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Fluid dynamics secret to pressure-booster record

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Editor's note

At the recent EuroMed conference in Tel Aviv, Israel, those on the FEDCO booth at the exhibition were all wearing big smiles. The reason was the performance achieved by the company's turbocharger energy-recovery device (ERD) for the Jeddah III seawater reverse-osmosis desalination project. A condition of the contract was that the ERD transfer efficiency exceeded 80%, something which had never before been achieved. Not only did the FEDCO machine hit the target, but the company predicts it can go even higher.

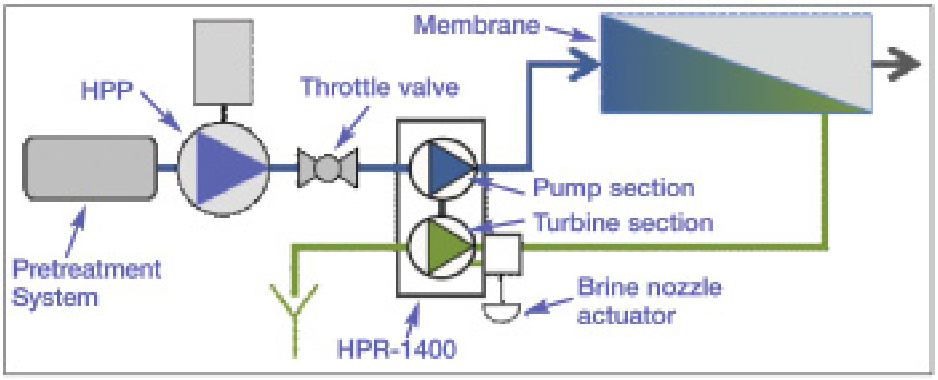

Figure 1 – SWRO system with HPB

The history of science and industry is littered with famously wrong predictions. This article will address yet another prediction and show how FEDCO proved the "expert" wrong.

Background

With 240,000 m^3/d of permeate production divided into 16 trains, the Jeddah III seawater reverse-osmosis (SWRO) desalination facility will be the latest major SWRO plant in Saudi Arabia.

Both Saline Water Conversion Corporation (SWCC), as the system owner, and Doosan Heavy Industries, as the engineering, procurement and construction contractor, sought a combination of high-energy efficiency, reliability and low capital cost in this prestigious project. The energy-recovery device (ERD), now ubiquitous in large SWRO projects, plays a decisive role in achieving those objectives.

FEDCO was selected to provide the ERDs in the form of 16 HPB-1400 Hydraulic Pressure Boosters (HPBs, also known as turbochargers). A key requirement was to obtain a transfer efficiency of 80.4%. The supplier was mindful of the challenge of achieving this target, since no commercial turbocharger had achieved a reliably reported efficiency near that value.

As indicated in Figure 1, the HPB consists of a pump section and a turbine section linked by a common shaft. The HPB turbine section converts brine hydraulic energy into mechanical power, which then drives the pump section. The feed boost provided by the HPB reduces the high-pressure pump (HPP) discharge pressure, thus reducing energy consumption as well as the size of the HPP and motor.

Brine flow and pressure control is provided by a variable-area auxiliary turbine nozzle. Brine never mixes with the feed, and the streams can be of different pressures and flow rates.

A few years ago, a desalination industry ERD expert confidently predicted that a turbocharger would never reach 80% transfer efficiency. As a measure of his confidence, he made an open US$ 10,000 challenge payable to anyone who could achieve it. This is the story of how FEDCO met the contract requirements and in the process proved the ERD expert wrong.

> *"Everything that can be invented has been invented."*
> *– Charles H Duell, Commissioner, US Office of Patents, 1899*

Defining the challenge

Transfer efficiency (Nte) is defined as the ratio of hydraulic energy in the feed stream added by the ERD to hydraulic energy in the brine stream available to the ERD and may be calculated by:

$$Nte = Nf \times Nr \qquad [1]$$

where
- **Nr** = Efficiency of extraction of brine hydraulic energy
- **Nf** = Efficiency of increasing feed hydraulic energy from net available brine energy

Transfer efficiency is an imperfect measure of ERD performance. For example, isobaric chamber ERDs claim a high transfer efficiency, but create other energy losses not captured by this parameter, such as brine/feed mixing and energy required by external booster pumps.

In the case of the HPB, transfer efficiency comes without any caveats, disclaimers or exceptions. But, why would an ERD expert claim that 80% was an impossible performance?

Transfer efficiency equals HPB turbine efficiency (Nr) times HPB pump

The starting point

All FEDCO HPB impellers and diffusers are machined from bar stock using customized Computer Numerical Control (CNC) machining programs generated by propriety hydraulic design software. Thus, the HPBs were already beneficiaries of smooth flow channels with precise control of the flow path geometry from inlet to outlet.

All HPB rotors are manufactured as a one-piece unit thus displaying exceptional rigidity. This permits precise tolerances thereby allowing reduced internal clearances and hence reduced leakage losses.

The most daunting challenge was to obtain accurate CFD performance predictions for the complex HPB fluid system. Once accomplished, numerous hydraulic designs could be analytically evaluated before cutting metal. Hundreds of CFD analyses were performed, some of them requiring trillions of computer calculations.

First partial scale test

The company decided to apply its optimized CFD analysis to an HPB-350 (nominal feed flow of 350 m^3/h) being built for another customer. The quoted efficiency requirement was 73%; an ambitious value by current turbocharger standards.

However, FEDCO used this opportunity to perform an in-depth CFD design development to push the efficiency to a higher value. The final design displayed significantly different flow channel geometry from the company's standard designs. The developers were in unknown territory, and the test would tell a lot about their mastery of CFD in a complex fluid system.

The results exceeded FEDCO's best hopes. The system achieved 77% efficiency at the customer duty point and the desired turbine flow resistance on the first test. Just as importantly, the test data matched predicted values within 1%.

Given the fact that the HPB-1400 would be 4 times of capacity of the HPB-350 and additional refinements would be performed, there was good reason to expect 80+% efficiency. Note that scaling up the size of a flow machine such as the HPB automatically provides an efficiency improvement as frictional losses become proportionately smaller.

Figure 3 – General view of HPB test system

A note about testing

FEDCO's test system needs high accuracy to confirm that customer requirements have been achieved. However, for advanced performance optimization, an extra measure of accuracy is needed. Therefore, highly precise pressure measurements were developed with consistencies of better than 0.1% across the test pressure range.

With this level of measurement, various minor design increments can be evaluated and implemented as warranted. A series of minor improvements can quickly add up to a significant performance gain.

Figure 3 shows the test loop. The tall vertical pipes meet requirements of the Hydraulic Institute Test Codes for precision pressure measurements but are not required for HPB operation.

As illustrated in Figure 4, simulated permeate flow is reintroduced into the HPB feed inlet pipe. This reduces the flow through the high-pressure pump (HPP) to that of the brine flow. Thus a given size of HPP can test a somewhat larger HPB than would be otherwise possible. There is absolutely no effect on the accuracy of the test data and its applicability to standard RO system configurations.

Transfer-efficiency testing requires measurement of the pressure at the four pipe connections to the HPB, two flow rates and feed temperature. Please refer to Figure 4 for instrumentation layout.

A cooling system controls test-loop temperature. Note that valve V1 is used to adjust simulated permeate production.

The company has a high level of confidence in the test data, partly due to the fact that Pratt & Whitney

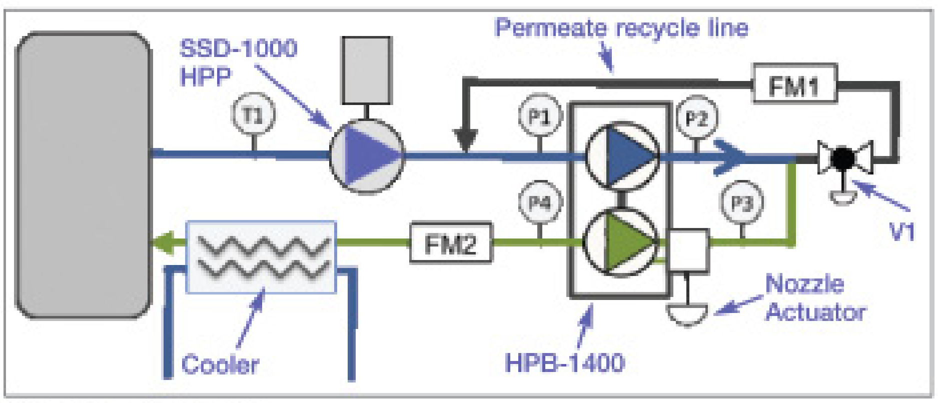

Figure 4 - Test loop diagram

Figure 5 - SSD-1000 HPP with motor and test

Figure 6 - HPB-1400 on the test stand

Rocketdyne conducted a third-party review of the turbocharger test system.

Project spin-off

An interesting spin-off of this project was development of a new HPP to test the HPB-1400. Notable features include single stage end-suction design and an impeller and diffuser machined from bar stock. This pump joins other models in the SSD product line.

All hydraulic passages were optimized with CFD analysis just as with the HPB-1400. Designated the SSD-1000, this pump exhibited exceptional performance that will be reported in a future paper. Figure 6 shows the pump on the test stand.

The SSD-1000 was designed to develop maximum efficiency at the HPB-1400 duty point brine flow and pressure. Due to motor power limitations, testing was at about 75% of the duty flow.

The moment arrives

On 27 September 2010, the first HPB-1400, serial number 3053, was tested. The team was elated when the test computer showed readings of transfer efficiency ranging from 80% to nearly 81% with an average set of data points of 80.4%. It is important to note that this was a true efficiency, not adjusted or extrapolated in any way.

Increasing the flow to the duty value would be expected to raise efficiency by approximately 0.3% thus taking the efficiency to about 80.7%

The unit was designed for a fluid density on the feed side about 2% lower than on the turbine side (due to different TDS levels between the feed and brine streams). However, on the test stand, the fluid densities were the same. Using fluids with the design densities would have raised efficiency by approximately 0.1%.

From the above factors, the efficiency in field operation is expected to be about 80.8%.

The FEDCO team

One of the authors (Kitzmiller) developed FEDCO's CFD analysis and the hydraulic design of the HPB-350 and HPB-1400 among others. Jason Hunt designed the test loop and the data-acquisition system. Ryan Osborn was the test technician. After the successful test, the entire FEDCO staff and management enjoyed a long and happy lunch at a nearby restaurant.

What next?

FEDCO's present designs in larger units with further refinements may achieve 83-84%. More exotic hydraulic designs may achieve 86% (92.7% component efficiency) or higher.

HPBs with feed flow rates of up to 4,000 m^3/h are being designed. Units of 10,000 m^3/h or more are feasible.

It remains to be seen if the ERD expert will make good on his US$ 10,000 challenge. The company hopes that he does, as the money will be donated to several water-related charities and scholarship programs.

Figure 7 - Ryan Kitzmiller (right), Ryan Osborn (front) and Jason Hunt with the HPB-1400