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Energy recovery through a water-hydraulic motor in a small-scale RO desalination system

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ABSTRACT

The use of energy recovery devices (ERDs) is now well known in seawater desalination. These devices are classified into two kinds of ERDs — one is the centrifugal turbine type and the other is the positive displacement type. However, because these ERDs are appropriate for large-scale reverse osmosis (RO) systems, a different type of ERD suitable for small-scale RO systems is required. For energy recovery in small desalination plants, hydraulic pump-hydraulic motor assembly is preferred due to the benefits including high efficiency, low pulsation, and no maintenance. For this reason, we are developing an integrated pump combined with energy recovery function. That is, the pump and motor pistons are contained in one cylinder barrel so that this integration can provide compact design. In this work, we present the experimental results of the small reverse osmosis system equipped with a water-hydraulic motor of axial piston type based on the swashplate principle for feasibility test about the mechanism of ERD-integrated pump under development. This motor converts hydraulic energy (brine pressure) to mechanical energy (torque) and reduces the energy used by the electric motor driving the axial piston pump. By using the water-hydraulic motor, the energy consumed by pump was recovered by approximately 60%. In addition, the power consumption of the pump and the power production of the motor were compared at the different motor speeds and feed temperatures. As a consequence, it is expected that the ERD-integrated pump based on the mechanism of the hydraulic pump-motor assembly will be a suitable alternative to ERD in a small-sized RO desalination system in the future.

Keywords: Energy recovery; Reverse osmosis; Desalination; Axial piston pump; Water hydraulic motor

1. Introduction

SWRO desalination is an energy intensive process because of the low water recovery ratio (30–40%) and the high operating pressure (60–80 bar). In reverse osmosis (RO) systems without an energy recovery device, more than half of the energy in the high pressure feedwater to the membranes is ultimately wasted. The energy consumed by high-pressure pumps accounts for up to 70% of energy consumption in an RO membrane system.

Recently, the efforts to create improvements in membranes, energy recovery devices (ERDs), and high pressure pumps (HPPs) have been made in the related industry. As a result of the new developments, there were surprising achievements in efficiency. However, these advanced technologies are focused on large-scale

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plants. Specifically, the ERDs such as centrifugal type and positive displacement type have been designed only for large-scale RO desalination plants. There have been no practical ERDs suitable for small-scale systems of less than approximately 100 m^3/d. Centrifugal type devices capture pressure energy of brine with a turbine and transfer it to a shaft of the main high pressure pump. Francis turbines, Pelton wheels, and turbochargers are examples of centrifugal ERDs [1,2]. Positive displacement type devices transfer the energy from the brine stream directly to the feed stream (seawater) in constant pressure chambers. Dual work exchanger energy recovery (DWEER) [3,4] and pressure exchanger (PX) [5,6] are examples of positive displacement type ERDs. These kinds of ERDs are also neglected in small-scale plants due to the comparatively high capital cost of ERDs for the small scale. Owing to these reasons, the devices such as hydraulic pump-motor assembly [7,8] and Clark pump [9,10] have been introduced for the small scale. Especially, compared with the unique fluid-driven system like Clark pump, hydraulic pump-motor assembly is preferred in terms of simplicity, cost, and maintenance. For energy recovery, axial piston type is mainly used in hydraulic pump-motor assembly due to characteristics of positive displacement. An axial piston pump used to pressurize the feedwater is connected to an axial piston motor driven by the brine rejected by an RO membrane. This reduces the energy consumed by the electric motor driving the hydraulic pump. That is, through the water-hydraulic motor of positive displacement type, the energy in the pressurized brine is converted into mechanical energy to be re-used by the electric motor, since the rotor shaft of the motor is directly (or indirectly) connected with the rotor shaft of the pump [7,8].

In this work, we present the experimental results of a small reverse osmosis system equipped with water-hydraulic pump-motor assembly of axial piston type based on the swashplate principle for feasibility test about the mechanism of the ERD-integrated pump under development. The swashplate is known to be a device used to translate the motion of a rotating shaft into reciprocating motion. It was demonstrated that the water hydraulic motor converts hydraulic energy (brine pressure) to mechanical energy (torque) and reduces the energy used by the electric motor driving the axial piston pump. By using a water-hydraulic motor, the energy consumed by the pump was recovered to a degree of 53–60% with motor speeds of 1200–1800 rpm and feed temperatures of 15–25°C. The water recovery was approximately 27–28%.

2. Experimental details

Fig. 1 represents the configuration of our RO system: (a) RO plant with a water hydraulic pump-motor assembly, (b) RO plant with a conventional high-pressure pump. A 10 m^3/d SWRO membrane setup having the pump-motor assembly attached with an inverter (called a variable frequency drive) was used to investigate the feasibility of energy recovery through the water-hydraulic motor. The water hydraulic pump (Danfoss, PAH 12.5) and water hydraulic motor (Danfoss, MAH 12.5) used for the assembly are based on the axial piston type and both

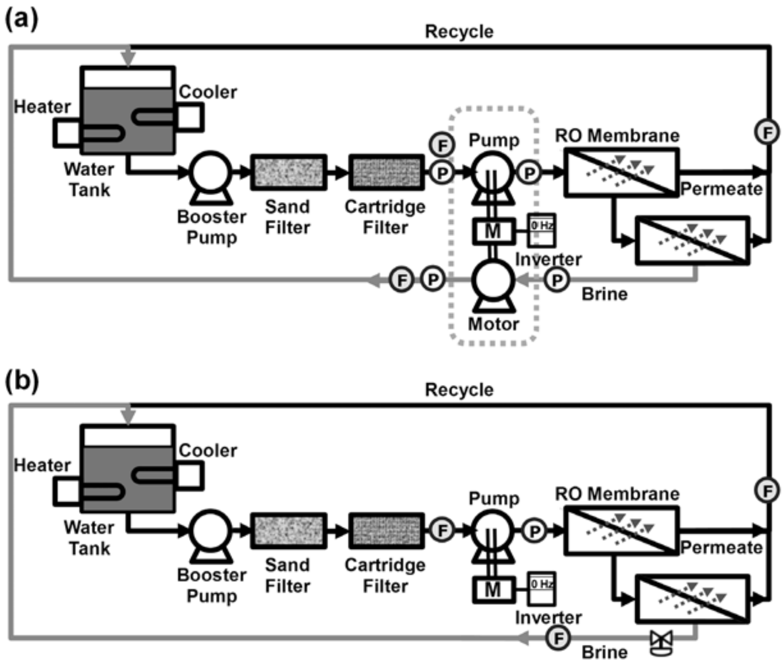

Fig. 1. Schematic diagrams of experimental setup. (a) RO system equipped with water hydraulic pump-motor assembly, (b) RO system equipped with a conventional high-pressure pump.

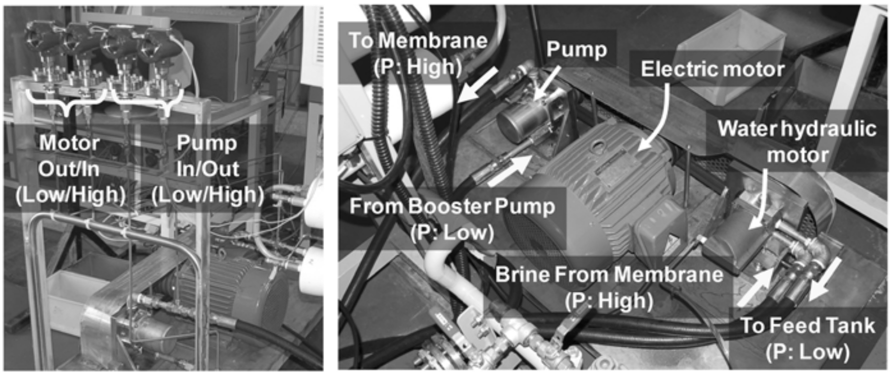

Fig. 2. Photographs of the water hydraulic pump-motor assembly.

of them have a geometric displacement of 12.5 cm^3/rev. As shown in Fig. 2, the water-hydraulic motor driven by the brine rejected by the RO membrane is coupled by a V-belt to the electric motor driving the swashplate type axial piston pump. Accordingly, the ratio between the volumetric displacement of the piston pump and piston motor determines the water recovery ratio of the RO system. In our system, water recovery ratio was adjusted by the ratio of pulley size. The pulleys of electric motor and water hydraulic pump were 114.3 mm in diameter, and the pulley of water hydraulic motor was 165.1 mm in diameter. The size ratio of the pulley of the pump to that of the water hydraulic motor was 0.69. Then, the system was supposed to be operated at approximately 31% recovery. For comparison, a conventional high-pressure pump of plunger type was also tested.

The membrane was composed of two elements (Hydranautics, SWC1-4040) connected in series. In small-scale plants, the operating pressure is normally adjusted using a valve on the brine. However, our RO system does not have a pressure control valve to provide the backpressure in the concentrate because the operating pressure is automatically fixed through the water hydraulic motor of axial piston type driven by brine. To be sure, the operating pressure can be controlled by the electric motor speed at the cost of the feed flowrate.

The water tank equipped with a heater and a cooler was used to feed salt water at constant temperature. And this study was carried out using salt water of 32,000 parts per million (ppm) NaCl. Data obtained from the plant included electric power consumed by electric motor, pump inlet/outlet pressure, motor inlet/outlet pressure, flow rate (feed, product and reject), total dissolved solids (TDS) (feed and permeate), and feed temperature. In addition, the actual speed of the electric motor was measured by a speed measuring device (i.e., tachometer). By controlling the frequency of the electrical power supplied to the motor through the variable-frequency drive, the rotational speed of an AC electric motor was controlled. The synchronous speed of an AC motor is determined by the frequency of the AC supply and the number of poles in the stator winding (RPM = $(120 \times f)/p$, where f: AC power frequency, p: number of poles). Here, the number of poles (p) is 4.

3. Results and discussion

By controlling the rotational speed of the electric motor through an inverter, feed water flowrate was controlled. The feed flowrate had a linear relation with the revolutions of the motor. Fig. 3 shows the change of the membrane inlet pressure in the sequence of the motor speed. The membrane inlet pressure increased with the motor speed since the feed flowrate increased linearly with the rotational speed of the motor as shown in Fig. 4. Undoubtedly, the feed flowrate by the pump was nearly independent of feed temperature but the permeate flowrate was dependent on feed temperature due to viscosity effects. The operating pressure of our RO system was regulated not by a pressure control valve but by the water hydraulic motor. The membrane inlet pressure was in the range between 48 and 62 kgf/cm^2. This operating pressure changed with temperature of feed water since temperature affected the feed flowrate. The feed flowrate decreases with feed temperature because the membrane's net driving pressure (NDP) decreases with temperature if the hydraulic pressure differential (ΔP) is maintained at a constant value. Here, the osmotic pressure is proportional to temperature and NDP is a differential between hydraulic pressure differential (ΔP) and osmotic pressure differential ($\Delta\pi$). Thus, as downstream pressure increased as a result of osmotic pressure, the feed flowrate slightly decreased.

The value of the power consumption and production can be obtained through a performance equation including the flowrate, pressure differential, and efficiency of the pump and motor. Here, the feed/brine flowrate, pump inlet/outlet pressure, and motor inlet/outlet pressure were measured and a typical average value (87.5% efficiency) in data sheet, the efficiency of the pump and motor, was

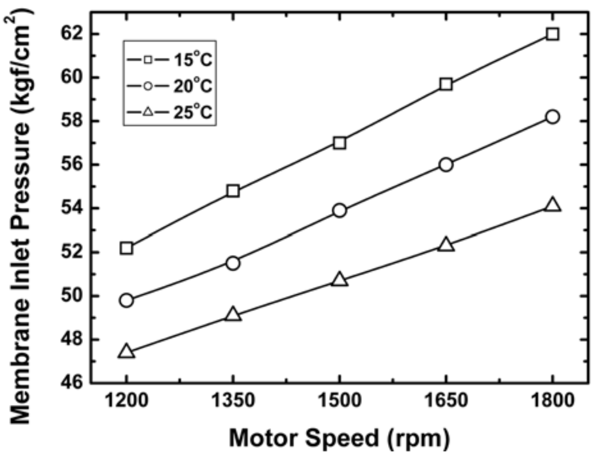

Fig. 3. Change of membrane inlet pressure in response to the motor speed and feedwater temperature.

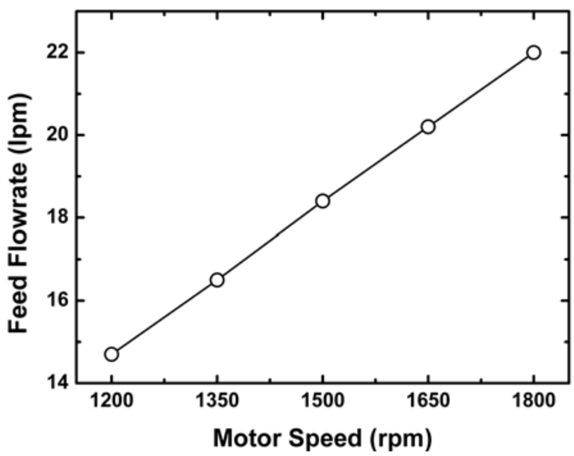

Fig. 4. Change of feedwater flowrate in response to the motor speed.

exploited. Fig. 5 represents the calculated pump power consumption (PPC) and motor power production (MPP) against the motor speeds. To be sure, the power consumption and production increased as the motor speed increased. However, the power consumption and production decreased as the feed temperature increased. The energy recovery through the water hydraulic motor ranged from 53 to 60%. Fig. 6 shows the comparison between the calculated net power consumption and the measured net power consumption against five different motor speeds and three different feed temperatures. Because the efficiency of the pump and motor used for calculation was not constant against the motor speed, there was a slight difference between the calculated net power consumption and the measured net power consumption.

In RO systems equipped with the water hydraulic motor, the water recovery ratio is fixed by the ratio of volumetric displacement of the pump and motor. In other words, the size of the water hydraulic motor determines the water recovery ratio in the RO systems. Therefore, we adjusted the ratio of the pulley size to obtain approximately 30% water recovery. Fig. 7 shows the water recovery ratio against the five different motor speeds. From this figure, it can be known that the water recovery in the RO system equipped with the water hydraulic motor was independent of the motor speed. The water recovery ratio was approximately 27.8% at 25°C feed temperature. As is well known, the water recovery is influenced by feed temperature. Regularly, the water recovery data at 20°C should have been positioned between the water recovery data at each temperature (15 and 25°C). This fluctuation

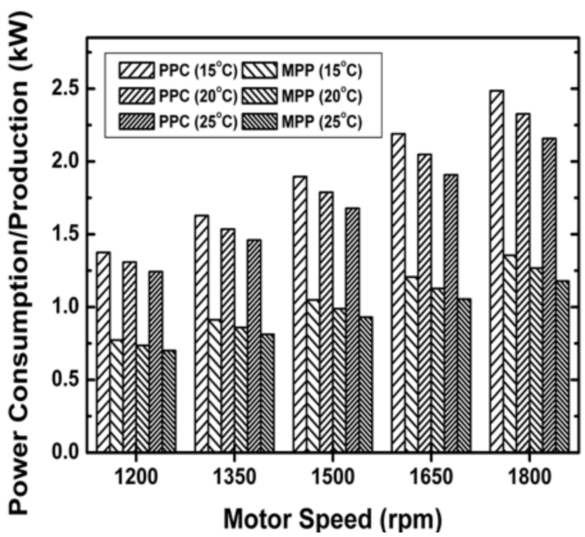

Fig. 5. Calculated pump power consumption (PPC) and calculated motor power production (MPP) in response to the motor speed. Here, the motor means the water hydraulic motor for energy recovery.

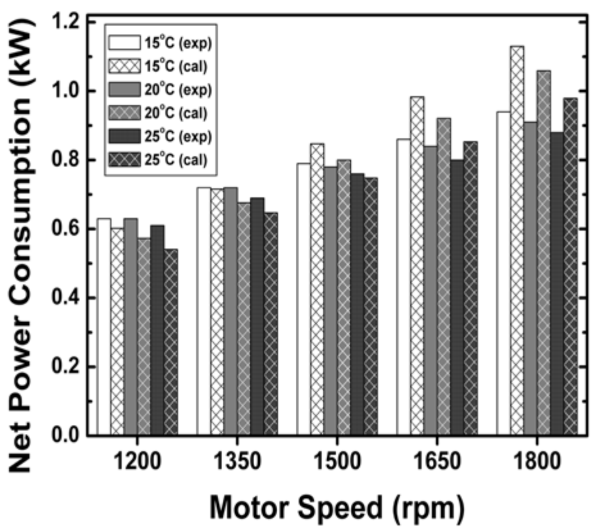

Fig. 6. Calculated net power consumption and measured net power consumption in response to the motor speed.

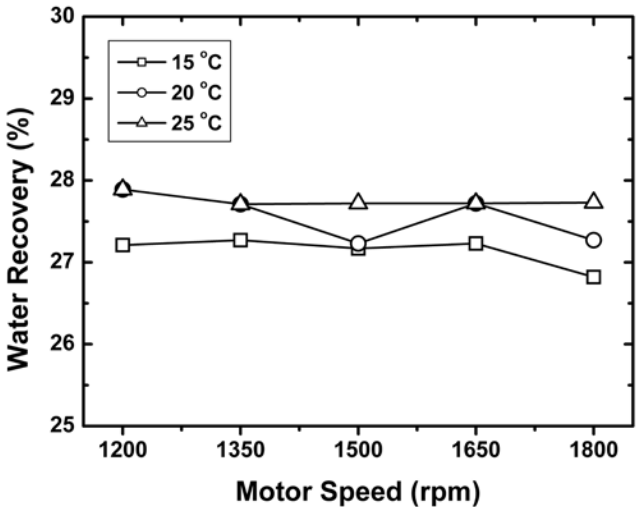

Fig. 7. Water recovery ratio in response to the motor speed and feedwater temperature.

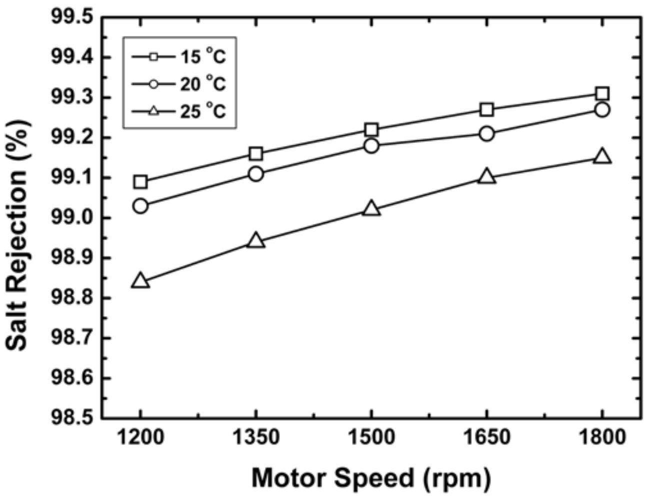

Fig. 8. Salt rejection in response to the motor speed and feedwater temperature.

is supposed to have been caused by measurement error. In this type of pump and motor, the leakage from the face between the cylinder housing and the body block is used to cool and lubricate all moving parts. For this reason, there was a difference between the expected water recovery ratio (31%) and the actual water recovery ratio (approximately 27.5%). The salt rejection increased with the motor speed since the membrane inlet pressure increased with the motor speed as shown in Fig. 8.

To investigate the effect of the energy recovery device, the system performances between the RO system with ERD and that without ERD were compared as shown in Fig. 9. In all cases for comparison, feed water temperature was 25°C and feed water flowrates were 30 LPM (HP pump without an inverter), 21 LPM (HP pump with an inverter), and 21 LPM (water hydraulic pump-motor assembly). The pumps used for comparison were as follows: high-pressure pump (plunger type) without an inverter, high-pressure pump (plunger type) with an inverter, and water hydraulic pump-motor assembly (axial piston type) with an inverter. The high pressure pump in the RO system is conventionally designed to be oversized for bad conditions such as low temperature and high salinity of seawater and aging of the membrane. Normally, the feed flowrate of a high pressure pump is controlled by adjusting the motor speed using an inverter for energy saving. The operating pressure and feed flowrate in an RO system are known to affect both the product flow and the specific energy (kWh/m^3) [11]. Specific energy consumption which is expressed in kWh/m^3 is calculated by dividing actual electrical power input to pumps (in kW) with total product flow (m^3/h). In other words, specific energy is defined as the energy required per unit output of permeate. Accordingly, the specific energy of the high-pressure pump with an inverter was significantly reduced by reducing both operating pressure and feed flowrate. That is, the specific energy showed 30% reduction in the case of the high pressure pump with an inverter compared with that without an inverter. Also, the specific energy reduction of approximately 27% was additionally feasible through the water hydraulic pump-motor assembly. The measured specific energy consumption in the last case reached as low as 2.61 kWh/m^3 at 1800 rpm and 25°C. This data shows reduction in energy consumption up to approximately 3.56 kWh/m^3.

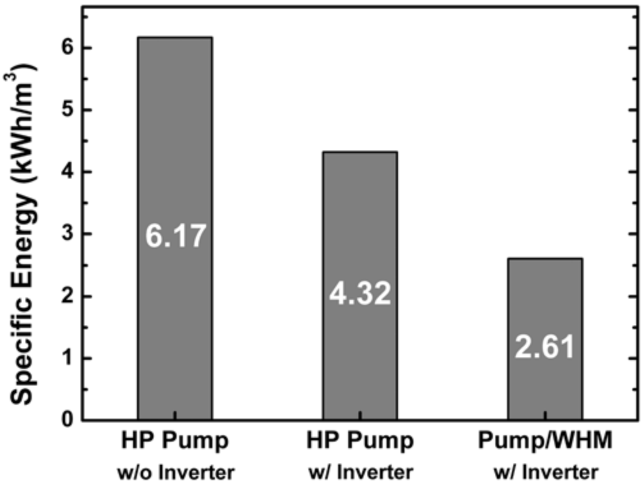

Fig. 9. Effect of water hydraulic motor (WHM) as energy recovery device on specific energy consumption.

In addition, the water recovery and salt rejection were compared as shown in Figs. 10 and 11, respectively. Since the water recovery was dependent on feed flowrate, the water recovery changed for the better in the case of the

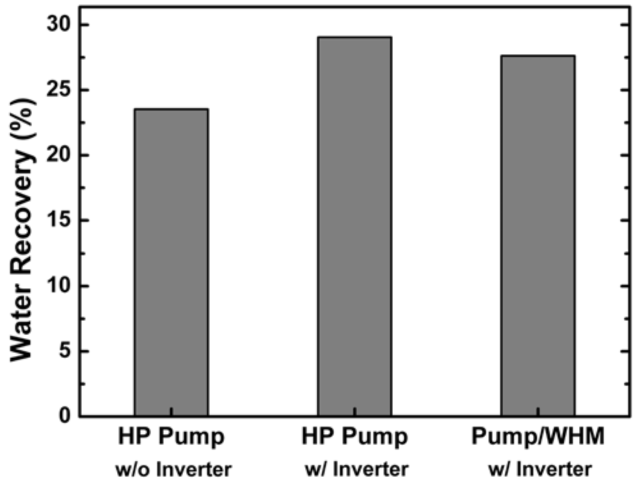

Fig. 10. Effect of the water hydraulic motor (WHM) as an energy recovery device on water recovery ratio.

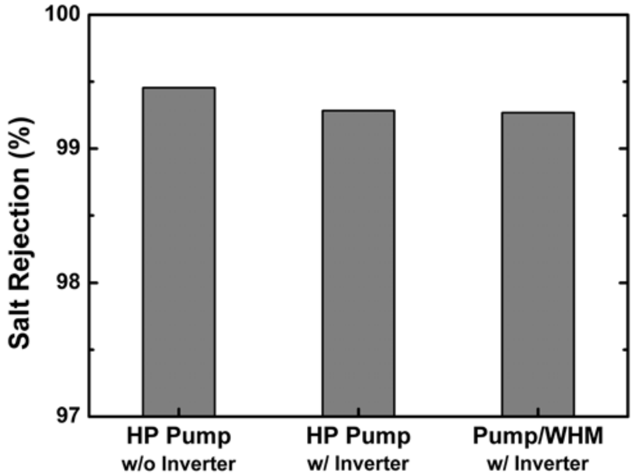

Fig. 11. Effect of the water hydraulic motor (WHM) as an energy recovery device on salt rejection.

use of the HP pump with an inverter and water hydraulic pump-motor assembly. That is, the salt rejection slightly dropped with increasing the recovery ratio through the reduction of the feed flowrate, as has been observed in our previous work [11]. As the recovery ratio increased, the concentration of salt in the brine flow also increased. From these facts we can find that the reduction of feed flowrate led to the negative effects on both permeate flowrate and permeate water quality. As a result, the energy recovery through the water hydraulic pump-motor assembly gave approximately 50% energy saving.

4. Conclusions

We have presented the energy recovery through the water-hydraulic motor in a small-scale RO desalination system. The results reported here show that energy recovery through the water hydraulic motor driven by brine pressure significantly reduced energy consumption. The setup and operation of the water hydraulic pump-motor assembly is easy and simple. Therefore, it is expected that similar pump-motor assembly will be frequently exploited in small-scale RO plants. So we are developing an ERD-integrated pump of which a cylinder barrel contains both pump and motor piston. In conclusion, a novel structured pump-ERD device based on swashplate axial piston type under development is supposed to be a suitable alternative to various kinds of ERDs in small SWRO desalination systems.

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