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Modeling the impact of using multi-port RO pressure vessels in seawater reverse osmosis desalination plants using special simulation software

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ABSTRACT

The present paper describes the modeling of RO plant processes and systems using the simulation program IPSEPro^{TM} which has helped to improve the design and optimization process in several large desalination projects. The program also covers power plant processes, which allows integrated power and desalination plants to be simulated in a single flow sheet. Hydraulic calculations including pipe work, pressure vessels, membranes and pumps are conducted simultaneously with mass transfer phenomena in the membranes. Mass transfer calculations in the membranes are based on the solution diffusion model. This paper presents an analysis of the impact of using multi-port RO pressure vessels on flow distribution between the various pressure vessels, and how this impacts the relative operating conditions of the individual membrane elements. Because the pipework hydraulics and membrane performance models are integrated within a single simulation environment, a true understanding of the impact of multi-porting on membrane system performance can be attained.

Keywords: Simulation; Seawater reverse osmosis; Energy demand; Hydraulic calculation; Multi-port pressure vessels

1. Introduction

In recent years there has been a great proliferation of the so-called multiport pressure vessel in the design and construction of reverse osmosis (RO) membrane racks. With this type of vessel, each vessel contains two side ports for the feed flow and two side ports for the brine flow. This enables the feed and brine to flow directly from one pressure vessel to its adjacent pressure vessel, thereby reducing the amount of pipework required to connect the vessels to the main manifolds. According to Shachaf et al. [1], the material cost of a multiport system can be 50% cheaper than the material costs of an end port system).

Because the feed flowrate into the first pressure vessel and the brine flowrate out of the last pressure vessel in a multiported array is much greater than in a conventional parallel feed system, the size of these ports must be increased. In addition, there are additional feed and brine side pressure losses resulting from the consecutive expansion and contraction which the feed flow experiences in flow between successive pressure vessels.

This paper describes an approach whereby the impact of these pressure losses and the resulting flow maldistribution on the performance of the overall membrane plant can be quantified using an integrated simulation

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software (IPSEpro^{TM}) by SimTech simulation technology, which combines the hydraulic model of the pipework and pressure vessel system with the membrane model [2].

2. Multiport configurations

There are two possibilities to connect the vessels with each other (Fig. 1): first, the Z-Type, in which the concentrate leaves the array at the opposite end from the inlet; and second, the U-Type, in which the concentrate leaves the array at the same end as the inlet.

The feed pressure in the first vessel is always higher than the feed pressure in the last vessel. With the Z-Type arrangement, the brine pressure is also higher in the first vessel than in the last vessel. However, with the U-Type arrangement, the highest brine pressure occurs in the last vessel (note that the first/last vessel is always the first/last vessel viewed from the direction of feed flow). The membrane feed side pressure drop (feed pressure less concentrate pressure) directly affects the flow through the pressure vessel. Since with the U-Type arrangement, the last vessel has the lowest feed pressure and the highest brine pressure, it can be seen that this arrangement will result in poorer flow distribution than the Z-Type arrangement where the last vessel has the lowest feed pressure and the lowest brine pressure. Thus, Codeline advise that vessels are connected in a Z-Type arrangement to keep the pressure loss through the vessels as constant as possible [3]. Interestingly, Bel recommend the U-Type connection and explain, that the Z-Type arrangement is rarely used [4].

Because poor distribution of feed flow between the vessels causes problems with the performance of the membrane system, the pressure vessel manufacturers give some guidelines to ensure acceptable flow distribution. Codeline advise that the feed flow velocity through the first port should not exceed 3.35 m/s [3]. They also recommended that the port size in a particular array is not reduced, since the effect on the array must be carefully evaluated.

Bel make no restrictions to the feed flow velocity, but they do limit the number of vessels connected in series, depending on the port size. The flow mal-distribution increases with the number of vessels connected in series. The guideline ranges from maxima of two vessels with 2.0″ ports to seven vessels with 3.0″ ports [4].

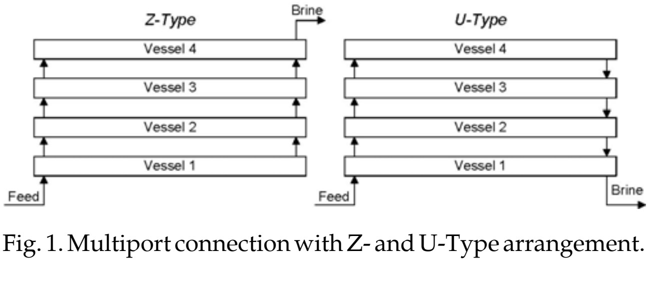

Fig. 1. Multiport connection with Z- and U-Type arrangement.

3. Consequences of flow mal-distribution

A commonly held misconception about pressure drops in RO membrane feed and brine pipework is that these pressure drops have no effect on flow distribution because they are insignificant compared to the trans-membrane pressure drop. Traditional flow distribution requires that the pressure drop across the individual flow element is much greater than the pressure drop in the distribution pipework, and this is certainly the case comparing the trans-membrane pressure drop to the feed & brine pipework.

However, it must be remembered that there is not only flow distribution to the permeate, but also flow distribution from the feed to the brine. This means that the pressure drops in the feed/brine distribution systems must be compared with the feed to brine pressure drop across the pressure vessel. A typical rule of thumb [5] is that the pressure drop across the individual element should be at least 10 times greater than the pressure drop along the flow distribution manifold. Since the typical feed side pressure drop for a single RO pressure vessel is of the order of 2 bar, it can be seen that pressure drops of more than 0.2 bar along a multiport array could cause a mal-distribution of feed flowrate to the various pressure vessels. Since the permeate flowrate is dependent on the trans-membrane pressure drop, the permeate flowrate will be the same at the front of each pressure vessel. This means that a vessel which receives more flow will have a lower recovery rate than a vessel which receives a reduced flow.

If the lead element in one vessel operates at a lower recovery than the lead element in a different vessel, then the lead element with the lower recovery will generate a higher permeate flowrate since it has a lower average feed side salinity and osmotic pressure. Since lead element flux is one of the key membrane system design parameters which must be limited, it is clear that poor flow distribution could result in contravention of membrane supplier design guidelines.

This paper provides an example of an evaluation in which the membrane design is dictated by the lead element flux, and the consequence of poor flow distribution is that extra pressure vessels must be provided to meet the lead element flux constraint.

An additional implication of increased pressure drops along a multiport array is that the pumping energy of the high pressure system has to be increased accordingly, with a consequent increase in power costs.

4. Method

This paper reports the findings of investigations made using an integrated software package (IPSEpro) in which the hydraulic system and the membrane performance are simulated in the same simulation environment. Fig. 2 shows an IPSE flowsheet for a typical configuration evaluated for this study.

Each membrane element is simulated using the solution diffusion theory, calibrated to the performance of Hydranautics SWC4+ membrane elements determined from the Hydranautics projection software IMSDesign [6]. In this case, there are five pressure vessels, multiported together, and each pressure vessel contains seven membrane elements in series. In addition, a hydraulic module is inserted in the feed and brine flow paths between each pressure vessel, which is used to model the feed and brine side manifold pressure drops, using the pressure drop functions provided by the pressure vessel manufacturer [3].

A comparison between IPSE and IMSDesign, shown in Table 1, is carried out for one vessel with seven new SWC4+ elements. The results show that the IPSE model agrees with the IMSDesign very well.

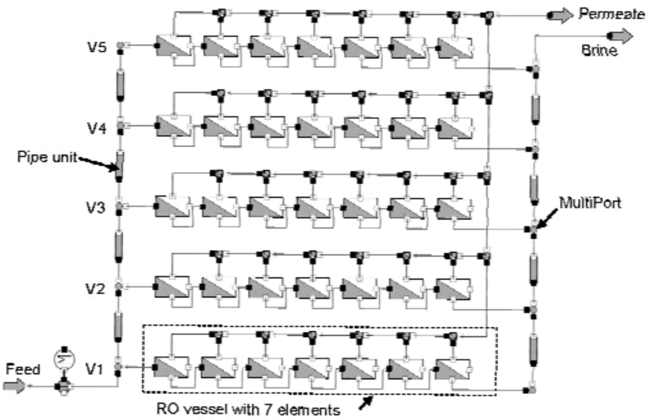

Fig. 2. IPSEpro flowsheet with five pressure vessels.

Table 1
Comparison IPSEpro/IMSDesign (35°C, 40% recovery, 115.3 m^3/d product flow)

	Feed, mg/l	Permeate, mg/l	
		IPSE	IMSDesign
Ca^{2+}	470.0	0.53	0.53
Mg^{2+}	1,464.2	1.66	1.65
Na^+	12,297.2	66.98	66.52
K^+	455 .2	3.1	3.08
HCO_3^-	119.6	1.05	1.05
SO_4^{2-}	3,093.7	3.81	3.77
Cl^-	22,073.5	108.37	107.62
TDS	39,996.0	186.67	185.3

One of the great benefits of the IPSE software is that the user can decide which parameters should be fixed and which should be calculated. It is therefore possible to fix the overall total feed to permeate recovery, and the lead element flux of the first element in the first pressure vessel, and IPSE automatically calculates the feed and brine flow.

Therefore, for this investigation, it was decided to investigate the average membrane system production of a single seven-element pressure vessel as a function of the number of vessels multiported together, the multiporting arrangement (Z or U) and the size of the individual ports. The more vessels multiported together and the smaller the diameter of the ports, the greater the mal-distribution of flow and hence the lower the average production per pressure vessel.

5. Investigation parameters

Port sizes of 2.0″, 2.5″ and 3.0″ nominal diameter have been investigated, assuming the same port size in each pressure vessel, and the same feed and brine port size. The inner diameters of the ports conform to ANSI schedule 40 and the pressure vessels are arranged horizontally at 0.3 m centers. The feed water composition is equal to standard seawater [7] with 40 g/l salinity and the properties are shown in Table 2.

The lead elements flux in the first vessel is set to 34 l/m^2h, according to the Hydranautics typical design limit for an open seawater intake [6].

6. Results

6.1. *Lead element flux*

Fig. 3 shows the average permeate production per seven element pressure vessel as a function of the number of vessels multiported together in a Z arrangement. This figure clearly demonstrates that as the number of vessels multiported together increases and as the size of the port decreases, the average permeate production per vessel decreases. In all cases, the lead element flux in the first vessel is 34 $l/m^2.h$, but with more vessels and smaller ports, pressure losses mean that there is significantly less flow in the end pressure vessel, resulting in

Table 2
Feed water composition and RO stage design

Temperature, °C	35
Pressure, bar	1.8
pH	7
TDS, mg/l	40000
Cl^-, mg/l	22117
No. of vessels	1 to 7
Membranes/vessel	7
Recovery, %	40

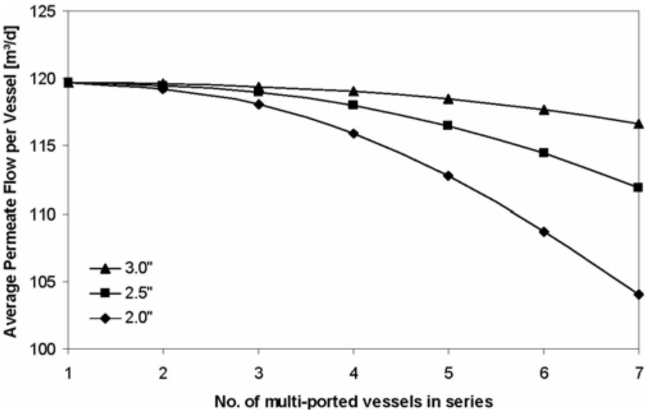

Fig. 3. Total permeate flow, divided by the number of connected vessels.

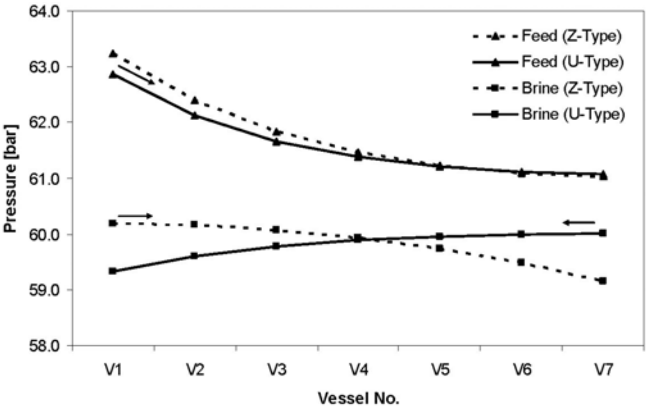

Fig. 4. Pressure in front of the vessels with seven vessels per row, 2.0″ ports and U/Z-type connection.

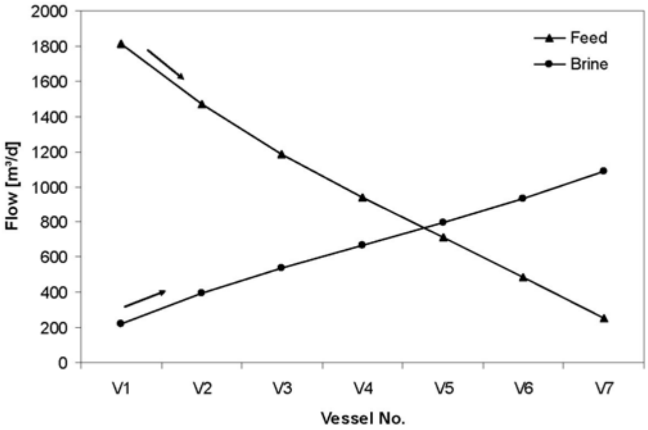

Fig. 5. Total feed/brine flow through the ports.

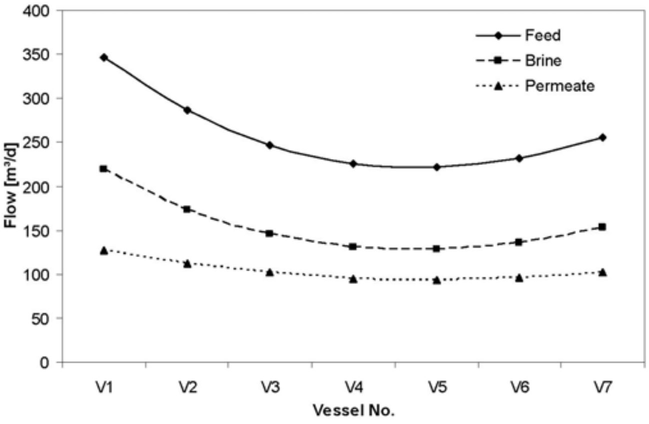

Fig. 6. Flow distribution (feed, brine, permeate) with seven multi-ported vessels and 2.0″ port size.

higher recovery and reduced productivity from the end vessels.

It is interesting to note that a typical recommendation for the maximum number of vessels to be multiported together is two for 2″, four for 2.5″ and seven for 3″ [4], in which cases you would expect to see a 0.35/1.39/2.53% reduction in average pressure vessel production to maintain maximum lead element flux in the first vessel.

Fig. 4 demonstrates the feed and brine pressure in front of the vessel. As expected, the pressure decreases with the flow direction, which is illustrated by the arrows. And because the pressure drop through a port is proportional to the square of the velocity, the slope is the highest at the feed inlet and the brine outlet connection. Thus, for the U-Type, the pressure difference from feed to brine is the highest at the first vessel and the lowest at the last vessel. For the Z-Type connection, the pressure difference at the first vessel is also the highest. But the lowest pressure difference occurs at the fifth vessel. The reason is demonstrated in Fig. 5, which shows the total flow through the ports. At the fifth vessel, the port flow at the concentrate side is higher than the feed side port flow. This leads to a higher pressure drop at the concentrate side and the pressure difference between feed and brine becomes higher again.

As described in Chapter 2, the pressure difference with the Z-type connection is more uniform. The highest and lowest pressure differences are 3.04 and 1.49 bar. With the U-Type it is 3.55 and 1.07 bar, respectively.

Fig. 6 shows the distribution of feed, brine and permeate flow between the different vessels for the case of seven vessels multiported together in a Z arrangement with 2″ ports. Whilst it is understood that this is not a recommended arrangement, the extreme conditions illustrate the capabilities of the simulation very well. In this figure, the feed and brine flows are the feed and brine flows dedicated to each particular pressure vessel (i.e., to the membranes inside the vessel), and not the total feed and brine flow flowing through the vessels ports. The first vessel gets the maximum feed and brine flow Feed and brine flow decrease with increasing vessel number and reach a minimum in the fifth vessel. From the fifth to the seventh vessel, a slight increase of the feed and brine flow can be observed. The flow in the seventh vessel is by far smaller than the flow in the first vessel. This behavior can be explained looking at Fig. 4. For the Z-type arrangement, the difference between feed and brine pressure reaches a minimum in the fifth vessel, from that point on it increases slightly.

The relative deviation for the feed side is +33.5% on average for the first vessel and -14.5% on average for the fifth vessel. Because the flux at the very start of each pressure vessel is the same, and the first vessel has the highest feed flow, the first vessel has the lowest recovery. Because the recovery is lower, the average feed side salinity is reduced, and hence there is a lower osmotic pressure in the first vessel. This means that the net driving pressure is higher in the first vessel, and therefore the flux.

6.2. Membrane recovery and permeate quality

Another important parameter in membrane design is the individual membrane element recovery, which should not exceed the maximum value recommended by the membrane manufacturer (some manufacturers specify this as the Beta factor rather than the single element recovery). Fig. 7 shows the cumulative recovery after each membrane element as a function of pressure vessel. As explained above, recovery increases from the first vessel to the last vessel, and this can clearly be seen in Fig. 7 where the first vessel recovery is 36.8% and the fifth vessel recovery is 42.1%. In this case, the brine TDS value for the first vessel is 63,357 mg/l, whereas the brine TDS in the fifth vessel is 70,450 mg/l.

The individual element recoveries can also be read from the IPSE output, and warning messages can be configured to occur should any element exceed the membrane manufacturer's design guideline value. The lead element recovery is displayed in Fig. 8, as a function of the number of vessels multiported together and the port size. The recovery in the first vessel decreases with the number of multi ported vessels. To keep the total recovery constant at 40 %, the recovery in the vessels with lower flow increases with the given conditions. Hence, the lead element recovery in the 5th vessel reaches 11.09 % with 2.0″ ports.

6.3. Designing port arrangement to minimise mal-distribution

An interesting benefit of the IPSE software is that it is possible to carefully design the size of the feed and brine ports in each vessel so as to minimize the flow maldistribution. This is done by using a Z arrangement, and attempting to balance the pressure drop profile on the feed side with the pressure drop profile on the brine side.

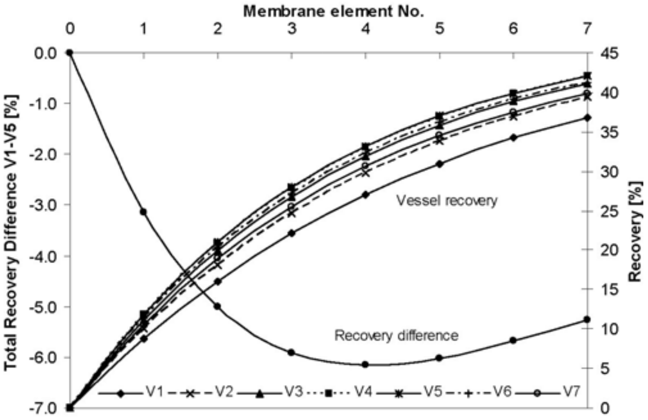

Fig. 7. Membrane recovery with seven multi-ported vessels and 2.0″ ports.

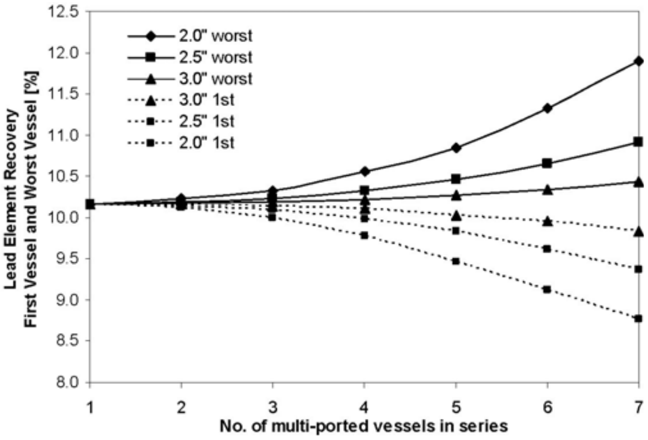

Fig. 8. Lead element recovery in the first vessel and the vessel with lowest flow as function of the number of multi-ported vessels and the port size.

As a result, the ports become smaller with the flow and the brine ports are smaller than the feed ports. This is shown for a seven-vessel multiport arrangement in Table 3. The table shows, that the deviation is reduced to only 2.35 % in total. Hence, recovery and permeate TDS are nearly equal. Compared to Fig. 3, the average permeate flow is 118.1 m^3/h.

6.4. Feed pressure

Another aspect of a multiport system which should be taken into account when making the decision as to whether to use a conventional flow distribution or a multiport system is that the higher pressure drops in the feed and brine distribution system mean that a higher feed pressure is required at the high pressure pump. In the case of five vessels multiported together with 2″ ports, the feed pressure is 2.3 bar higher.

Table 3
Effect on seven multiported vessels with adapted port sizes

			V1	V2	V3	V4	V5	V6	V7	Total
Ports	Feed	[inch]	4	3	3	2.5	2.5	2	1.5	—
	Brine	[inch]	1.5	2	2	2.5	2.5	3	3	—
Flow	Feed	[m^3/d]	297	297	294	296	292	294	290	2061
	Permeate	[m^3/d]	119	119	118	119	117	117	116	826.4
	Recovery	[%]	40.2	40.2	40.2	40	40.1	39.9	40	40.1
Δp	Membrane	[bar]	2.33	2.34	2.3	2.33	2.27	2.3	2.26	—
Permeate	TDS	[mg/l]	198	198	200	199	202	201	203	200.3
Deviation	Feed	[%]	0.92	1	0	0.58	−0.9	−0.2	−1.4	—

7. Conclusions

The IPSE software allows the integration of hydraulic and membrane simulation within a single software environment, which enables a detailed understanding of the impact of the membrane brine and feed arrangements on overall membrane performance to be quantified. Without this software, the designer has to rely on rules of thumb, and has to assume that design rules of thumb will result in acceptable membrane performance.

The IPSE software allows the disadvantages of poor flow distribution with a multiport arrangement to be compensated for by the membrane design (i.e., addition of pressure vessels) such that the membrane design guideline values are not contravened. It also allows a proper evaluation of the hydraulic losses in the feed and brine distribution arrangements, which must be compensated for in the design of the pressure generation system. All of these factors should be taken into account when making the decision as to whether to use a multiport arrangement or a conventional arrangement.

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