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Change of energy consumption through the adjustment of feed flow rate in RO membrane process

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ABSTRACT

The reverse osmosis (RO) process requires a large amount of energy for pressurizing feed flow, most of which is wasted through the brine stream. To recover the brine energy and deliver it to the feed, several methods using energy recovery devices (ERDs) have recently been used. However, the way to achieve efficient RO membrane process without ERD is also required in small RO desalination systems. In this work, the change of energy consumption upon the alteration of recovery ratio through the adjustment of feed flow rate was demonstrated. A variable frequency drive (VFD) was used to regulate feed flow rate. Permeate flux, recovery ratio, and salt rejection which are the key performance parameters of reverse osmosis were compared at the different feed flow rates, operating pressures, and feed temperatures. In addition, the power consumed in both high pressure (HP) pump and booster pump was measured and the specific energy consumption was compared. The control of feed flow rate reduced the specific energy consumption by 20%. Thus the adjustment of feed flow rate was effective to some extent in energy saving at a light cost of permeate volume and product water quality.

Keywords**:** Energy consumption; Feed flow rate; Specific energy; Reverse osmosis

1. Introduction

Recently, extensive studies have been carried out on energy saving in seawater desalination. The energy efficiency of reverse osmosis in desalination is heavily dependent on recovering hydraulic energy from the pressurized concentrate (i.e., brine). Most of the energy input to the system is wasted through the reject brine line [1,2]. The use of ERDs such as pelton wheel, hydraulic turbo charger, pressure exchanger (PX), and work exchanger (DWEER) is well known in seawater RO desalination plants [3–7]. The major energy consumer in any RO membrane plant is the high pressure pump. In particular, the plant using the positive displacement type ERDs such as PX and DWEER has a smaller capacity of high pressure pump than conventional plant without ERD. Thus when the capacity of high pressure pump is decreased by the aid of ERD, the specific energy consumption is also reduced.

In this work, the effects of the adjustment of feed flow rate through the variable frequency drive (VFD) were investigated. Basically, the performance of RO membrane is affected by the feed water composition, feed temperature, feed pressure, and permeate recovery ratio. Among these design parameters, the composition and temperature of feed water vary in different localities but feed pressure and recovery ratio are adjustable through system operation. Recovery ratio can be also adjusted by regulating feed pressure or feed flow rate. Here, an increase of recovery ratio through the elevation of feed pressure results in the increase of permeate flux and salt rejection but an increase of recovery ratio through the reduction of feed flow rate results in the slow decrease of permeate flux and salt rejection. However, the down

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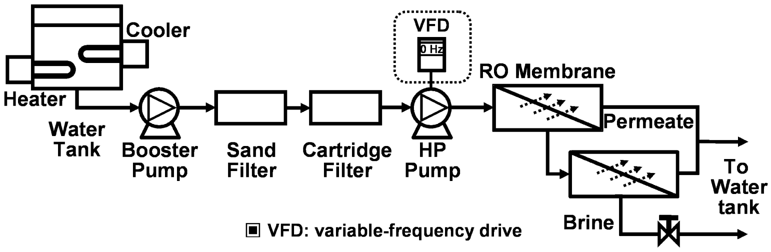

Fig. 1. Schematic diagram of experimental setup.

trend of permeate flux and salt rejection is known to take a sudden turn for the worse at a certain point. Accordingly, it is supposed that the power consumption can be reduced at a light cost of permeate flux and salt rejection.

This paper presents the experimental results of a small RO desalination system equipped with a variable frequency drive. The specific energy consumption of this system has been experimentally found to be in the range of 4.8~8.6 kWh/m^3 according to the operating parameters. Finally, we have obtained an interesting result that the adjustment of feed flow rate was effective to some extent in energy saving.

2. Experimental details

A 10 m^3/day SWRO membrane setup having a high pressure (HP) pump attached with a variable frequency drive (VFD) (called an inverter) was used to investigate the effect of feed flow rate. Fig. 1 represents the configuration of this system. The membrane was composed of two elements (hydranautics, SWC1-4040) connected in series. This RO system has a pressure control valve (throttle valve) to provide the backpressure in the concentrate. Then the valve was adjusted until the membrane inlet pressure as an operating parameter was obtained. The other parameters should be kept constant or altered at regular intervals to determine the effect of feed flow rate. So a water tank has a heater and a cooler 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 include electric power consumed by HP pumps, flow rate (feed, product and reject), total dissolved solids (TDS) (feed and permeate), operating pressure 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 is 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=$(120\times f)/p$,

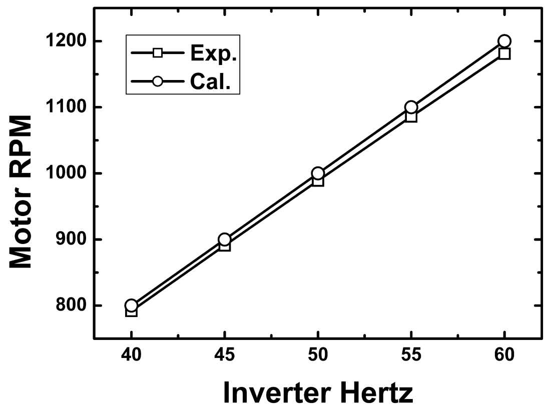

Fig. 2. Rotational speed of electric motor according to the frequency of the AC supply.

where f: AC power frequency, p: number of poles). Here, the number of poles (p) is 6.

3. Results and discussion

3.1. The adjustment of feed flow rate

The rotational speed increased linearly with the frequency of the AC supply as shown in Fig. 2. Accordingly, the feed flow rate also increased linearly with the rotational speed of motor at five different feed pressures as shown in Fig. 3(a). It seemed as if there were no change in feed flow rate but the feed flow rate decreased slightly with operating pressures as shown in Fig. 3(b–d). The reason for this is that the osmotic pressure in the membrane is lower at low recovery rates by low feed pressure.

Temperature also affected the feed flow rate as shown in Fig. 4. The feed flow rate 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 flow rate decreased.

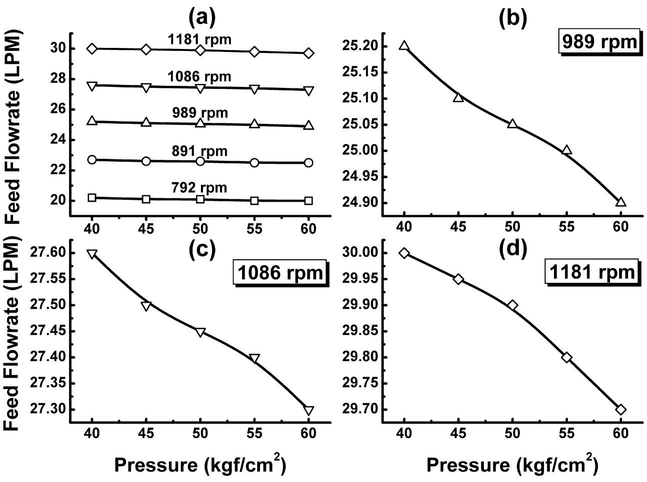

Fig. 3. Effect of rotational speed of motor and operating pressure on feed flow rate (at 20°C).

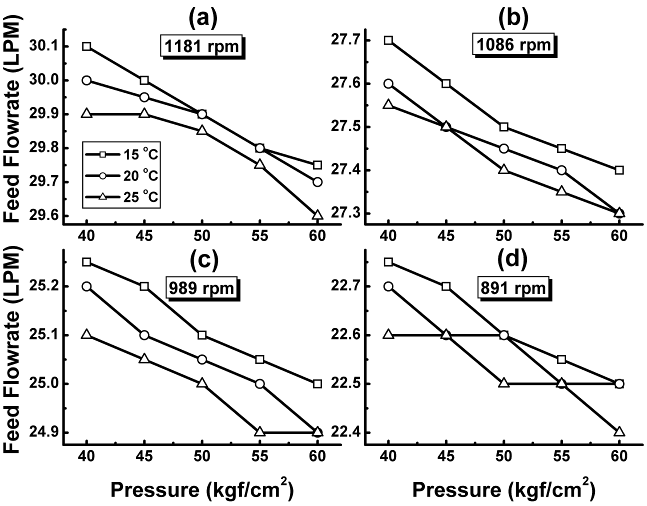

Fig. 4. Effect of feed temperature and operating pressure on feed flow rate.

3.2. The change of specific energy consumption

Energy consumption in membrane process generally presents the energy consumed by pumps such as high pressure pump and booster pump. 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). That is, specific energy is defined as the energy required per unit output of permeate. Fig. 5 shows the specific energy consumption as a function of membrane inlet pressure for five different motor speeds. As the rotational speed of motor decreased at a fixed pressure, the specific energy consumption also decreased. Here, the total product flow was decreased with decreasing motor speed but the electrical power input to pumps was also largely decreased. On this account, specific energy consumption had lower value at lower motor speed. In addition, the higher operating pressure, the lower specific energy was consumed.

In case of temperature change, the specific energy consumption also changed as shown in Fig. 6. The results like this were due to the higher permeate flow at higher temperature. The membrane's permeability to water is inversely proportional to viscosity of water. As temperature increases, the viscosity of water decreases and the membrane becomes more permeable. This effect then leads to reduced power consumption and higher production. In addition, when the feed temperature is increased, the osmotic pressure is increased. For that reason, this led to the reduction of the net driving pressure, which then resulted in the reduction of specific energy consumption. Fig. 6 shows that the specific energy consumption could be reduced by 20% at 55 kgf/cm^2 and 20°C.

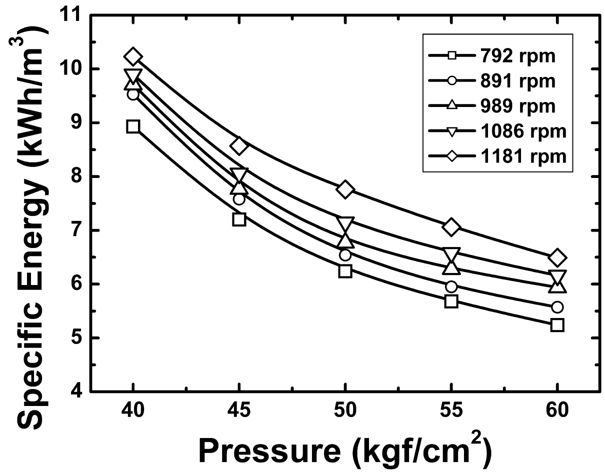

Fig. 5. Effect of rotational speed of motor and operating pressure on specific energy consumption (at 20°C).

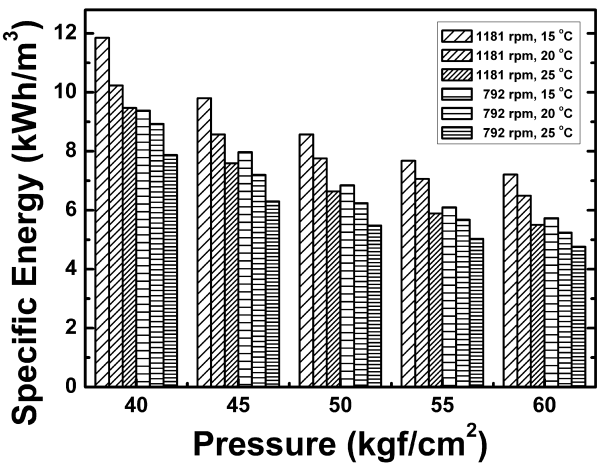

Fig. 6. Effect of feed temperature, rotational speed of motor and operating pressure on specific energy consumption.

Eventually, these facts show that the energy consumption of the RO membrane process is sensitive to the feed flow rate, operating pressure, and feed temperature.

3.3. The change of other performance

The change of permeate flow rate for several parameters is shown in Fig. 7 and 8. The permeate flow rate increased with the feed flow rate. In other words, permeate flux is greater at high feed flow rates since this minimizes concentration polarization. To be sure, as discussed above, it increased with operating pressure and feed temperature.

However, contrary to permeate flow rate, the recovery ratio decreased with the feed flow rate as shown in Fig. 9. The recovery ratio shows the tendency to increase with operating pressure and feed temperature. Fig. 10 also shows the variation of the recovery ratio at three different temperatures.

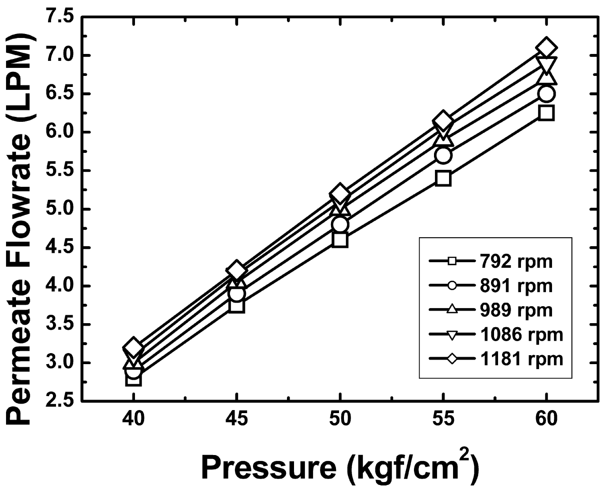

Fig. 7. Effect of rotational speed of motor and operating pressure on permeate flow rate (at 20°C).

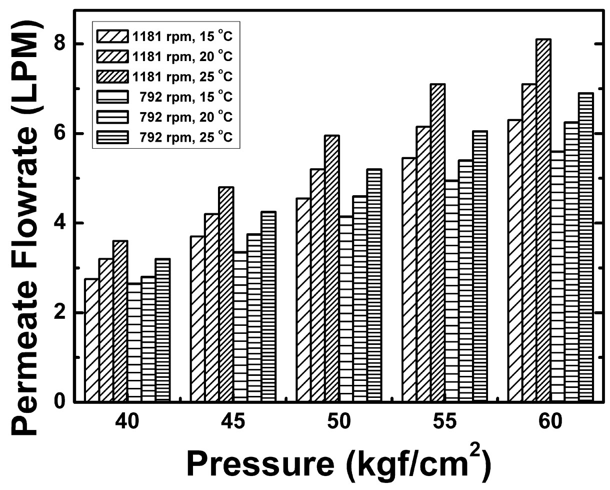

Fig. 8. Effect of feed temperature, rotational speed of motor and operating pressure on permeate flow rate.

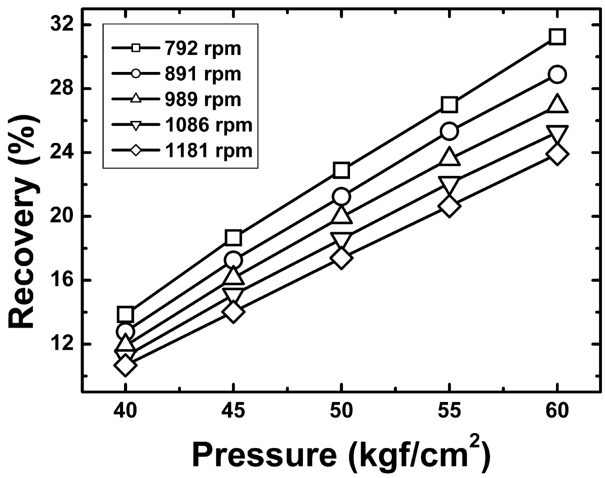

Fig. 9. Effect of rotational speed of motor and operating pressure on recovery ratio (at 20°C).

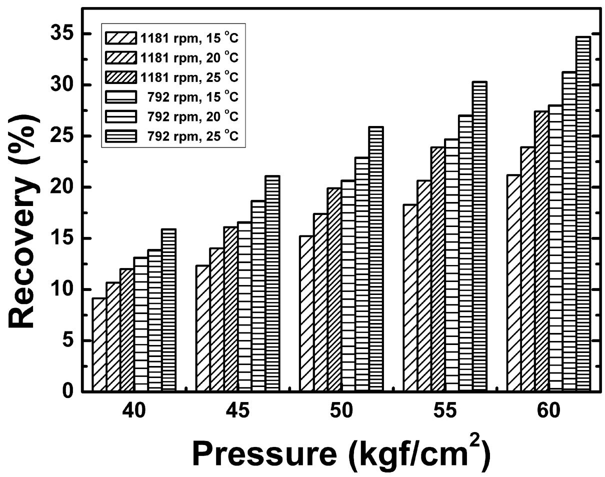

Fig. 10. Effect of feed temperature, rotational speed of motor and operating pressure on recovery ratio.

On the other hand, the solute rejection dropped with increasing recovery ratio through the reduction of the feed flow rate as shown in Fig. 11. As the operating pressure decreased and feed temperature increased, the solute rejection decreased as shown in Fig. 12. Here, temperature affected solute rejection because increase in temperatures results in increase in solute permeability. As the recovery ratio increased, the concentration of solute in the brine flow also increased. From these facts we can find that the reduction of feed flow rate led to the negative effects on both permeate flow rate and permeate water quality.

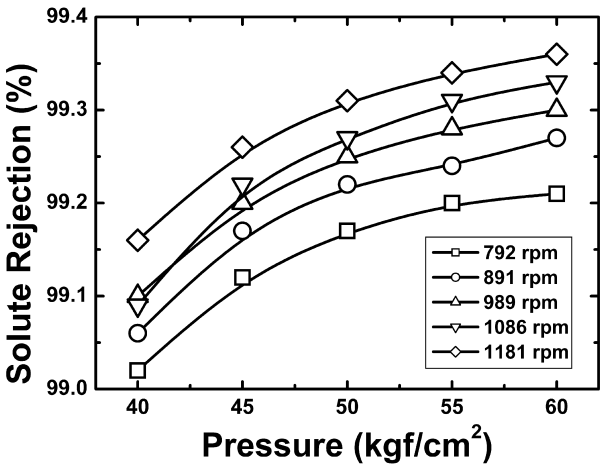

Fig. 11. Effect of rotational speed of motor and operating pressure on solute rejection (at 20°C).

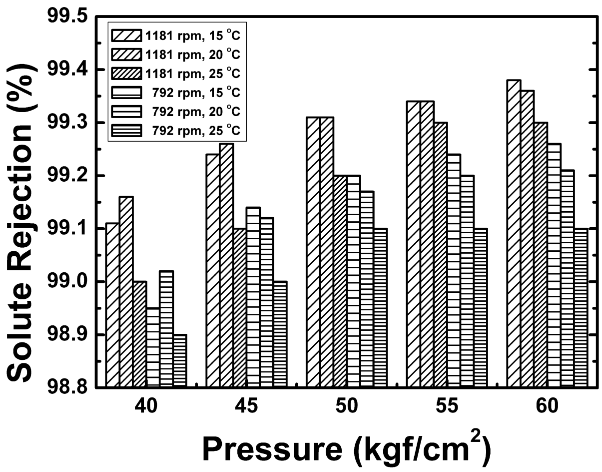

Fig. 12. Effect of feed temperature, rotational speed of motor and operating pressure on solute rejection.

4. Conclusions

The investigations presented in this paper were to understand the behavior of the RO system with the feed flow rate. It is well known that energy consumption in well designed reverse osmosis systems without energy recovery device ranges from 6~8 kWh/m^3. However, the high pressure pump in RO system is conventionally designed to be oversized for bad conditions. For energy saving, the feed flow rate of high pressure pump was controlled by adjusting the speed of the motor using variable frequency drive in this work. As a result, the VFD reduced unproductive pressure losses and then decreased the specific energy consumption to 4.8 kWh/m^3. Only the control of feed flow rate reduced the energy consumption by 20%. In conclusion, the adjustment of feed flow rate was effective to some extent in energy saving at a light cost of permeate volume and product water quality.

Acknowledgements

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