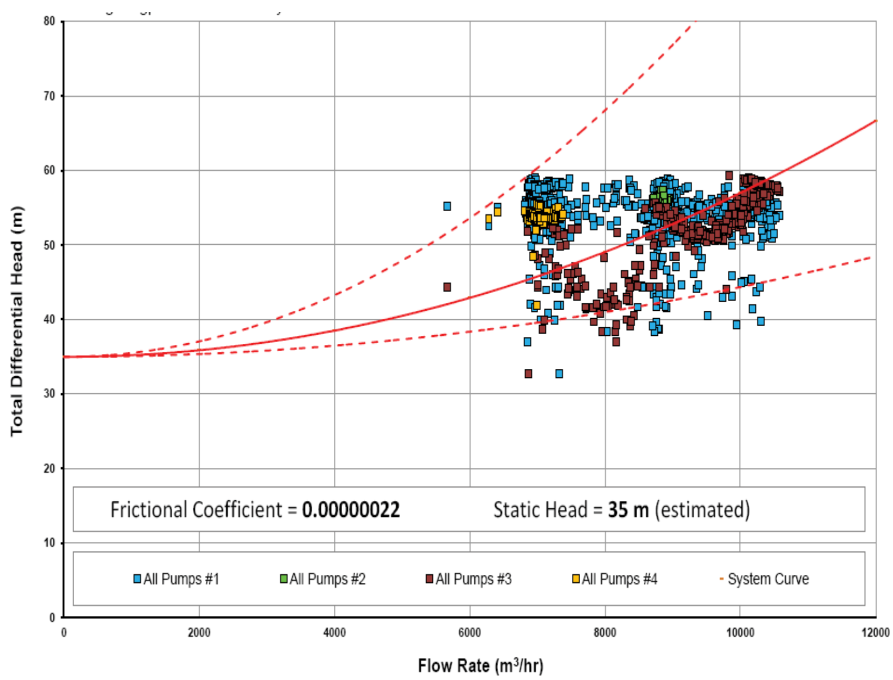

Fig. 8. Analysis of differential head according to flow rate.

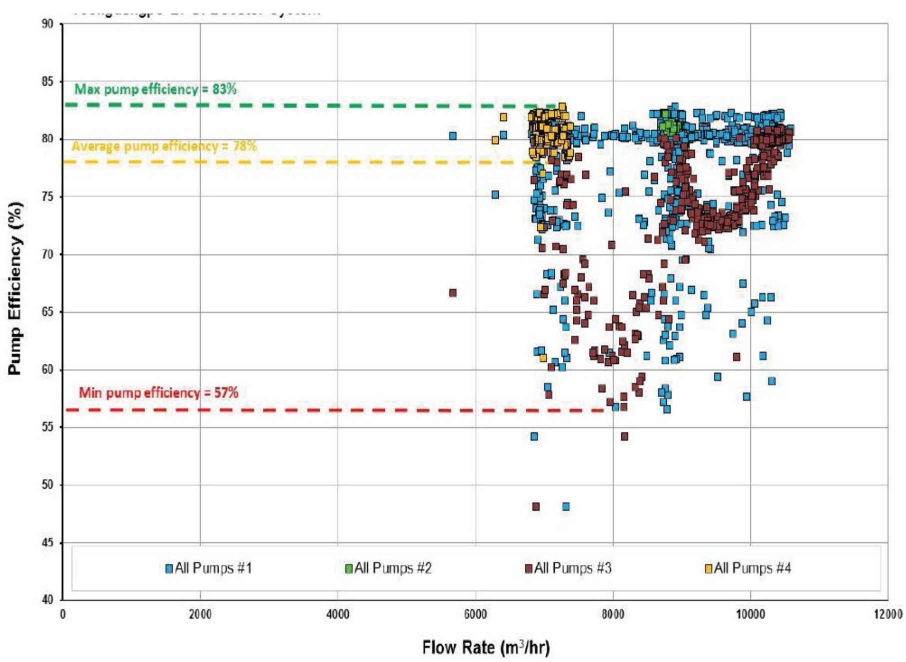

Fig. 9. Analysis of pump efficiency according to flow rate.

3.2. Analysis of fluid temperature

Fig. 10 shows the result of real-time monitoring of the fluid temperature of # 2 pump when pumps of unit #2, #4 and #6 were operating in the winter season. As shown in Fig. 9, the real-time temperature difference could be calculated and the average temperature difference between suction and discharge was 0.03°C which would be continuously used to calculate the efficiency of individual pump as described in Eq. (3).

The temperature difference of fluid across the pump was analyzed for various flow conditions according to the pump combination. The correlation between fluid temperature and pump efficiency was also analyzed as shown in Fig. 11. The temperature difference and pump efficiency were inversely related. When the temperature difference was more than 0.05°C, the pump efficiency decreased to 70%. Therefore, to maintain the efficiency of the individual pump more than 80%, the temperature rise of fluid across the pump should be less than 0.03°C. Therefore, it was possible to diagnose the real-time state of the pump by measuring the fluid temperature.

3.3. Calculation of flow rate

Each flow rate and total were calculated by the thermodynamic method under the combination conditions of units

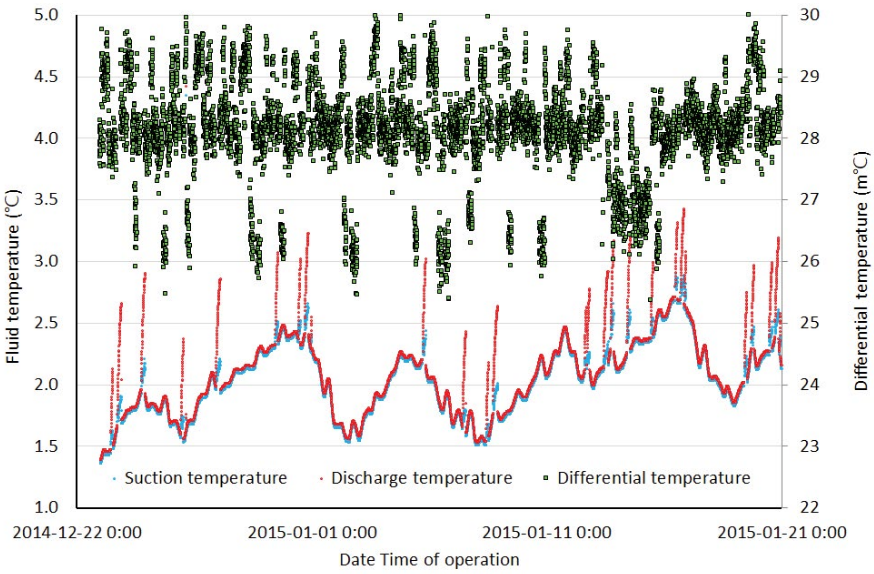

Fig. 10. Analysis of fluid temperature at the suction and discharge of a pump.

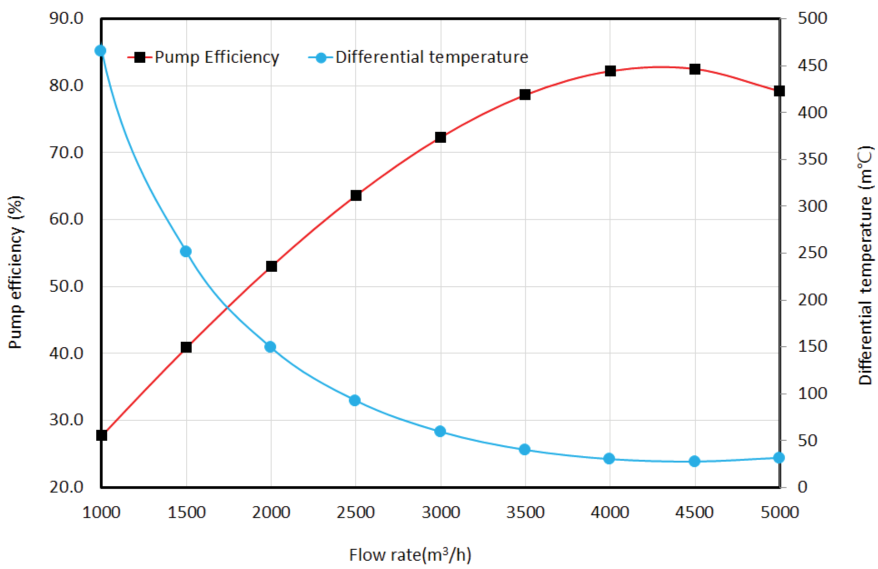

Fig. 11. Relationship between differential fluid temperature and pump efficiency.

1, 4, and 5 of pumps. Fig. 12 compare the results calculated by the electromagnetic measurement and the thermodynamic method for the total water flow. The error was within 0.1% for stable pump combinations except for the transition stage, which changed the pump combination conditions.

3.4. Analysis of pump system curve

The system curve was the combined representation of the fluid, pipework resistance and the difference in elevation between source fluid level and destination fluid level. In this study, the differential head was analyzed by the volumetric flow rate in the pump system curve (Fig. 13). The existing operating methods were similar in pattern of system curves with the methods based on thermodynamic analysis. However, in the same flow range, the differential head distribution of the existing pump scheduling was somewhat wider, and it was considered that the optimum pump scheduling could narrow the head distribution and reduce power consumption. The sporadic data off the maximum and minimum system curves was resulted from a shift stage in pump combination conditions and had a minor effect on pump scheduling. The change of pump combination was carried out 4–9 times a day to achieve the flow rate. The time for the operation pump shift was short, so there was no significant effect on pump scheduling. Any change levels or network configuration would change the system curve. Variation in tank levels also would the static head of the system,

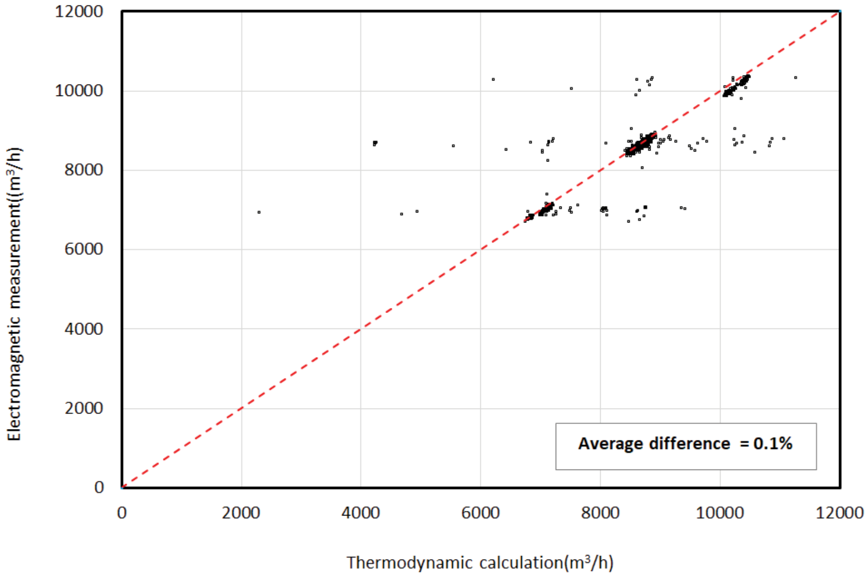

Fig. 12. Comparison of thermodynamic calculation and flowmeter measurement.

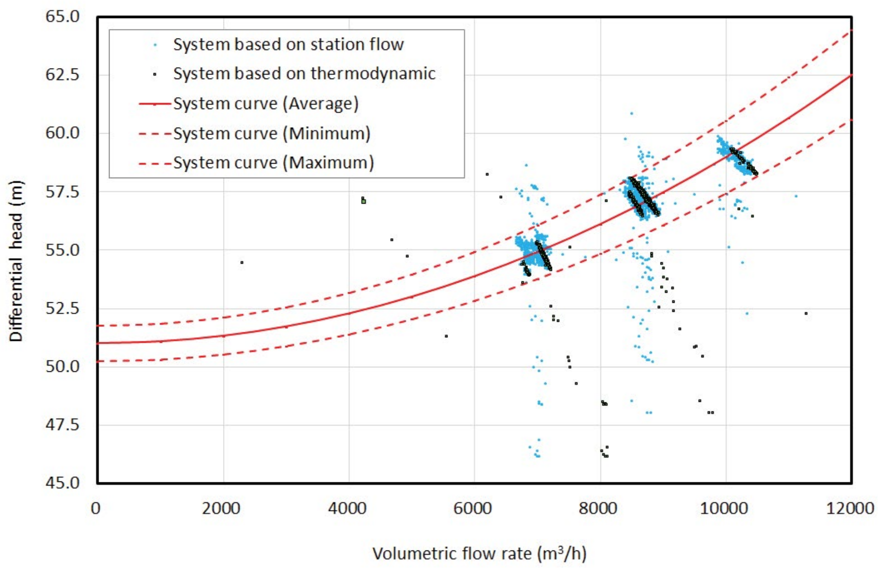

Fig. 13. Plot of system curve between station flow and thermodynamic flow.

particularly the suction tank as often the discharge tank was top-fed. These considerations in the next research should be studied for analysis of the system curve.

3.5. Analysis of energy efficiency

The specific power was analyzed according to the volumetric flow rate. As shown in Fig. 14, three groupings of flow rate were mainly caused by pump scheduling, and the specific power ranged from 0.185 to 0.205 kWh/m^3. The grouping patterns were divided into the pump schedules consisting of one main pump and one auxiliary pump, the pump schedule consisting of two main pumps, and the pump schedule of two main pumps and one auxiliary pump. Since the specific power was vertically distributed in each flow group, it was found that the specific power deviation was high at the same flow rate. Therefore, the optimum pump scheduling was required to reduce more energy consumption using high pump efficiency.

The hydraulic pump efficiency was analyzed according to the flow conditions (Fig. 15). It was found that the pump efficiency was different according to the pump operating conditions in the same flow rate, and the pump efficiency increased with increasing the flow rate.

The optimized pump scheduling was tested for 4 months. During this test, the operators followed the recommendations of pump combination. Fig. 16 shows specific power reduction up to 4.1% after applying the optimized pump scheduling using real-time data of flow and efficiency of the individual pump based on the hybrid hydraulic and thermodynamic simulation. This was equivalent to savings of about 54,000 US$, calculated as an annual power cost. The

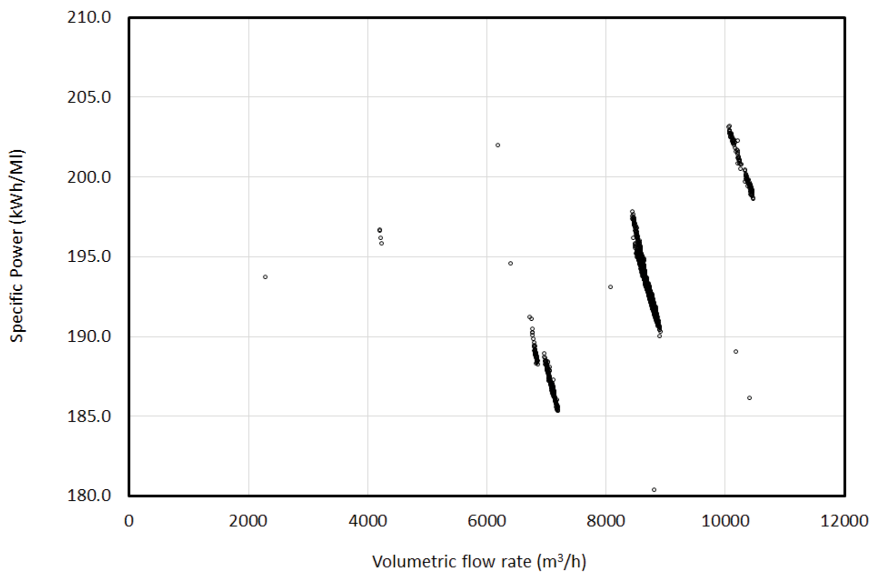

Fig. 14. Analysis of specific power based on the volumetric flow rate.

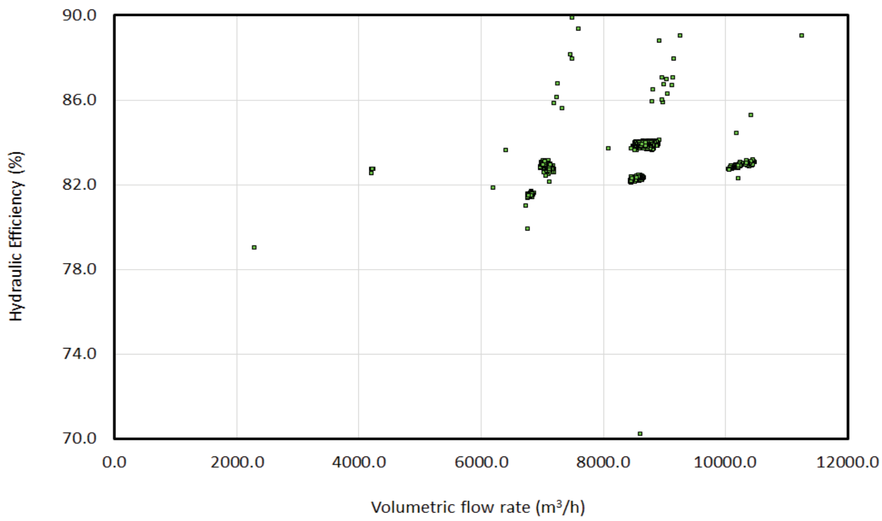

Fig. 15. Analysis of hydraulic pump efficiency based on the volumetric flow rate.

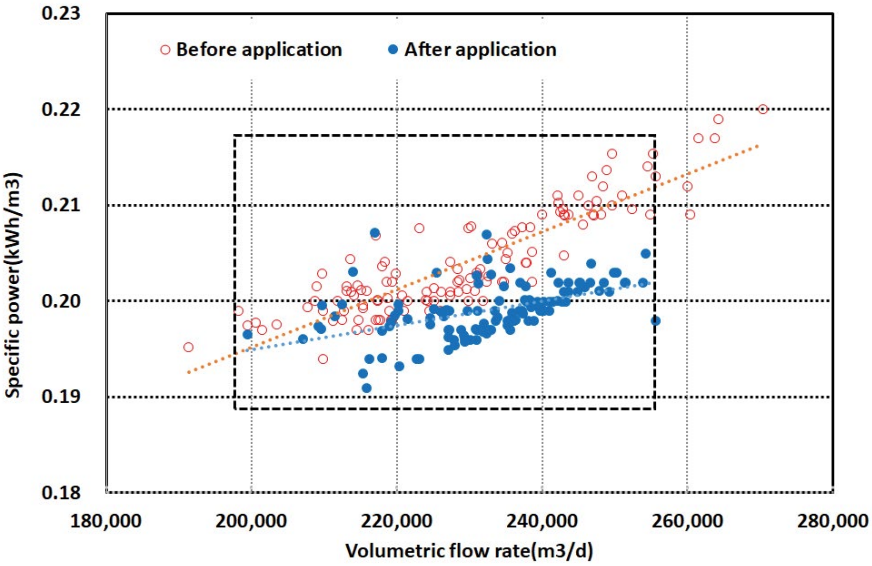

Fig. 16. Comparison of unit specific power after optimizing pump schedule.

thermodynamic calculation method could reduce the measurement error of less than 1% because of the consideration of energy loss of water temperature at the inlet and outlet of the motor. In general, the flow rate and efficiency of entire pumps could be measured on-site during operation, however, those of each pump was available to the operator during scheduling. Therefore, scheduling of the pumps assigned to each shift results in pump operation outside of the best efficiency point of the pump system curve.

4. Conclusions

In this study, scheduling six pumps of fixed-speed were optimized using the sensors of water temperature, pressure, and electricity in real-time and the hybrid hydraulic and thermodynamic method. The temperature rise of fluid across the pump should be less than 0.03°C to maintain the efficiency of the individual pump more than 80%. The hybrid algorism using the real-time delta fluid temperature could produce the individual pump flow rate and pump efficiency even without individual flow meter. The error of flow rate between the electromagnetic measurement and the thermodynamic method was within 0.1% for stable pump combinations except for the transition stage of pump combination. The specific power could be reduced by 4.1% after applying this technology to the water pump station for 4 months, resulting in savings of 54,000 US$ of annual power cost.

Acknowledgment

This subject is supported by the Korea Ministry of Environment as "The Eco-Innovation Project (Global Top Project)".

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