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| **MULTI-PORT RO PRESSURE VESSEL HYDRAULICS** |

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# Introduction and Purpose

RO Pressure Vessels (PVs) are often multi-ported together, such that the feed to multiple vessels enters the first vessel, which take the portion of feed it requires, and the remainder passes through a side port in the first vessel into the next vessel. It is very common for maybe 4 or 5 vessels to be multi-ported in this fashion. The brine is collected from the far end of the PVs in a similar fashion, with all the brine from the vessels being collected and exiting through the side port of the last PV in the series.

As the water flows through the ports, it loses pressure due to the headloss incurred from contraction and expansion. Consequently, the feed pressure in each of the vessels multi-ported together is not the same, and in the same way, the brine pressure in each of the vessels is also not the same. Because of this variation in feed and brine pressures between vessels, the feed to brine pressure drop (DP) is different in each of the PVs making up the multi-port set. Because it is this DP that drives the feed flow from the feed end of the vessel to the brine end of the vessel, there will consequently be a different feed flowrate in each of the PVs. A PV with a low feed flow will see a higher permeate to feed recovery ratio, whereas one with a higher feed flow will see a lower recovery. The purpose of this Design Guide is to evaluate the variability in flow / recovery between the PVs to establish whether or not the design is acceptable.

# Vessel Arrangement

## Vertical vs. Horizontal Ports

Full venting of air from a PV before pressurisation is critical. If air remains in the PVs, then there is the possibility of air hammer occurring, which can cause mechanical damage to the RO membranes (broken Anti Telescoping Devices, broken end adapters, abrasion of active membrane layer, feed spacer protrusion). In addition, if the air reaches the PX Energy Recovery devices during pressurisation, it is possible to shatter all of the PX rotors.

During the start-up sequence, any air in the PV will tend to get pushed to the brine end of the PV by the water flow. Therefore, the best vessel arrangement for venting is to have the brine exiting the vessel vertically through the top side of the PV. If the PVs are arranged with horizontal ports, then an air gap will remain in the PV above the soffit of the port, which can only be removed by dissolution of the air under pressure. For this reason, it is strongly recommended that the multi-ported PVs are arranged vertically, with the brine exiting from the top of the top vessel.

## U-Flow vs. S-Flow

U-FLOW

S-FLOW

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Figure 1 Illustration of S and U Flow Regimes

Figure 1illustrates the S and U-Flow regimes. In the left-hand image, the S-Flow, the feed flow enters from the bottom of the bottom PV and the brine exits from the top of the top PV. In the right-hand image, the U-Flow, the feed enters from the top of the top PV and the brine exits from the top of the top PV.

Because the most significant headloss occurs when the flow passes through the ports, the feed pressure is greatest in the first PV in the direction of flow and the brine pressure is greatest in the first PV in the direction of flow. Therefore, with the S-Flow arrangement, the maximum feed pressure occurs in the same PV as the maximum brine pressure. However, with the U-Flow arrangement, the maximum feed pressure occurs in the same PV as the minimum brine pressure. Therefore, the flow distribution is much better with an S-Flow arrangement, and this is the recommended arrangement.

Note: the system with multi-port RO PVs is not the same as a normal header, such as is the case with headers feeding multiple energy recovery PXs. In the case of the PXs, there is very little headloss due to the water flowing along the distributer pipe (because the pipe is relatively short and without flow restrictions) and by far the greatest impact on pressure comes from the flow velocity. In this case, the fastest flowing feed flow should be matched with the fasted flowing outlet flow, making the U-flow arrangement preferable. With multi-port RO PVs, the restriction between vessels (the ports) causes a significant headloss and it is best to match the inlet which has passed through the most restrictions with the outlet flow which has passed through the most restrictions, making the S-Flow arrangement preferable.

# Hydraulic Analysis

The arrangement for the hydraulic analysis is shown in Figure 2, for a 4-vessel multi-port arrangement. The feed flow is fed from the feed header pipe at pressure F0 and flows into the bottom vessel, where the pressure is F1. The feed pressure then drops through each PV in turn, to F2, F3 and F4. On the brine side, the brine pressure in the bottom vessel is B1, and this drops to B2, B3 and B4 as the brine flows up through the vessels. Finally, the brine is collected in the brine header pipe, with a pressure of B5.

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B5

B3

B2

B1

B4

F4

F3

F2

F1

F0

Figure 2 Arrangement for Hydraulic Analysis

Starting from the feed header pipe, the pressure is F0. Looking at the feed flow only, there is a pressure drop between F0 and F1 due to the flow of water through the restriction caused by the connection from the vessel port to the header. Approximately ¼ of the feed flow flows along the bottom vessel, PV1, and the remainder passes through to F2, with a further headloss due to the ports. This repeats until the final approximately ¼ of the flow enters the top PV with pressure F4, and flows along PV4.

A similar pattern can be seen at the brine end. The flow from the feed in the bottom vessel at F1 loses the feed-brine pressure drop and reaches the brine end of PV1 with a pressure of B1. There is a headloss from B1 to B2 as the brine flow from the bottom vessel flows into PV2 caused by the ports between PV1 and PV2. The difference in the feed pressure, F2, to the brine pressure, B2, in the second PV drives the feed flow along PV2. This pattern is repeated up to the top vessel PV4, with a brine pressure B4. Finally, the brine flows out of the top PV, with an additional headloss, to reach a final brine pressure of B5.

There are two primary pressure drops in this system: the pressure drop caused by the PV ports; and the feed to brine pressure drop caused by flow along the PV. To model this system, the flows in each vessel must be adjusted so that the pressure drops caused by flow along the vessel match the difference in the feed and brine pressures caused by flow through the ports.

## Pressure Drop Through Ports

The pressure drop between two adjacent pressure vessels can be estimated as the headloss of a sudden contraction followed by the headloss of a sudden expansion. The size of the contraction is the internal diameter of the port. The expanded size is far more complicated. It comprises the head space of the pressure vessel. The flow exiting from the upstream vessel port has a high velocity, which if it were directed directly at the downstream port, would reduce the overall headloss (which is based on steady flow been attained in the larger pipe). However, this flow is directed at the permeate connector, which will tend to diffuse the velocity from the upstream port. It is therefore a reasonable assumption to model the headloss as flow from a pipe with the diameter of the pressure vessel, followed by a sudden contraction, followed by a sudden expansion to pipe with the diameter of the pressure vessel. The arrangement is shown in Figure 3



Figure 3 Hydraulic Model for Port Headloss

The headloss can be calculated from the resistance coefficient, K, and the velocity head, v2/2g. Therefore,

Where,

* Δh = headloss (m)
* v = average velocity (m/s)
* g = acceleration due to gravity (9.81 m/s2)
* K = resistance coefficient

The resistance coefficient for sudden contraction is given by Crane[[1]](#footnote-1)

Where,

* d1 = the smaller internal diameter (port)
* d2 = the larger internal diameter (pressure vessel)

Similarly, the resistance coefficient for sudden expansion is given by Crane[[2]](#footnote-2)

Table 1 presents the internal diameter of schedule 40 ports and the contraction/expansion resistance coefficients based on a larger diameter of 200mm (the internal diameter of standard RO pressure vessels).

Table 1 Port Sizes and Resistance Coefficients

|  |  |  |  |
| --- | --- | --- | --- |
| Nominal Port Size (“) | Sch 40 ID (mm) | Contraction K | Expansion K |
| 1 | 26.6 | 0.491 | 0.965 |
| 1.5 | 40.9 | 0.479 | 0.918 |
| 2 | 52.5 | 0.466 | 0.867 |
| 2.5 | 62.6 | 0.451 | 0.814 |
| 3 | 77.9 | 0.424 | 0.720 |
| 4 | 102.3 | 0.369 | 0.545 |

## Flow and Pressure Drop Along the Pressure Vessels

The flow of feed water along the pressure vessel is dictated by the available pressure drop (DP) between the feed and the brine, and this in turn impacts on the permeate flowrate and recovery. With increasing DP, the feed flowrate increases, which increases the permeate flowrate (because the brine osmotic pressure is reduced) and reduces the recovery ratio.

To be able to evaluate the variation in flows caused by the hydraulics of the multi-port system, it is necessary to create functions for the feed flow into the pressure vessel and the permeate production of the pressure vessel against the feed to brine pressure drop (DP).

This function depends on the system design (water quality, flowrates, feed pressure, recovery, type of membrane, number of elements etc.) and needs to be generated for the specific design being evaluated.

Generally, a 2nd order polynomial function with DP as the x-axis and single vessel feed flowrate as the y-axis gives a suitable correlation. Although permeate flow can also be plotted against DP, a better correlation coefficient is achieved if the permeate flow is plotted against feed flow. An example is provided in Figure 4 and guidelines on generating this data for different projection softwares are provided in the following sections. (Note Figure 4 is pasted as an excel workbook so that the values in the top left table can be updated and the chart and regression analysis will automatically update).



Figure 4 Single Vessel Flowrates vs DP

In all cases, the system design projections should be created normally. The feed pressure and membrane design for a single vessel should then be taken from these projections. The feed pressure is fixed and the DP adjusted to give different feed and permeate flows, which can then be entered in Figure 4. For seawater systems, nominal flowrates of 2 to 12 m3/hr per vessel should be adequate for the vast majority of system designs.

### Procedure Using WAVE

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Figure 5 Fixing Feed Pressure in WAVE

In WAVE, the feed pressure can be fixed simply by entering the value in the field indicated in Figure 5 and this value should be used for all cases.

The nominal feed flow can then be varied from 2 m3/hr to 12 m3/hr in steps of 2 m3/hr by entering the appropriate value in the “Home” tab (as indicated in Figure 6).

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Figure 6 Entering Feed Flow in Home Tab

The feed flow, permeate flow and DP can then be read from the summary report table, as indicated in Figure 7 and entered in Figure 4.

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Description automatically generated

Figure 7 RO Flow Table from WAVE

### Procedure Using IMSDesign

With IMSDesign, it is not possible to fix the feed pressure – instead, it is necessary to fix the permeate flow and then adjust the recovery to achieve the required feed pressure. Permeate flows of 1.5, 2.3, 3.1, 3.9, 4.7 and 5.5 m3/hr generally give good data for the majority of seawater system designs.

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Figure 8 Enter Membrane Design and Permeate Flow in IMSDesign

Enter a single element of the design configuration in the Design tab (as indicated in Figure 8) and then enter each of the permeate flows to be evaluated. The permeate recovery is then adjusted, the projection run, until the required feed pressure is achieved (as indicated in Figure 9). The feed flow and DP (calculated by difference between feed and conc pressures) can then be entered in Figure 4).

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Figure 9 IMSDesign Calculation Results

### Procedure Using TorayDS

With TorayDS, it is not possible to fix the feed pressure – instead, it is necessary to fix the permeate flow and then adjust the recovery to achieve the required feed pressure. Permeate flows of 1.5, 2.3, 3.1, 3.9, 4.7 and 5.5 m3/hr generally give good data for the majority of seawater system designs.

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Figure 10 Procedure with TorayDS

Enter the membrane type and number of elements per vessel with a single vessel design and then enter the required permeate flowrate (eg 1.5, 2.3, 3.1, 3.9, 4.7, 5.5 m3/hr) in the appropriate fields. Then adjust the recovery and calculate until the feed pressure is as required. The Stage DP, feed flow and permeate flow can then be read from the results screen and entered in Figure 4.

## Combined Hydraulic Analysis

The combined hydraulic analysis is provided in the spreadsheet given as Figure 13.

The system design is entered in the box titled “System Design” – the fields in this box are self-explanatory.

The regression analysis results for the projected feed and permeate flows as a function of pressure vessel DP are entered in the box titled “Regression Analysis”. This is a copy of Figure 4 (and can be linked to it in excel).

The box titled “Expansion and Contraction K Factors for Different Port Sizes” is used to calculate the velocity head K factors for the ports. This table is used as a look-up table, based on entering the port size (in inches) – excel then looks-up the port ID (as entered in the table) and calculates the contraction and expansion K factors. Note that the Vessel ID is actually the equivalent diameter of the flow path as explained in Figure 3. It is assumed that a value of 200mm – the internal diameter of a standard 8” pressure vessel – is an appropriate value to use for this purpose, as explained in Section 3.1.

The calculation is then performed in the boxes titled “Hydraulic Calculations”. Note that the excel sheet has been set up to be able to calculate up to 10 pressure vessels multi-ported together and the un-used vessels are blanked out (which explains why there are apparently empty boxes in the spreadsheet).

The vessel port sizes (in inches) are entered in the two rows entitled “Feed Port Nominal Size (“)” and “Brine Port Nominal Size (“)”. It is possible to enter different port sizes for each of the vessels to try and balance out the pressure drops between the feed and brine sides – however, this creates complications for the installation contractor and for spares inventory.

The “Feed Apparent Pressure (Bar)” for Vessel 1 is taken as the Feed Pressure entered in the System Design and is the starting point for the iterative calculation.

The logic flow of the calculation sequence and iteration are indicated in Figure 12. The nomenclature is indicated in Figure 11 and described below. The *{blue italics in curly brackets}* are the description in the spreadsheet.



Figure 11 Calculation Nomenclature

* QFeed = Total feed flow to the rack (m3/hr) *{Feed Flow (m3/hr)}*
* QBrine = Total brine flow out of the rack (m3/hr) *{Brine Flow (m3/hr)}*
* QPermeate = Total permeate flow out of the rack (m3/hr) *{Permeate Flow (m3/hr)}*
* NPV = total number of PVs in the rack *{Total Vessels Per Rack}*
* NMP = number of PVs multi-ported together *{Number of vessels multiported}*
* n = position number of PV – main feed is into PV 1 and main brine is out of PV NMP  *{Vessel n}*
* Qinn = flowrate (m3/hr) of feed into PV n through port *{Entry Flow (m3/hr)}*
* Qoutn = flowrate (m3/hr) of brine out of PV n through port *{Brine Flow (m3/hr)}*
* QFn = flowrate (m3/hr) of feed flow into the membranes in a single PV in position n *{Vessel Feed Flow (m3/hr)}*
* QPn = flowrate (m3/hr) of permeate flow from the membranes in a single PV in position n *{Vessel Permeate Flow (m3/hr)}*
* QBn = flowrate (m3/hr) of brine flow from the membranes in a single PV in position n *{Vessel brine Flow (m3/hr)}*
* PappFn = the apparent gauge pressure (Barg) of the feed in PV n *{Feed Apparent Pressure (Bar)}*
* PappBn = the apparent gauge pressure (Barg) of the brine in PV n *{Brine Apparent Pressure (Bar)}*
* PtotFn = the total gauge pressure (Barg) of the feed in PV n *{Feed Total Pressure (Bar)}*
* PtotBn = the total gauge pressure (Barg) of the brine in PV n *{Brine Total Pressure (Bar)}*
* VHInn = the velocity head (m) of the feed flow flowing between the feed ports in PV n *{Feed Side Velocity Head (m)}*
* vInn = the velocity (m/s) of the feed flow flowing through the feed ports in PV n *{Entry Velocity (m/s)}*
* vXFn = the velocity (m/s) of the feed flow across PV n *{Feed Side Cross Velocity (m/s)}*
* VHOutn = the velocity head (m) of the brine flow flowing between the brine ports in PV n *{Brine Side Velocity Head (m)}*
* vOutn = the velocity (m/s) of the brine flow flowing through the brine ports in PV n *{Brine Exit Velocity (m/s)}*
* vXBn = the velocity (m/s) of the brine flow across PV n *{Brine Side Cross Velocity (m/s)}*
* ΔHInn = the headloss (m) across the feed ports connecting PV n-1 to PV n *{Entry Headloss (m)}*
* ΔHOutn = the headloss (m) across the brine ports connecting PV n to PV n+1 *{Brine Exit Headloss (m)}*
* ΔPInn = the pressure drop (Bar) across the feed ports connecting PV n-1 to PV n *{Not in Excel Sheet}*
* ΔPOutn = the pressure drop (Bar) across the brine ports connecting PV n to PV n+1 *{Not in Excel Sheet}*
* ΔPPVn = the feed to brine pressure drop (Bar) for PV n. *{Feed-Brine DP (Bar)}*
* g = acceleration due to gravity (9.81 m/s2)
* ρF = feed density (kg/m3) *{Feed Density (kg/m3)}*
* ρB = brine density (kg/m3) *{Brine Density (kg/m3)}*
* Dfn = feed inlet port internal diameter for PV n (mm) *{Feed Port Nominal Size (“) – Lookup Port ID (mm)}*
* Dbn = brine outlet port internal diameter for PV n (mm) *{Brine Port Nominal Size (“) – Lookup Port ID (mm)}*
* DV = cross vessel equivalent diameter (mm) *{Vessel ID (mm)}*

The following calculations are used:

The “Entry Velocity (m/s)” is calculated from the “Vessel Entry Flow (m3/hr)” using:

Equation 1

The “Entry Headloss (m)” is then calculated by:

Equation 2

Where,

* ∑k = the Contraction K Factor + the Expansion K Factor for the inlet port to the vessel in question

Note that since the starting point for the calculation is the apparent pressure in the feed side of vessel 1, the entry headloss from the header pipe into vessel 1 has no purpose in this calculation, and the cell is therefore left blank.

The “Feed Side Cross Velocity (m/s)” is the flow velocity of feed from the inlet feed port to the outlet feed port. It is taken as the feed flow based on the equivalent diameter of the vessel, taken from the cell “Vessel ID (mm)”. The calculation is:

Equation 3

The feed side cross velocity is used to calculate the “Feed Side Velocity Head (m)” using:

Equation 4

The “Brine Exit Velocity (m/s)”, “Brine Exit Headloss (m)”, “Brine Side Cross Velocity (m/s)” and “Brine Side Velocity Head (m)” are calculated in exactly the same way as their feed side equivalent described above, but using “Brine Flow (m3/hr)” and “Brine Port Nominal Size (“)”.

Equation 5

Equation 6

Where,

* ∑k = the Contraction K Factor + the Expansion K Factor for the outlet port from the vessel in question

Equation 7

Equation 8

For both the feed side and the brine side, the following pressure relationships apply:

Equation 9

Equation 10

From Figure 4

Equation 11

Equation 12

Where aF, bF, cF, aP, bP, cP are the regression constants for feed and brine respectively in Figure 4

The following convergence function appears to work reasonably well:

Equation 13



Figure 12 Calculation Sequence



Figure 13 Combined Hydraulic Calculation

# Evaluation

As a general rule, I would consider the following, based on the most extreme value of Deviation calculated in the spreadsheet:

* Worst Deviation ≤ ± 2% - Very Good
* Worst Deviation > 2% and ≤ ± 5% - Probably Acceptable
* Worst Deviation > 5% and ≤ ± 10% - Very Poor
* Worst Deviation > 10% - Unacceptable.

Strictly speaking, the level of deviation depends on how aggressive the membrane system design is. The most thorough method of evaluating these results is to run all of the feed and permeate flow combinations in the membrane projection software to confirm that there are no design errors generated. Thus, with a very conservative membrane system design, it would be possible to accept much more variation in the flows between different pressure vessels, whereas a membrane system design on the limit requires perfect flow distribution.

1. Crane Co; Flow of Fluids Through Valves, Fittings, and Pipe Technical Paper 410; October 2010 Edition; Equation 2-16 [↑](#footnote-ref-1)
2. Crane Co; Flow of Fluids Through Valves, Fittings, and Pipe Technical Paper 410; October 2010 Edition; Equation 2-15 [↑](#footnote-ref-2)