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Demonstration of an energy recovery device well suited for modular community-based seawater desalination systems: Result of Danfoss iSAVE 21 testing

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ABSTRACT

The option of building smaller, decentralized plants is more feasible now that HP pumps and energy recovery devices (ERD) are available for use in small-scale seawater desalination plants with efficiencies comparable to those typically associated with larger plants. A demonstration SWRO system producing 125 cubic meters of product water per day was designed and commissioned utilizing the Danfoss iSave 21 energy recovery device. The desalination subsystem utilizes an inter-staged membrane configuration, low flux, and low recovery design to reduce specific energy consumption, fouling potential, and membrane cleaning requirements. Test results show that a specific energy consumption lower than 2 kWh/m^3 is easily achievable utilizing standard components, and that the improved second-generation iSave 21 unit has significantly lower lubrication flows than the previous model.

Keywords: Isobaric energy recovery device; Seawater reverse osmosis; Decentralized SWRO facilities

1. Introduction

Over the last two decades, seawater desalination by reverse osmosis has become an affordable option for regions where natural freshwater resources are dwindling in quality and quantity. This transformation is primarily due to efficient energy recovery devices (ERDs) which transfer energy from the high-pressure concentrate stream to the membrane feed, improvements in efficiency in HP pumps, and advances in low-energy seawater reverse osmosis (SWRO) membranes [1].

Traditionally, the total cost of desalting seawater was reduced by commissioning large capacity desalination plants [2] to take advantage of the economies of scale associated with the capital cost of intake and brine discharge structures and pre-treatment and civil engineering works, together with the fact that typically, larger flow rates imply more efficient centrifugal pumps and ERDs [3]. The availability of HP pumps and ERDs offered for use in small/medium-scale seawater desalination plants with efficiencies comparable to those typically associated with large plants has made the option of building smaller, decentralized plants (treatments facilities located close to feedwater source and near product water demand) more

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feasible. Adopting a decentralized approach to water supply offers a number of advantages such as reduced pumping costs, leakages, and associated distribution costs, shorter project implementation cycles, and ensuring water security through the availability of multiple sources.

Campbell Applied Physics has developed the Advanced Seawater Reverse Osmosis (ASWRO) desalination system which incorporates a system engineering approach to desalting of seawater at a total energy of less than 2.6 kWh per cubic meter of fresh water (for intake seawater salinity < 40 PSU), reduced chemical usage (on-site generation of all chemicals employed), quieter systems, small plant footprints, and shorter lead times to commissioning. The ASWRO desalination system is being designed for the small-to-medium-scale market (4,000–24,000 m^3/day), utilizing a modular architecture, which is containerized for ready transport, reduces capital costs, and minimizes on-site design and construction variables during the build out phase. The subsystems integrate to form a standard module designed for the production of 1,000 m^3/day of potable water, which can be assembled in parrallel to form larger capacity plants.

A demonstration unit of the ASWRO system was constructed and commissioned at the company's R & D facility in El Dorado Hills, California. The plant is designed and configured to produce 125 m^3/day of drinking water to meet California's drinking water standards and WHO drinking water quality guidelines. The design, equipment, operation, and controls of the system closely matches those of a typical full-scale plant ASWRO system and was independently tested to meet target water quality requirements at a specific energy consumption between 1.7–2.0 kWh per cubic meter of produced water for the desalination subsystem, excluding intake pumping, pre-treatment, post-treatment, and product water pumping.

A number of state-of-the-art high pressure (HP) pumps and ERDs are available for seawater duty for the small-scale SWRO systems with ERD capacities between 10 and 41 m^3/hour all having efficiencies above 90%. The iSave 21 from Danfoss RO Solutions was selected as the preferred means of recovering the brine pressure from the reverse osmosis process for several key reasons. Firstly, it incorporates a pressure exchanger and booster pump in one seamless unit that could be brought online and operated by a single Variable Frequency Drive (VFD), simplifying automation and eliminating the need for a high-pressure flow meter. Secondly, the device has a lower acoustic signature than other ERD devices on the market and thirdly, the iSave offered the highest efficiency energy recovery solution tailored to CAP's modular philosophy. This paper describes test results and experience gained with the iSave 21 ERD.

2. Materials and methods

The iSave 21 consists of an isobaric pressure exchanger, a high pressure positive displacement booster pump, and an electric motor integrated into a single device. The booster pump is of the vane type (fixed displacement) in which the flow is proportional to the number of revolutions of the driving shaft enabling flow control. Coupled to this shaft is the pressure exchanger, enabling simultaneous flow control of both the pressure exchanger and booster pump using the VFD-controlled electric motor provided preventing over spin [4]. The demonstration unit is equipped with a Danfoss APP 8.2 axial piston HP pump designed, so lubrication of internal moving parts is provided for by seawater feed, similar to the iSave unit. Both the iSave 21 ERD and APP pump are standard commercially available off-the-shelf products. Fig. 1 shows a schematic of the high-pressure loop of the dASWRO system giving average process parameters for the system.

Raw feedwater is delivered periodically to the test site via tanker truck and stored on-site in tanks. Permeate water is recombined with concentrate after processing for repeated use. After pre-treatment, utilizing filtration, oxidation, micro-screening, and oxidant removal, water is directed into the SWRO membrane system. The membrane system is equipped with two side-ported pressure vessels each containing seven 8-inch SWRO membranes in series utilizing an inter-stage design configuration. The ASWRO desalination subsystem utilizes a low flux (low feed pressure) and low recovery design to reduce fouling potential and membrane cleaning requirements, while maintaining low specific energy requirements [5]. The inter-stage membrane configuration further reduces feed pressure when compared to typical membrane designs [6].

Following Danfoss and DOW Filmtec guidelines for system start-up [7,8], the iSave is brought up to speed from a cold start over a span of 50–60 s to a nominal operating speed of 653 rpm. The high-pressure Danfoss Axial Piston Pump (APP) follows in a similar fashion, accelerating to a nominal operating speed of 1,180 rpm over a 190 s period. These speeds correspond to design recovery and permeate flow conditions while the ramp-up ensures feed pressure increase to the elements does not exceed 10 psi/s.

Upon system shutdown, the presence of concentrate or seawater in the vessels leaves residual pressure in the vessels, high-pressure piping, and high-pressure chambers of the APP and iSave. The

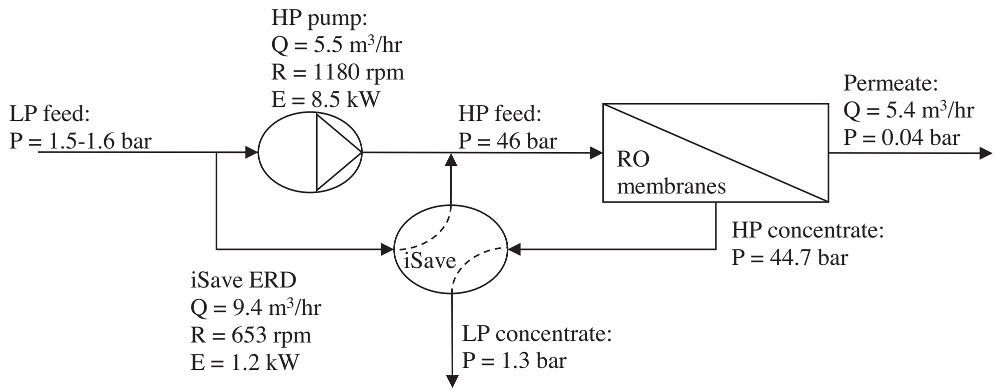

Fig. 1. Schematic of the high-pressure loop with iSave ERD giving average process parameters (HP = high pressure, LP = low pressure, P = pressure, Q = flow, E = power, and R = rpm).

pressure bleeds off through tolerance gaps within 1–3 h.

During testing, it is often required to restart the high-pressure segment of the RO shortly after shutting it down. This forces the iSave and APP to start against residual pressures up to the typical operating 650 psig, though more commonly in the 200–300 psig range. By their design, the APP and iSave are not adversely affected by starting against pressure as long as a maximum torque of 36 Nm is not exceeded [4].

The start, stop, and operation of the dASWRO system are done remotely from a central control station, though the pumps may be controlled manually from the VFD keypad. CAP has successfully demonstrated the autonomous start-up, operation, and shutdown sequence for the entire dASWRO system, which is initiated and managed remotely through a SCADA programmable logic controller (PLC).

Lubrication of the moving parts within the iSave is accomplished with a portion of the brine stream as shown in Fig. 2. Combined with the leakage within the booster pump, this volume is ultimately lost to discharge and its pressure not reclaimed. The HP pump is responsible for pressurizing the flow rate equivalent to the permeate flow and the iSave "lubrication flow." iSave lubrication flow can be calculated by subtracting the permeate flow from the flow through the HP pump both of which were measured directly with flow meters.

Specific power consumption for the desalination subsystem reported below includes the power requirements solely for the HP pump and the iSave ERD. The power requirements for these two components were obtained as the multiple of motor voltage and current. This power is divided by the permeate flow rate to obtain specific power consumption. Independent testing showed that the value obtained for power

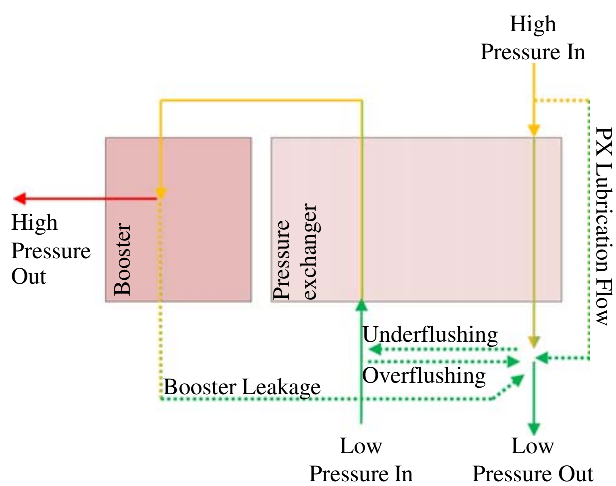

Fig. 2. Illustration of flows within an iSave ERD.

consumption from the VFD voltage and current was not accurate. Tests were carried out (Itron Quantum Q1000 power meter) to obtain a correction factor for both devices to obtain accurate power readings from the voltage and current values logged by the SCADA system.

In October 2011, the iSave 21 was replaced by second-generation iSave 21 unit which had a number of design improvements including the redesign of the pressure exchanger to be a single piece with 12 machined ports from the earlier design which had 12 individual sleeve cylinders captured between two perpendicular plates.

All parts of the device are made of high corrosion resistant materials, with all critical parts made of Super Duplex 1.4410 (UNS S32750) or equivalent materials. The first-generation iSave device showed slow seepage through the bolted seam near the nose end-cap; however, the manufacturer has since moved to Super Duplex for this part instead of Duplex to eliminate the problem.

Although as an ERD, the iSave unit is slightly larger than contemporary ERD devices, other devices do not include the footprint of the booster pump required to complete the energy recovery loop. Dimensions of the complete device including the electric motor are 981 x 320 x 378 mm.

3. Results

Formal performance testing was carried out to determine whether the demonstration ASWRO system can consistently meet design specifications and performance goals in relation to fresh water production, stable plant recovery, energy use, reliability, noise levels, and permeate water quality. These tests were carried out under the guidance and supervision of an independent expert to validate and monitor results.

3.1. Specific energy

Fig. 3 presents the specific energy consumption (kWh/m^3) for the operation of the desalination subsystem. Specific energy consumption was consistently below 2 kWh per cubic meter of produced water for a feedwater having salinity between 37,000 mg/L and 39,000 mg/L. Following commissioning and the independently supervised test period, the demonstration system has been in continuous operation, apart from short periods of downtime associated with the routine testing, checks, and management of plant instrumentation, controls, and software. The specific power consumption fraction was reduced by 0.08 kWh/m3 when changing from the generation one to generation two iSave unit.

3.2. Lubrication flow

According to iSave Selection Tool [9], the projected lubrication flow rate of the first-generation unit was 7.3 l/min; our testing showed this value to be 6.3 l/min. At a typical feed pressure of 44.8 bar, this effect accounts for 800 watts or 0.15 kWh/m^3 specific power consumption. Significant reduction in lubrication flow rate within the second-generation iSave model led to a measurable reduction in power consumption. Fig. 4 shows that after replacement of the unit in October 2011, the lubrication flow rate dropped significantly from an average lubrication flow rate of 6.3 l/min in the first-generation unit to 2.3 l/min in the second-generation unit.

3.3. Noise level

ASWRO system level requirements allow for a maximum level of 65 dB(A) at a distance of 10 meters from the perimeter of the plant. The iSave21, rated at 86 dB(A) directly at the device, is not only a means of achieving this specification, but allows for a much quieter work environment for the maintenance crew. Fig. 5 gives a comparison between the noise level for the first and second-generation iSave units. The second-generation iSave gave average sound meter readings of 87 dB(A) directly next to the iSave unit, while the APP pump had a sound level reading of 86.5 dB (A) directly at the pump. These readings are down from 102.9 dB(A) for the first-generation iSave unit directly at the pump. Vibrations and noise was minimized by the use of vibration dampners and the use of high-pressure and low-pressure flexible hoses between the iSave unit and pressure vessels and feed and concentrate manifolds.

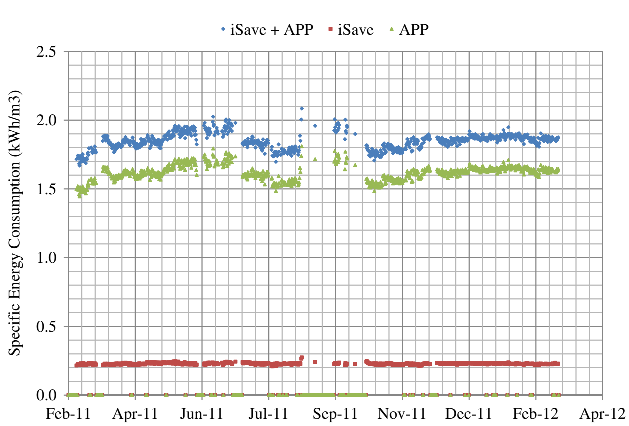

Fig. 3. Specific energy consumption (kWh/m^3) for iSave and HP pump.

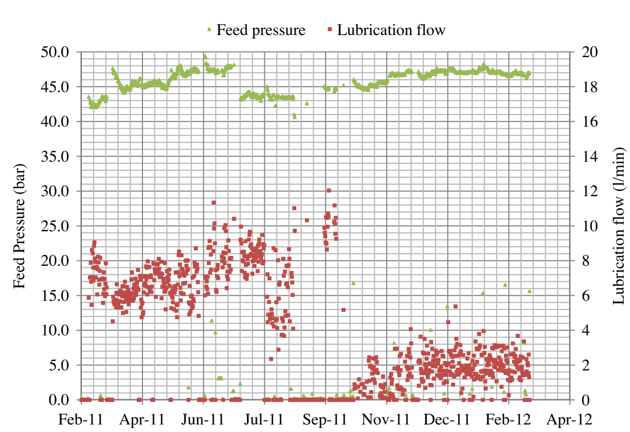

Fig. 4. Lubrication flow and feed pressure over the course of testing.

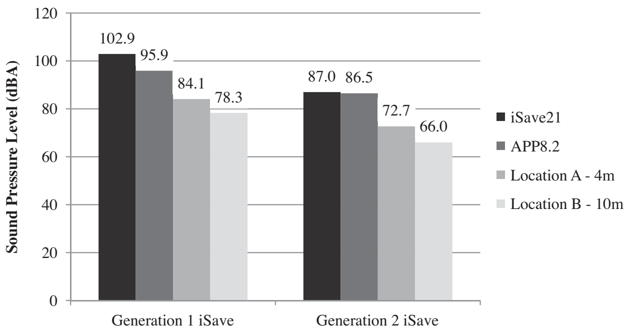

Fig. 5. Comparison of acoustic performance between first- and second-generation iSave models.

3.4. Operational observations

The iSave device requires a VFD to dial in the optimum rpm, which should not be neglected when performing an energy audit, especially if operating the unit at speeds below 50% of the motor rating. Starting up the system is fairly straightforward, by first, ramping up the unit once it sees sufficient feed flow and pressure. Care must be taken to bleed the piping, as this can lead to noise, vibrations, and failure when air pockets are compressed and then expelled from a high-pressure region. After the iSave achieves a predetermined operating speed, there is typically ample time to ensure system integrity before starting the HP pump. The process is reversed for a shutdown, with the HP pump being shut off first. As a safety precaution, the HP pump should never be operated without the iSave running for the risk of overpressurizing the system and setting off pressure relief valves.

A subtle trick in controlling the feed pressure to the iSave relies almost entirely on the back-pressure in the downstream low-pressure discharge piping. A minimum of 1 bar of back-pressure prevents cavitation at the the low-pressure concentrate port. The low-pressure feed pressure is a resultant sum of the discharge back-pressure and friction loss through the device. The back-pressure is typically maintained by regulating the upstream intake pump and downstream throttling valve located at the low-pressure concentrate outlet of the device. The low-pressure feed and discharge pressures are independent of iSave rpm.

While the device is typically very forgiving of system fluctuations, operators can typically assess flow dynamics by merely listening. In a flow-balanced system, the HP pump and iSave achieve a harmonous tone. If the feed pressure approaches minimum operating levels, as is typically the case, the iSave emits loud buzzing noise—indicating cavitation.

Because the process connections of the iSave are IPS grooved-ends, it can be a challenge mating the unit to low-pressure piping without resorting to corrosion-prone metals. Plastic, especially CPVC adapters, should be avoided as prolonged vibrations and misalignment stress may cause the molded grooves to change shape and eventually promote leaks.

As long as the iSave is flushed with fresh water for a prolonged shutdown, corrosion-related problems can be eliminated. The unit typically needs to run at reduced speed along with the HP pump while purging the vessels and manifolds with a fresh water feed.

4. Conclusions

Results from testing of the demonstration system utilizing the iSave 21 ERD show that a specific energy consumption of lower than 2.0 kWh/m^3 is achievable utilizing standard components available for use in small-scale decentralized SWRO systems. Experience with the second-generation iSave 21 showed significantly lower lubrication flows of 2.3 l/min and noise levels compared to the first generation of iSave device.

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