

A study on the individual pump flow estimation processor for optimal operation

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Abstract. The booster pump is an energy-saving system that controls the number of turns of the pump and optimal operation by installing an inverter to control the discharge pressure of the pump in accordance with the flow rate. The development of an optimum operation algorithm and flow rate information for the individual pumps without flow sensors is critical of a smart booster pump system. The objectives of this study was to investigate the algorithm based flow detection method without use of a flow sensor for each pump. Therefore, it was developed an algorithm-based flow rate detection method of individual pumps without the use of a flow sensor that has not been studied in the conventional booster pump system. The software-based processor development and experimental verification for detecting the flow rate of individual pumps were confirmed. The ensemble error was within 2%. For optimal operation, the result of examining the accumulated flow rate for the sequential operation method and the optimum operation method. The flow measurement accuracy of the system was confirmed by experiment and the development of a booster pump system without a flow sensor was found effective.

1 Introduction

In large-scale apartments and commercial buildings, rapid response to flow rate changes is required. In most systems, multiple pumps are connected in parallel to deliver the required flow rate, and pressure and flow rate are measured as overall values for the booster pump. An inverter can be installed to drive the booster pump system (BPS) and control the rotation speed of the individual pumps. Currently, flow detection and energy savings method are the hot topic for BPSs [1]; however, few studies have investigated only on energy savings in BPSs both experimentally and numerically [2-6]. Rakibuzzaman *et al.* (2015, 2017) recently investigated on energy saving rates for a multistage, centrifugal pump with variable speed drive through numerically and experimentally [7], [8]. In order to improve the reliability of the booster pump, the optimum operation algorithm and flow rate information for the individual pumps of the booster pump system is required. The general booster pump system is controlled by using an integrated inverter and controller. By knowing the flow rate of each

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pump allows us to understand the operating conditions of individual pumps, which can be used to detect and maintain pump abnormalities. In the booster pump, if the master pump fails, other individual pumps automatically perform the function of the master pump. So, continuous water supply is possible and the durability of the pump can be improved. For the booster pumps, a pressure gauge is installed on the suction side and the discharge side of the pump system, so the head can be predicted, but it is not possible to measure the flow rate of each pump since only one flow meter is installed at the rear of the exit area. The device for measuring the flow rate by the hardware method is not only expensive but also there is a problem of the flowmeter error, and there is a concern of failure due to the substance. Recently, flow measurement accuracy has been studied and the accuracy of flow measurement in flow sensors has been discussed [9]. This paper focuses on the technology without the use of the flow sensor.

The objectives of this study are to the development of flow detection method without the use of a flow sensor that has never been studied in conventional booster pump systems and the development of a flow calculation processor for individual pumps in a booster pump system. Also, the optimum operation using flow rates readings was studied. In this study, the flow measurement accuracy of a developed flow control algorithm was evaluated.

2 Methodology

2.1 Booster pump system

Booster pump is a package system that combines a series of devices such as centrifugal pump, pressure tank, inverter, motor, pressure transmitter, suction/discharge conduit, control panel, base, etc. Booster pump operates by combining two or more centrifugal pumps in parallel. Figure 1 represents the booster pump system.

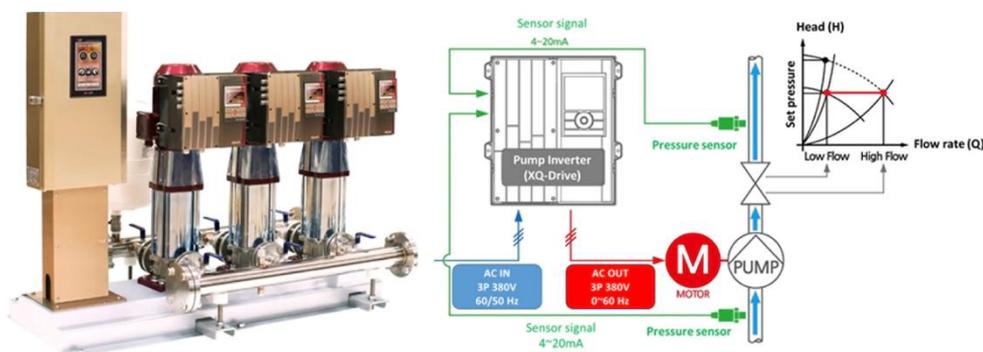


Fig. 1. Booster pump (IOP-3XRL15-3S) and its block diagram.

2.2 Flow measurement method of individual pump

For the booster pumps, a pressure gauge is installed on the suction and discharge side of each pump, so the head can be measured, but it is not possible to measure the flow rate of each pump since only one pump is installed at the rear of the exit pipe. For booster pumps that perform the optimum operation by controlling the inverter pressure (rotation speed change), flow rate information of each pump is required. There are two types of flow measurement methods; (1) hardware-based flow measurement and (2) software-based flow measurement method. In the hardware-based flow measurement method, a flow sensor is used to measure

flow rates. The methodology for measuring the flow rate through this flow sensor was as follows: the turbine flow meter rotates as fluid flows through the check valve [10]. The flow rate sensor consists of a part of a hall sensor that detects movement of a rotating rotor, a part of a rotor, and an output part that processes and outputs electromotive force values generated by a hall sensor. The hall sensor part detects a change in current caused by magnetic fields inserted into the rotor when the rotating body rotates, the hall sensor represents the magnetic field as an electromotive force through the hall effect. Fig. 2 shows the check valve with a flow sensor. In the software-based flow control method, an algorithm was developed to estimate the flow rate by calculating the rotational speed and shaft power of the motor at the inverter and measuring the total head at the pump, and applying it to the flow rate-power curve and the flow rate-head curve of the pump.

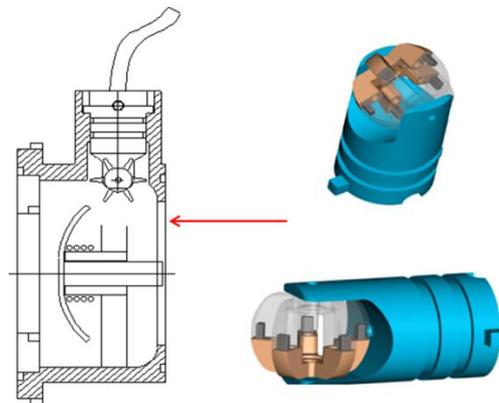


Fig. 2. Check valve with flow sensor in Booster pump system.

2.3 Flow calculation processor for individual pumps

The motor speed (n_{est}) of an individual pump [11] is calculated using the Eq. 1:

$$n_{est} = n_{ref} - n_{slip} \tag{1}$$

$$n_{slip} = n_{slip_rated} \left(\frac{I_{out} - I_{no_load}}{I_{rated} - I_{no_load}} \right)$$

$$I_{out} = \sqrt{i_{ds}^2 - i_{qs}^2}$$

where n_{ref} is the inverter output speed, n_{slip} is the motor slip speed, n_{slip_rated} is the motor rated slip speed, I_{out} is the motor output current, I_{rated} is the rated current, and I_{no_load} is the no-load current. The estimation shaft output power of each pump is calculated using the Eq. 2:

$$P_{est} = T_{est} \bullet n_{est} \tag{2}$$

$$T_{est} = \frac{3}{2} \frac{P}{L_r} \frac{L_m^2}{2} i_{ds} i_{qs}$$

where T_{est} is the motor torque, L_m is the motor mutual induction, L_r is the motor rotor inductance. And the flow estimator provided in the inverter is calculated the total head of the

pump from the measured pressure, flow velocity, and height at the suction and discharge measuring sections as [12]

$$H_{total} = \frac{P_{real} - P_{in}}{\gamma} + \frac{V_{real}^2 - V_{in}^2}{2g} + (E_{real} - E_{in}) \quad (3)$$

where γ is the fluid specific weight, P_{real} and P_{in} are the pressure at discharge and suction of the pump, V_{real} and V_{in} are the average flow velocity at discharge and suction pressure sensor position, E_{real} and E_{in} are the discharge and suction pressure sensor height.

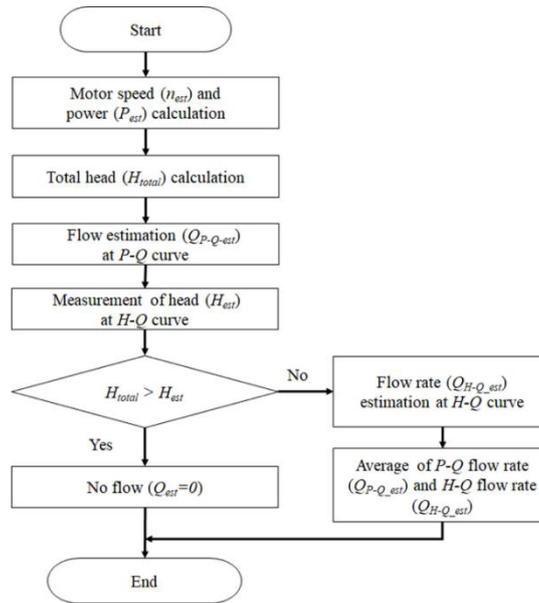


Fig. 3. Algorithm for calculating the flow rate of each individual pump.

Then an algorithm was developed for estimation of the flow rate. The algorithm configuration of the processor is shown in Fig. 3. In this system, firstly, find out the rotation speed and shaft power of the motor by the dedicated inverter and measure the total head in the pump. Then, the flow rate and the head are estimated using the P - Q curve and the H - Q curve. If the estimated head is smaller than the total head, there is no flow rate. If the estimated head is larger than the total head, calculate the flow rate using the H - Q curve. Then calculate the average discharge flow rate from the P - Q curve as shown in Fig. 4.

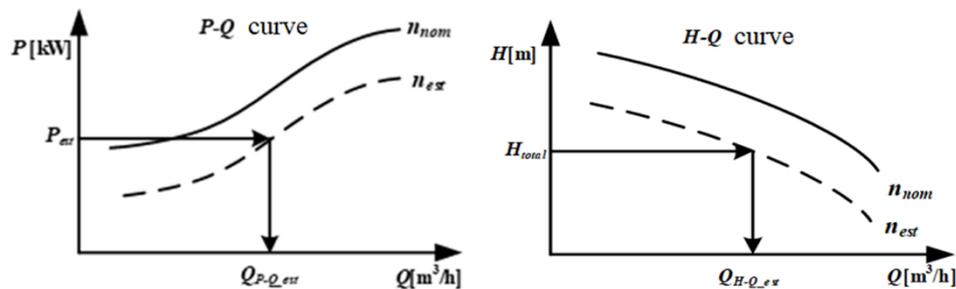


Fig. 4. Flow rate and head estimation method using P - Q curve and H - Q curve.

This technology is commercialized by improving the algorithm for optimal operation control method using flow rate calculation of individual inverter booster pump system. It detects individual flow rates and calculates the accumulated flow rate for each pump and controls the operating priority, number of operations, and rotation speed of the pump based on this. The optimal operation algorithm starts in the order of $P_A \rightarrow P_B \rightarrow P_C$ and then controls the pump with the least accumulated flow to start first (e.g. $P_B \rightarrow P_C \rightarrow P_A$). When the number of pumps increases, the pump with the lowest accumulated flow rate of each pump is operated first. When the number of pumps decreases, the pump with the highest accumulated flow is stopped. In this case, it is necessary to have an optimal operation technology that switches the pump with the most accumulated power and the pump with the least. This technology can reduce power consumption by controlling the number of rotations, and can significantly improve the reliability of the booster pump. Figure 5 illustrates the optimal operation algorithm for each pump.

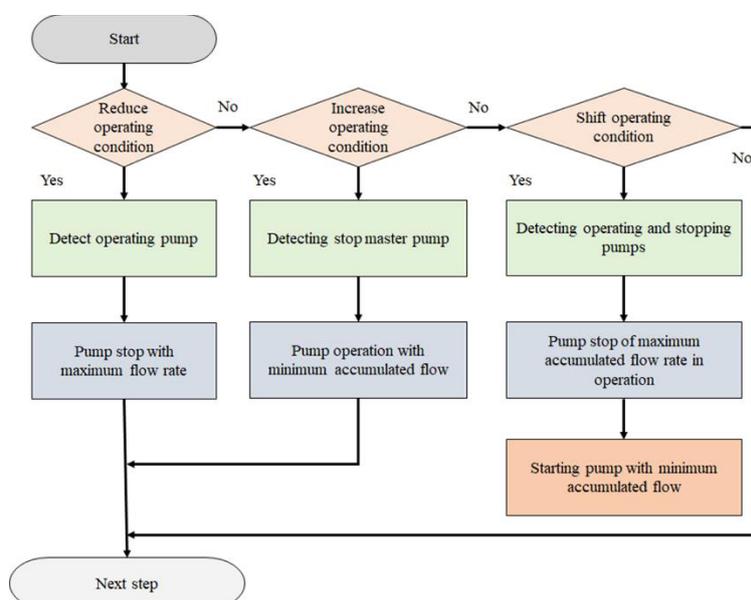
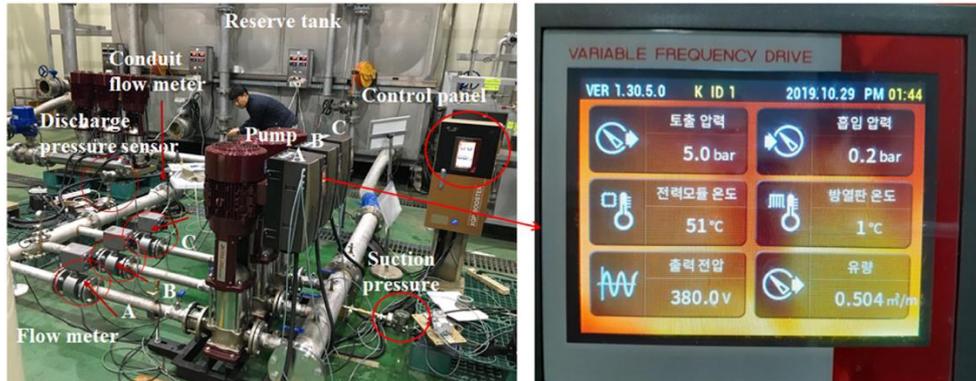


Fig. 5. Optimal operation algorithm.

2.4 Experimental method

The test facility was constructed according to KSB-6302 and ISO-5198 [13]. Flow measurement was performed at the Dooch test site as shown in Fig. 6. Three centrifugal pumps were installed with a reserve tank of 35 m³, and a pressure gauge and electromagnetic flowmeter were installed downstream of individual pumps. The pressure gauge ranges from 0 to 30 bar. The pressure tank operating range was 1.4-10 bar. The inlet pipe diameter was 125 mm and the outlet pipe diameter was 100 mm. Also, for measuring the estimated pump performance of the individual pumps, three digital VFD monitors were installed. This system was connected to a computer (PC) to obtain pressure, flow rate, and frequency without flow sensor readings. Experimental flow was measured with an electronic flow meter. Electronic flow meters were installed at the outlet of each pump and behind the outlet conduit. The total flow is measured by the electronic flow meter of the booster pump system. The test of the pump was, in principle, with clean water at a temperature (0 to 40)° C. However, the density at this time should be calculated. The standard density of water was 1000 kg/m³. The test

rotation speed was, in principle, AS-RUN speed. Here, the rotational speed generally means a speed converted into an inverter frequency. Set the required pressure to the inverter. The pressure sensor senses the pressure change in the pipe and sends it to the drive. The drive uses the set pressure and sense pressure to rotate the motor at the proper speed and control the discharge pressure of the pump.



(a) Experimental devices of booster pump

(b) Display panel of VFD

Fig. 6. Experimental facilities of the booster pump.

3 Results and discussion

3.1 Performance characteristics of booster pump system

In the experiment, three centrifugal pumps were installed and operated at the designed layout as pump A, B, and C. To measure the performance of the individual pump, the suction pressure was set to 20 kPa during one operation and the discharge flow rate was measured by changing the discharge pressure from 800 to 200 kPa with 100 kPa interval. Figure 7 shows the performance characteristics and % of error of pump A. It is seen from the figure that the error rate between reference and estimation value of pump A was within 1%. It was also confirmed that the error of the pump B and C lies within 3%.

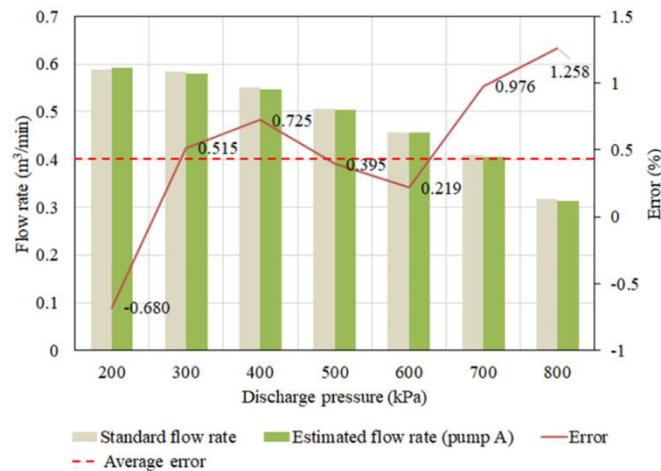


Fig. 7. Difference between estimated flow rate and actual flow rate of pump A.

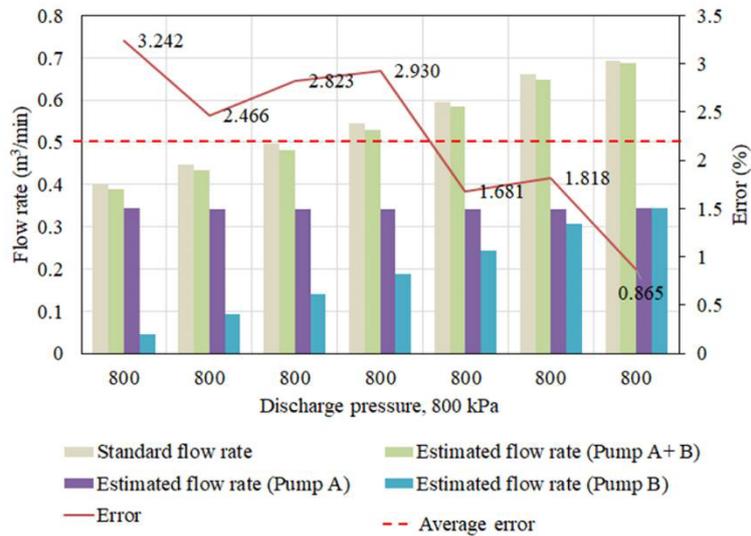


Fig. 8. Difference between estimated flow rate and actual flow rate during operation of two pumps.

For parallel operation in two pumps, the suction pressure was 20 kPa and the discharge flow rate was measured at the discharge pressure of 800 kPa. Figure 8 illustrates the performance and error of two pumps in parallel. In this figure, it is observed that the error of the two pumps was within 1~3%. For parallel operations in three pumps, the flow rate was measured at the discharge set pressure of 600 kPa. Figure 9 shows the performance comparison of reference and estimation of the three pumps in operations, and % of errors of three pumps. It is seen from the figure that the error rate of three pumps was less than 2%. Table 1 shows the % of error of three pumps in parallel. Based on the experimental results, it was judged that using an algorithm-based flow detection method, the flow rate could be estimated without the use of a flow sensor.

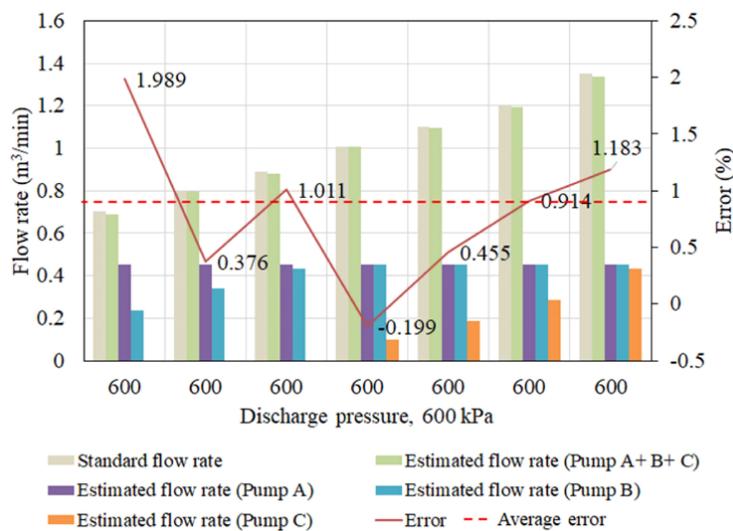


Fig. 9. Measurement, estimated flow rate and error of three pumps.

Table 1. Pump experiment and estimation error of flow rate.

Test items		Test results (m ³ /hr)	Error (%)	Remarks
Suction pressure: 20 kPa Discharge pressure: 600 kPa	Measured flow rate	0.704	1.989	Pump A: on Pump B: on Pump C: on
	Estimated flow rate (Pump A)	0.454		
	Estimated flow rate (Pump B)	0.236		
	Estimated flow rate (Pump C)	0.000		
	Estimated flow rate	0.690		
Suction pressure: 20 kPa Discharge pressure: 600 kPa	Measured flow rate	1.100	0.455	
	Estimated flow rate (Pump A)	0.453		
	Estimated flow rate (Pump B)	0.453		
	Estimated flow rate (Pump C)	0.189		
	Estimated flow rate	1.095		
Suction pressure: 20 kPa Discharge pressure: 600 kPa	Measured flow rate	1.352	1.183	
	Estimated flow rate (Pump A)	0.453		
	Estimated flow rate (Pump B)	0.452		
	Estimated flow rate (Pump C)	0.431		
	Estimated flow rate	1.336		

3.2 Sequential and optimal operations method

In the booster pump system, the conventional sequential operation method focuses on the accumulation flow rate of a particular pump, as shown in Fig. 10, while the optimal operation method of the booster pump was distributed evenly among individual pumps. For the flow pattern shown in Fig. 11, when the conventional sequential operation method and optimal operation method using the individual flow rate were operated, the excellence of the optimum equalization technology was verified by comparing the operation amount (accumulated flow rate) of the pump. The deviation of the experiment was calculated for each pump. Table 2 shows the comparison of flow rate between sequential and optimal operation methods. In this case, the suction pressure was set to 38 kPa and discharge pressure was set to 700 kPa. From this table, it is observed that the average deviation for the conventional operational control method was higher than the developed operational control method of individual pumps.

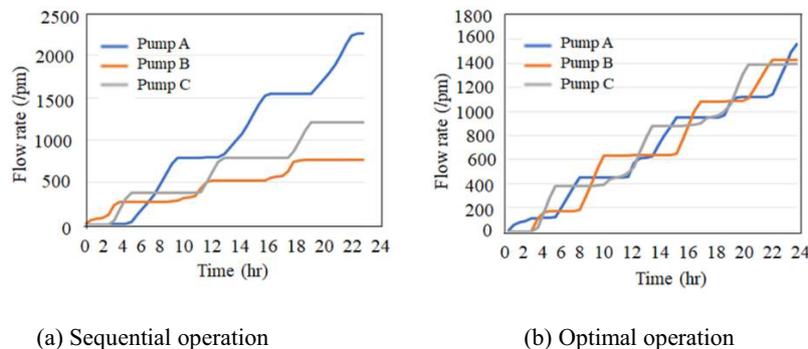


Fig. 10. Comparison of accumulated flow rate by pump between sequential operation method and application technology operation method.

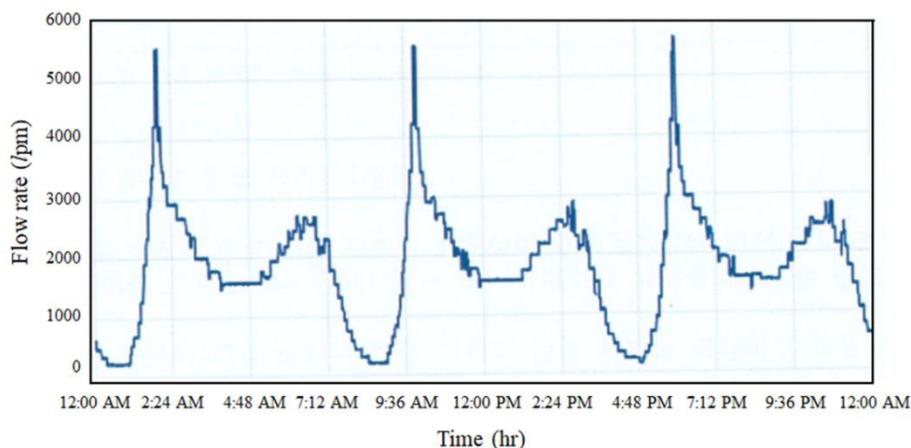


Fig. 11. Flow rate pattern for 24 hours (based on residential apartments).

Table 2. Standard deviation of individual pump.

Test items		Experimental results	
		Accumulated flow rate (m ³ /day)	Deviation (%)
Sequential operation method Suction pressure: 38 kPa Discharge pressure: 700 kPa Driving time: 24 hr	Pump A	226	59.9
	Pump B	76	-46.2
	Pump C	122	-13.7
	Subtotal	424	-
Optimal operation method Suction pressure: 38 kPa Discharge pressure: 700 kPa Driving time: 24 hr	Pump A	148	4.7
	Pump B	139	-1.7
	Pump C	136	-3.8
	Subtotal	424	-

* Deviation=[Accumulated flow rate per pump – (subtotal ÷3)]÷(subtotal ÷3)x100

4 Conclusion

The main goal of this study was to investigate the development of a software-based processor and experimental verification for detecting the flow rate of an individual pump in booster pump systems. In this study, integrated various functions without a flow sensor were developed and investigated in a smart booster pump system. The algorithm-based flow measurement method was developed to estimate the flow rate of each pump in the booster

pump system. To verify the validity of the individual pump flow calculation processor, the average ensemble error was within 2% and the results for the experiment have been verified the accuracy of the development process. As a result of examining the accumulated flow rate for the sequential operation method and the optimum operation method, the accumulated flow rate of the specific pump was focused on the sequential operation method, whereas the optimal flow method distributes the accumulated flow evenly. By using the flow rate pattern, the deviation of each pump for the optimal operation was less than $\pm 5\%$. Therefore, the algorithm-based flow estimation method was applied in a booster pump system and could be scaled in the industry.

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