field report

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New Desalination Pump and Energy Recovery Technologies

HISTORICALLY, THE EFFICIENCY OF SMALL SEAWATER REVERSE OSMOSIS (SWRO) SYSTEMS SIZED BETWEEN 200 AND 20,000 GPD (0.7–75 M^3/D) HAS BEEN VERY POOR COMPARED WITH THE EFFICIENCY BEING ACHIEVED IN LARGER PLANTS WHERE EFFICIENT ENERGY RECOVERY SYSTEMS HAVE BEEN DEVELOPED AND APPLIED FOR MORE THAN 20 YEARS.

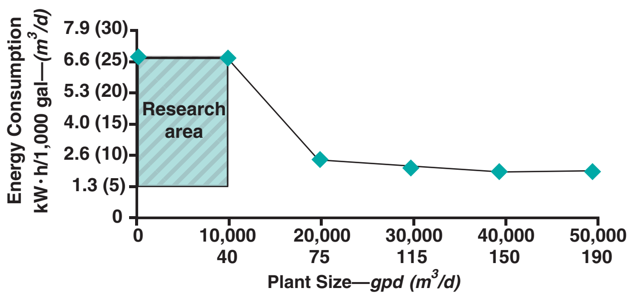
This inefficiency is the result of smaller systems being overlooked in terms of energy consumption and a near total lack of energy recovery solutions available in this arena. In the early days of desalination before energy recovery systems, both large and small SWRO plants consumed as much as 50 kW·h/kgal (13 kW·h/m^3). Because of the development potential for large-scale SWRO and the large amounts of power involved, the industry began to focus on lowering these numbers by improving the achievable recoveries of RO membranes and developing turbine-style energy-recovery devices. By the mid 1980s the specific power numbers for large-scale systems were reduced to as low as 30 kW·h/kgal (8 kW·h/m^3). These systems were still energy-intensive, however, and the industry redoubled its efforts through the 1990s to create improvements in membranes, energy recovery, and pumping technologies. By the late 1990s the industry had achieved energy consumption levels as low as 13 kW·h/kgal (3.5 kW·h/m^3). However, these pumping and energy recovery systems were still only 50–75% efficient. Then at the turn of the century, there were new developments in isobaric energy recovery technologies that could yield 93–97% net transfer efficiencies. As a result of these new technologies, large-scale SWRO energy consumption dropped to as low as 7.6 kW·h/kgal (2.0 kW·h/m^3) almost overnight. These were fantastic achievements in efficiency, but unfortunately there were no such improvements for the smaller systems. At that time, the smaller system market still consumed approximately 30 kW·h/kgal (8 kW·h/m^3). Theoretically, at 7.6 kW·h/kgal (2.0 kW·h/m^3), an SWRO unit could produce 264 gpd (1 m^3/d) and require only 80 W of high-pressure pumping power. Figure 1 shows the difference in energy consumption between small and large systems and defines the original area of development for the project described in this article.

There have been several commercial attempts to address the inefficiencies of the smaller SWRO units using small work-exchanger-type energy recovery systems. These go back to the late 1980s, including PUR's Survivor and Power Survivor series water makers (now manufactured by Katadyn, Wallisellen, Switzerland). The Survivor hand pump achieved some success in military survival kits and boating applications. The Clark pump has also been applied to very small systems and to the marine markets. These pumps achieved limited commercial success, and have only been applied to very small systems of less than approximately 600 gpd (2.3 m³/d).

However, in 2002 water hydraulic axial piston pump (APP) technology was introduced into the RO market. The benefits of this technology include high efficiency, low pulsation, and almost zero maintenance. Since 2002 APP technology has taken significant market share away from the previously dominant plunger pump design, and there are thousands of APP pumps in small SWRO systems today. Water hydraulic axial piston technology was developed and commercialized to replace oil hydraulic systems as early as 1987, but the technology did not make its way into SWRO until after the turn of the century. As in oil hydraulics, the water hydraulic axial piston pumps can be applied in reverse as axial piston motors (APM) or, as in the case of SWRO, an energy-recovery motor. Soon after the introduction of water hydraulic axial piston pumps into SWRO, the industry began to see early tests and field applications of APP and motor technology. These tests demonstrated energy consumption levels between 11 and 19 kW·h/kgal (3 and 5 kW·h/m³) over a range of small systems from 2,100 to 6,600 gpd (8 to 25 m³/d) (Drablos, 2005; Kunczynski, 2002).

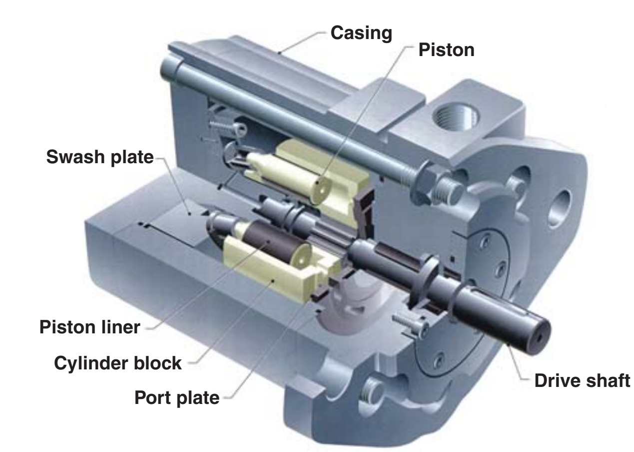
In conjunction with this previous work through a contract with the Office of Naval Research, Ocean Pacific Technology (OPT) has been testing water hydraulic, APP, and motor technologies for these smaller systems. Throughout the process, OPT has consulted and collaborated with US Army representatives to focus the performance of its equipment around an 1,800-gpd (6.8-m³/d) lightweight water purifier (LWP) system used by the army. The system must be able to operate under a variety of conditions, including a requirement to meet production with feedwater at up to 60,000 mg/L total dissolved solids. Under these extreme conditions, the RO feed pressure can reach energy-intensive levels of 1,200 psi (83 bar). The current LWP system uses a 5-hp engine to drive the main high-pressure pump and a 3-kW generator to run the other auxiliary pumps and systems. The existing 3-kW generator has approximately 0.9–1.4 kW of spare capacity depending on the operating mode. A specific goal of this work was to develop an APP–APM unit that could operate in this 0.9–1.4-kW window of spare capacity so that the 5-hp direct diesel–driven, high-pressure pump could be replaced by a smaller and simpler electric motor–driven high-pressure pump. This could greatly reduce the weight, maintenance, complexity, and logistical support requirements of the LWP system. In addition to specifically addressing the LWP system, another objective was to develop technology that would be scalable over the entire range of smaller systems—from approximately 200 to 20,000 gpd (0.7 to 75 m³/d). As this new technology is applied, it is hoped that it will greatly improve the commercial applicability of the smaller systems, especially for solar and renewable-power applications. Furthermore, it is hoped that this development program may be scaled up to help improve the efficiencies of the larger full-scale systems from approximately 0.1 to 1 mgd (400 to 3,800 m³/d) in which the necessity to use centrifugal main high-pressure pumps results in opportunities for improvement as well.

FIGURE 1 Typical seawater reverse osmosis energy consumption versus plant size



TECHNICAL APPROACH

OPT's approach to the project was to develop two separate breadboard pump and energy-recovery prototypes. After researching the theoretical and commercial options, OPT settled on two approaches: one prototype uses an APP combined with an APM, and the other approach combines an APP with



Cross section of an axial piston pump used for desalination.

a pressure exchanger (PX) to create an APX hybrid. Although the development program of the APX is proceeding well, this article will only address work on the APP–APM unit.

The APP design has been proven and used in the oil hydraulics industry in tens of thousands of applications for more than 50 years. Starting in the early 1980s, a program was initiated to develop a water-hydraulic APP in which plain water could be used as a lubricating and hydraulic fluid instead of oil. Initially it was envisioned that water hydraulics could replace oil hydraulics and create a simpler, lower-maintenance, more environmentally friendly technology. By 1987 the program had produced a commercially available water hydraulic APP as well as a host of related products. Early marketing efforts into hydraulic applications were successful in industries such as food processing, undersea applications, and firefighting in which the differentiation between water and oil held a special significance. The water hydraulic APP was recognized for having many benefits as a standalone high-pressure pump outside the hydraulic industry, and in 2002 the Danfoss Company created a duplex stainless steel (SS) version of its 316-SS tap water APP and began to market directly to the SWRO industry. A sectional view of a commercially available APP is shown in the photo on page 55.

Operating in reverse, APPs can be used as APMs to recover energy from the brine stream of an SWRO system. This approach has been applied in oil

Determining the RO Recovery of an APP–APM System

RO recovery = (product flow/RO feed flow) × 100 and RO feed flow = reject flow + product flow, therefore

$$\text{RO recovery} = \left(\frac{(\text{RO feed flow} - \text{Reject flow})}{\text{RO feed flow}}\right) \times 100 \tag{1}$$

APP flow rate = volumetric displacement per revolution × volumetric efficiency × number of revolutions per minute
APM flow rate = volumetric displacement per revolution/volumetric efficiency × number of revolutions per minute

The number of revolutions per minute for the APP and APM are equal; therefore,

$$\text{RO recovery} = \frac{[(\text{APP volumetric displacement} \times \text{APP volumetric efficiency}) - (\text{APM volumetric displacement} \times \text{APM volumetric efficiency})]}{(\text{APP volumetric displacement} \times \text{APP volumetric efficiency})} \times 100 \tag{2}$$

For the OPT system, and using the manufacturer's figures for displacement and efficiency, the calculation would be as follows:

$$\text{RO recovery} = (6.3 \times 0.94) - (3.75/0.9)/(6.3 \times 0.94) \times 100 = 30\%$$

It is critical to use the same units of displacement for the APP and APM throughout these calculations. The volumetric efficiency of these devices varies slightly with feed pressure and flow rate. For example, in the OPT system the actual recovery varied from approximately 30 to 36%, from 100 to 1,200 psi (7 to 83 bar), and at 3,450 rpm. If more precise calculations are necessary, the manufacturer should be consulted for more precise volumetric efficiency projections at a specific duty point.

A simple equation for calculating the product flow could also be derived as follows:

$$\text{RO feed flow} = \text{reject flow} + \text{product flow}$$

APP and APM flow rate = volumetric displacement per revolution × volumetric efficiency × number of revolutions per minute; therefore,

$$\begin{aligned}\text{Product flow} = {} & \text{rpm} \times [(\text{APP volumetric displacement} \times \text{APP volumetric efficiency}) \\ & - (\text{APM volumetric displacement}/\text{APM volumetric efficiency})]\end{aligned} \tag{3}$$

APP–APM—axial piston pump–axial piston motor, RO—reverse osmosis hydraulics for more than 50 years and in tap water hydraulic systems since 1987, but only recently and in limited applications has the concept been applied to seawater desalination systems. Figure 2 shows a simple flow diagram for an SWRO system based on this concept. The APP provides the high-pressure seawater supply and the APM provides the energy recovery.

When the APP and APM are connected on a fixed shaft, the SWRO system will operate at fixed recovery and constant product flow based on the relative displacement of the APP and APM devices. Increasing the pump speed will increase the product flow at the same fixed recovery rate. This fixed displacement/flow system eliminates many of the operating controls and much of the auxiliary equipment associated with traditional methods. It is also possible to provide a variable recovery system by changing the displacement of the APP and/or APM through a gear box, variable swash plate, or other variable transmission device. However, the testing for this study only included fixed-displacement equipment.

In an APP–APM system, the APP provides 100% of the feed flow to the RO system. Our APP had a volumetric displacement of 6.3 cm^3/revolution and was capable of producing a maximum flow of approximately 5 gpm (1.1 m^3/h) at 3,450 rpm. The APM for our system had a volumetric displacement of approximately 3.75 cm^3/revolution. Because the APP and APM are locked in rotation on a common shaft, the RO recovery ratio for the system is a fixed ratio of the volumetric displacement of each device. Calculations for determining the RO recovery of an APP–APM system and for calculating product flow are detailed in the sidebar on page 56.

Some of the advantages of the APP–APM system are

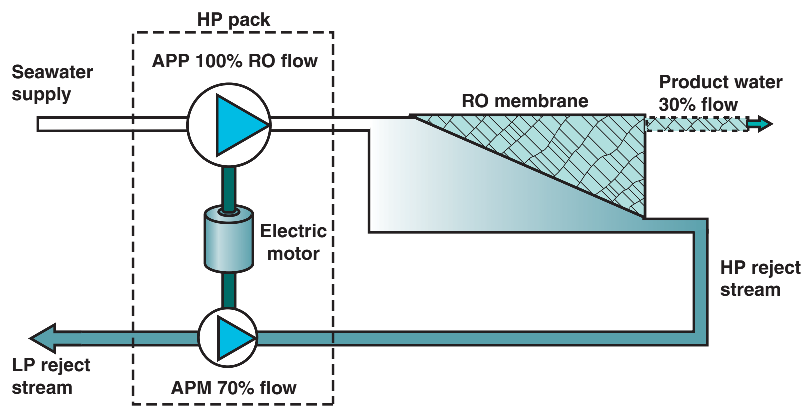
- reduced power consumption by approximately 50% compared with APP alone,
- simpler application compared with isobaric systems (i.e., fixed flows and no booster pump),
- no mixing between the brine and feed streams compared with other isobaric systems,
- smooth flow–high efficiency rotary piston design,
- ultralow-maintenance water hydraulic design,
- the fixed RO recovery simplifies control requirements (see disadvantages)

Disadvantages of the APP–APM system might include:

- limited efficiency because of "double-dip" hydraulic to rotational energy transfer,
- fixed RO recovery limits operational flexibility (see advantages),
- high cost of double-pump design (high-pressure pump and motor pump).

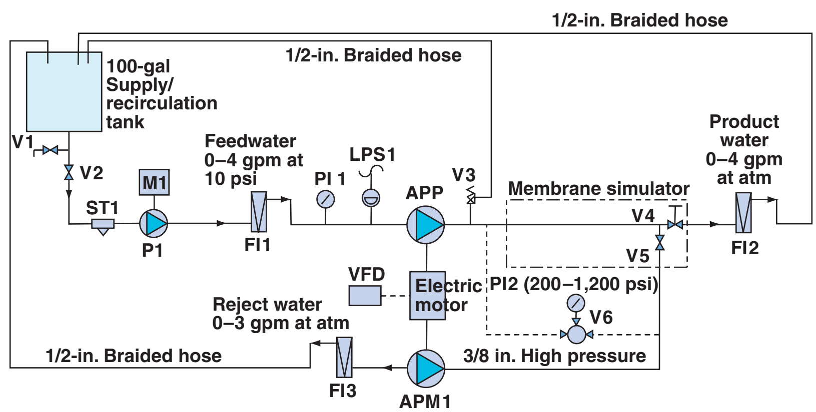
The APP–APM approach saves approximately 50% of the power

FIGURE 2 Diagram of an axial piston pump–axial piston motor system



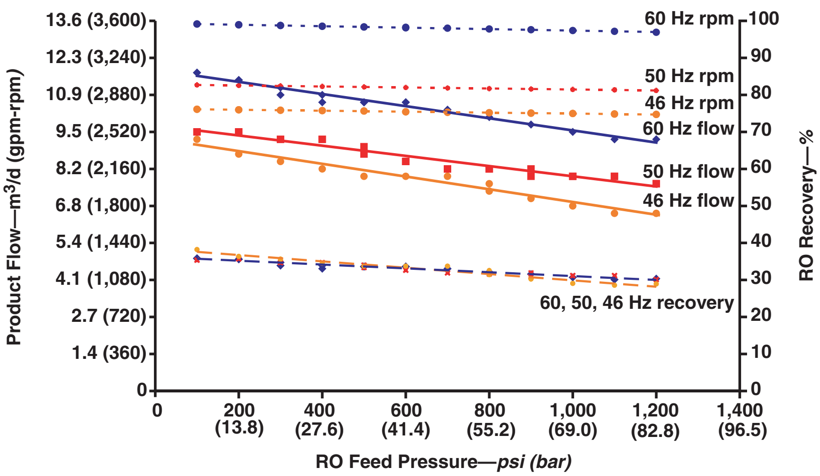
APM—axial piston motor, APP—axial piston pump, HP—high pressure, LP—low pressure, RO—reverse osmosis

FIGURE 3 Membrane simulator and test stand



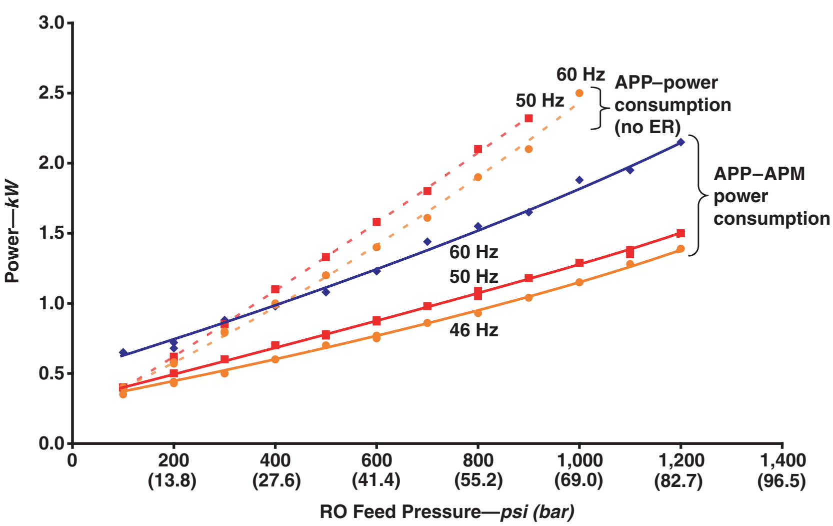
APM—axial piston motor, APP—axial piston pump, EM—electric motor, FI—flow indicator, LPS—low-pressure switch, PI—pressure indicator, VFD—variable-frequency drive, V—valve

FIGURE 4 Axial piston pump–axial piston motor product flow versus RO feed pressure



RO—reverse osmosis

FIGURE 5 Power versus reverse osmosis feed pressure



APM—axial piston motor, APP—axial piston pump, ER—energy recovery

required for the SWRO process described compared with systems with no energy recovery. Furthermore, these systems are very simple to operate and have recently become commercially available and proven.

Therefore, it is an ideal solution for small systems producing on the order of 200–20,000 gpd (0.7–75 m^3/d) below the range in which the isobaric devices (pressure exchangers) can be practically applied. In larger systems, because of the efficiency constraints of the APP–APM solution, the isobaric devices will always be slightly more efficient.

TESTS AND DATA

Although a general goal of this project was to create technology that will eventually lead to improving the efficiency of the full range of systems from 200 to 20,000 gpd (0.7 to 75 m^3/d), OPT's initial work has focused on the system requirements of the US Army's LWP unit. Through close work with army representatives, the exact requirements of the LWP system were defined as follows:

Seawater system requirements

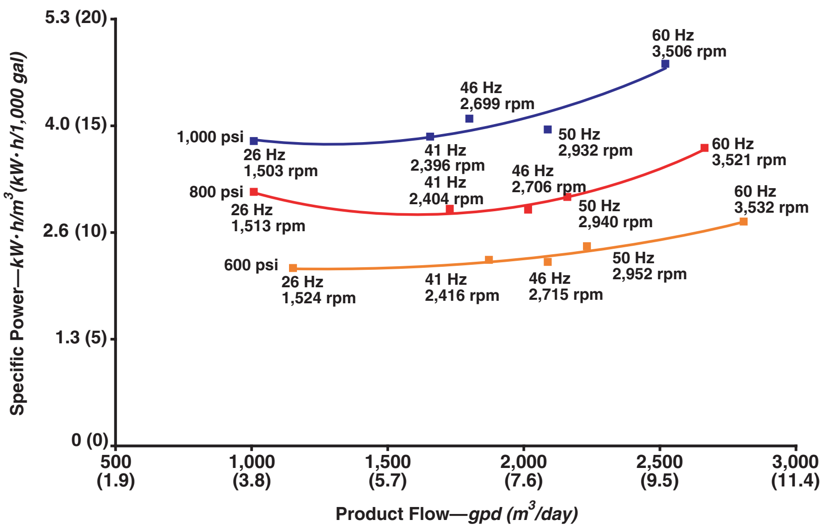
- Approximately 800–1,200 psi outlet pressure
- 3.8-gpm pump/RO feed flow
- 1.25-gpm (1,800 gpd) product flow (33% recovery)
- 2.5-gpm reject/motor inlet flow
- 3-kW generator set has 0.9–1.4 kW of spare capacity for high-pressure pump

Brackish system requirements

- <800-psi outlet pressure
- 3.8-gpm pump/RO feed flow
- 2.10-gpm (3,000 gpd) product flow (55% recovery)
- 1.7-gpm reject/motor inlet flow

A test stand was developed to simulate the operating characteristics of an SWRO system. The test stand includes a variable-frequency drive, supply/recirculation tank, membrane feed-pressure regulator, membrane differential-pressure control valve, axial piston pump, axial piston motor, electric motor, pressure gauges, and flow meters. Tap water was used to simulate seawater, and a feed and bleed stream was set up to maintain a constant temperature of around 75°F (25°C). Figure 3 shows the basic piping and instru-

FIGURE 6 Specific power versus product flow at 1,000 psi (69 bar)



ment diagram of the RO membrane simulator and test stand.

Figure 4 shows product flow and recovery versus RO feed pressure at the three settings of 60, 50, and 46-Hz. The 46 Hz data best fit the 1,800-gpd (6.8-m^3/d) LWP system. Similar data were collected at 13 settings from 26 to 60 Hz and production rates of 1,000–2,800 gpd (3.8–9.5 m^3/d).

At each hertz setting, the system pressure was varied from 100 to 1,200 psi (7 to 83 bar). Figure 4 shows how the product flow decreased approximately 20% as the pressure was increased from 100 to 1,200 psi (7 to 83 bar). A comparison of the slope of the revolutions per minute versus pressure curves (almost flat) with the product flow versus pressure curves indicates that the majority of the loss in product flow was the result of a decrease in volumetric efficiency of the APP–APM unit. Figure 4 also shows how recovery varied slightly from approximately 30 to 35% with increasing pressure. However, this variation was consistent over the range of hertz settings and production rates. In general, the data show that the recovery and production rates remained relatively constant over a wide range of feed pressures. Because a typical SWRO system might only vary 100–200 psi (6.9–13.8 bar) in feed pressure, the system flows would remain very stable. These constant flow-and-recovery performance characteristics greatly simplify the application and operation of an SWRO system.

Figure 5 shows the power consumption in kilowatts over the same operating conditions and hertz settings. The APP was also tested alone at the same operating points at 46 and 50 Hz. Compared with the APP alone, the APP–APM provides close to 50% reduction in power consumption at seawater operating pressures above approximately 800 psi (55 bar). The benefit of the APM diminished at lower operating pressures because of the lower availability of energy to recover and lower efficiencies associated with hydraulic losses in the APP–APM unit.

Figure 6 shows how the specific power consumption of the system varied over a range of production and flow rates and RO feed pressures for the APP–APM unit. The curves show that the system provided good energy recovery and system efficiency over the wide range of operation from approximately 1,000 to 2,800 gpd (3.8 to 9.5 m^3/d) and 600 to 1,000 psi (41 to 69 bar).

All power consumption figures cited in this study include the power of the APP pump electric motor only and do not take into account energy required for the seawater intake, prefiltration, or product water distribution. A constant pressure of approximately 15 psi (1 bar) was supplied to the inlet of the APP unit.

CONCLUSIONS

Historically, the efficiency of small SWRO systems between 200 and 20,000 gpd (0.7 and 75 m^3/d) has been very poor without any practical options for energy recovery. Typical systems in this size range would consume approximately 30 kW·h/kgal (8 kW·h/m^3). Through its contract with the Office of Naval Research, OPT has demonstrated that APP–APM technology can be reliably applied to smaller systems to achieve energy consumption levels at 8–18 kW·h/kgal (2.1–4.8 kW·h/m^3) depending on RO feed pressure. The equipment operates smoothly and because of the fixed-displacement design requires minimal instrumentation, controls, and operator involvement. Furthermore, tests and field demonstrations by Kunczynski (2002) and Drablos (2005) confirm these findings and have demonstrated long-term reliability with very little associated maintenance. In conclusion, water hydraulic APP–APM technology offers a suitable alternative to designers and operators of small SWRO systems who require energy-efficient operation.

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