This bulletin explains and defines the application of the mass conservation principle to the PX™ energy recovery device and its use as a valuable tool for troubleshooting PX systems. The reader is referred to Energy Recovery, Inc.'s Operations and Maintenance manuals, other technical bulletins and numerous technical papers posted on ERI's website for detailed consideration of the pressure transfer mechanism and the hydraulic performance of PX technology.

1. PX Pressure Exchanger Energy Recovery Devices

The PX device is a flow-driven positive-displacement device. A typical configuration for a Reverse Osmosis (RO) system equipped with PX technology is provided in Figure 1.

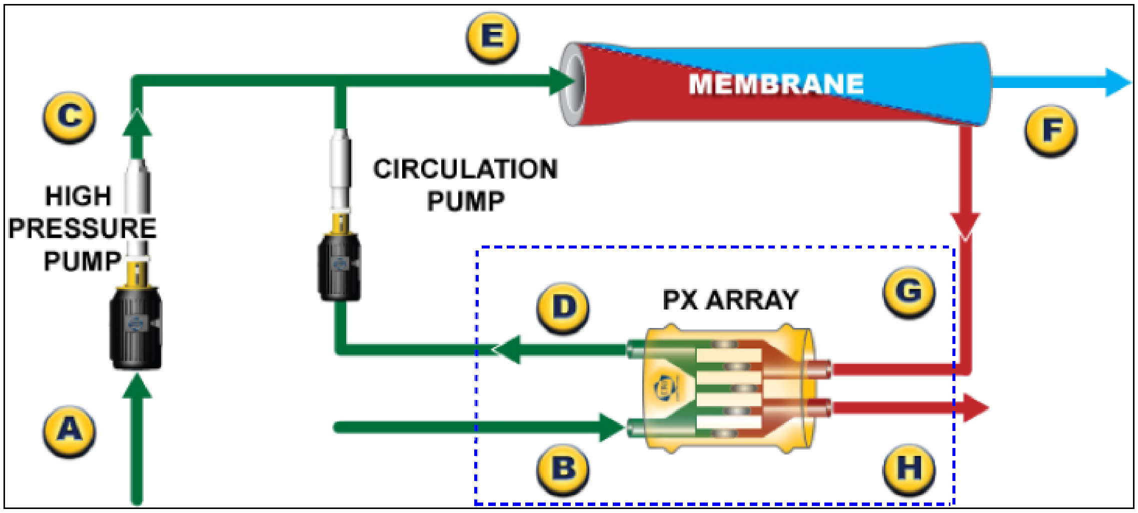


Figure 1. - RO system equipped with PX® Technology

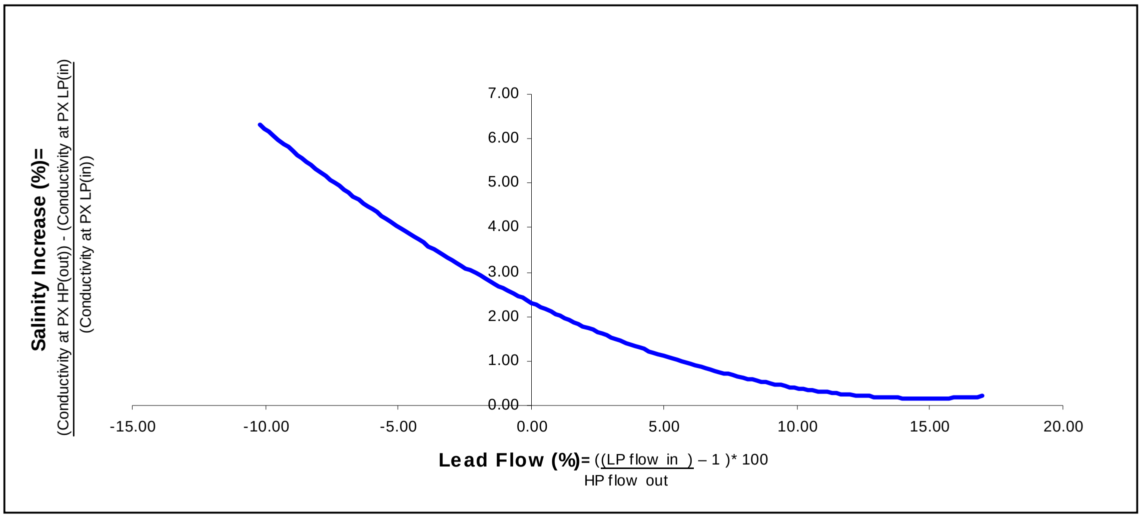
Operation and control of a PX unit or PX array in an RO system can be understood by considering two parallel pipes; one of high-pressure water and one of low-pressure water flowing in opposite directions. The high-pressure water flows in a circuit through the membranes, the PX unit, the circulation pump, and back to the membranes [E-G-D-E] at a rate controlled by the circulation pump. The low-pressure water flows from the pretreatment system, through the PX units and to the system discharge [B-H] at a rate controlled by the supply pump and a control valve in the brine discharge from the PX unit [H]. The high and low pressure flows are independent, so the RO plant must be designed for flow measuring and control of both streams.

Normally the plant operator sets the PX device flows to a balanced flow condition meaning that the measured low pressure flow entering the PX device [B] and the high pressure flow leaving the device [D] are equal. Under balanced flow conditions and typical membrane recoveries (i.e. 40%), the salinity increase at the membranes is approximately 2.5%. As a result of the inherent flexibility of the PX device, it can also be operated when the flow rates are unbalanced. An unbalanced flow condition exists when the low-pressure flow rate through the PX device does not equal the high-pressure flow rate through the device. If the low-pressure flow rate exceeds the high-pressure flow rate, the unit is said to be in a lead flow or over-flush state. Lead flow "flushes" concentrate from the PX device with extra sea water, thus reducing the salinity increase at the PX device outlet [D] and at the membrane feed. When the PX units are operated with a high-pressure flow rate greater than the low pressure flow rate – a condition referred to as lag

™ PX, PX Pressure Exchanger, ERI and the ERI logo are registered trademarks of Energy Recovery, Inc.

flow - the salinity of the membrane feed increases. Typical effects of operating in either lead-flow or lag-flow are shown in Figure 2. This relationship can be used as an important tool when optimizing or trouble-shooting an RO system and can assist in identifying inaccurate flow meter readings.

Figure 2. – Sample Salinity Increase vs. Lead Flow Curve



2. Mass Conservation Principle

The well-known mass conservation principle from classical mechanics says that the mass of a closed system will remain constant regardless of the processes acting inside the system, or simply, mass cannot be created or destroyed. Applying this definition to the figure 1, we can conclude that the PX system, which can be comprised of one or many PX units, must comply with the mass conservation principle: mass flows into the PX system through inlets [B] and [G] must equal mass flows going out the PX system through outlets [D] and [H]. Mass cannot be accumulated or originated inside the PX system.

3. Salt Mass Conservation

Flows in the PX system are also carrying or transporting salt as dissolved solids; the mass conservation principle also applies to this salt mass. Mass conservation means that the total amount of salt entering the PX from both inlets is the same as the total amount leaving the PX from both outlets. In other words, conservation of mass of salt must comply in the PX system.

Each flow stream has a different salinity due to mixing within the PX device (refer to ERI document 80088-01 Mixing Technical Bulletin). Also, each PX flow rate can be slightly different from the others. With reference to Figure 1, HP IN flow [G] equals HP OUT flow [D] plus a small amount of lubrication flow. In the same way LP OUT flow [H] equals LP IN flow [B] plus lubrication flow. Also LP and HP flows can be different since these flows are independently controlled. For further information regarding Lubrication Flow, please refer to ERI document 80171-01 PX Lubrication Flow Technical Bulletin.

Referring to the PX system enclosed by the dashed box on Figure 1, we can establish the following nomenclature:

F ≡ Flow;
S ≡ Total dissolved solids (TDS), also known as Salt concentration or Salinity.

The salt mass flow (mass of salt per unit of time) in any PX stream can be calculated as (e.g. for stream B): $F_B S_B$

Applying conservation of mass of salt in the PX system results in:

$$\text{Mass balance equation: } F_B S_B + F_G S_G = F_H S_H + F_D S_D \tag{1}$$

And substituting the following lubrication flow relations ($L \equiv Lubrication\ \ flow$) in the mass balance equation $F_B + L = F_H, \quad F_D + L = F_G$

And performing some algebraic operations, the following relations can be derived:

$$\text{Flow rate equations: } \quad \begin{aligned} F_D &= \frac{F_B(S_H - S_B) + L(S_H - S_G)}{(S_G - S_D)} \\ F_G &= \frac{F_H(S_H - S_B) + L(S_B - S_D)}{(S_G - S_D)} \end{aligned} \tag{2}$$

The above equations can be applied directly if the lubrication flow is physically measured by the plant operator. If not, the lubrication flow term can be dropped without introducing significant error because $L << F, \quad S_G \cong S_H, \quad S_B \cong S_D$. Therefore, the second term is negligible compared with the other terms in the flow rate equations. The flow rate equations therefore become simplified as follows:

$$\text{Simplified flow rate equations: } \quad \begin{aligned} F_D &= F_B \frac{(S_H - S_B)}{(S_G - S_D)} & \quad F_B &= F_D \frac{(S_G - S_D)}{(S_H - S_B)} \\ F_G &= F_H \frac{(S_H - S_B)}{(S_G - S_D)} & \quad F_H &= F_G \frac{(S_G - S_D)}{(S_H - S_B)} \end{aligned} \tag{3}$$

These equations can be used when all salinities are known and one flow meter is trusted more than the other.

Lead flow can be defined as:

$$LEADFLOW \equiv \frac{F_B - F_D}{F_D} = \frac{F_B}{F_D} - 1 \tag{4}$$

and substituted into the flow relations above:

$$LEADFLOW = \frac{S_G - S_D}{S_H - S_B} - 1 \tag{5}$$

$$LEADFLOW = \frac{HPIN_{TDS} - HPOUT_{TDS}}{LPOUT_{TDS} - LPIN_{TDS}} - 1 \tag{6}$$

If the value obtained with the above equation is a positive value, it means that the LP flow is higher than the HP flow. If the HP flow is higher than the LP flow, the value obtained will be negative.

4. Application of the Mass balance equations

Accurate and reliable instrumentation, especially flowmeters, is a key factor for regulating and controlling the water recovery rate, permeate production rate and other parameters in RO systems. Sometimes bad flowmeter installation, miscalibration or instrument malfunctioning can lead to inefficient operation of a RO plant. Inaccurate flowmeter readings on either PX device LP or LP streams will create unbalanced flow, inaccurate recovery rate indications and could also result in overflow through the PX system. Overflow can produce damage on the PX ceramic components while unbalance flow can create high volumetric mixing, leading to a high salinity at membranes feed and higher operating pressure.

A quick way to verify if the PX system is balanced is to use the LEADFLOW equation (6). It is necessary to take samples of all the four PX device streams to calculate it. As per its definition, the LEADFLOW value compares the LP flow to the HP flow. Therefore positive lead flow values indicate that LP flow is higher than HP flow. In the same way, negative lead flow or lag flow values indicate that HP flow is higher than LP flow. Lag flow increases the degree of mixing and can lead to the incorrect assumption that a problem exists with the PX units.

If the process flowmeter readings show a balanced flow condition (zero LEADFLOW) and the salinity-calculated LEADFLOW is non-zero, the salinity mass balance can help us to calculate the real flow rate. We can use flow rate equations or simplified flow rate equations described in section 3 above. ERI's field experience has demonstrated that differences between both equations are insignificant, so the simplified equations can be used without introducing any significant error. It will be necessary to take samples of the four PX device streams and use one of the flowmeter readings, the more trusted one, as a base for the calculation. According to ERI experience, HP flowmeters are less reliable than the LP flowmeters.

5. Conclusions and Recommendations

- Salinity balance equations are a useful tool to verify flow rates through a PX system. As they are an application of the mass conservation principle, they apply to any system using PX technology regardless of system configuration i.e. single stage, multiple stages or hybrid reverse osmosis systems. The equations are also applicable in the unlikely event of PX unit(s) malfunctioning.

- All the salinity readings need to be taken with the same instrument to minimize measurement error. ERI recommends using a hand-held high-quality conductivity meter with TDS conversion features. The application of these equations using conductivity values can result in excessive error on the calculated values. If TDS readings are not available, the conductivity should be converted to TDS using the temperature and a seawater equation of state.

- ERI has learned over the years that the best way to get an accurate flow readings is by using a flowmeter properly installed and calibrated as per the manufacturer instructions. A calculation based on salinity is only a good approximation when used as troubleshooting tool.