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Forward osmosis for applications in sustainable energy development

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ABSTRACT

Forward osmosis (FO) provides a method of harvesting the osmotic potential difference between fresh and saline waters to produce electricity. FO occurs when fresh water and saline water are placed on opposite sides of a semi-permeable membrane. When this occurs water naturally flows from the freshwater side of the membrane to the saline side. This water flux continues until the osmotic pressure difference on both sides of the membrane equalize. The water flux will cause the pressure to increase in the saline water. If the saline water is seawater the pressure can reach as high as 410 psi. This pressure can be harvested as hydraulic power, similar to that of a hydroelectric dam. Such a system is called pressure retarded forward osmosis (PRO) and it can be used anywhere fresh water mixes with saline water. The worldwide potential energy of this resource, based on locations where rivers mix with oceans, is reported to be in excess of 1600 tera-watt-hour (TWH) per year [1]. In arid regions, such as California, where few major rivers reach the ocean, the applicability of PRO is limited. In these regions it makes sense to look for alternative sources of fresh water. This project evaluates an approach where, rather than siteing a PRO power plant in ways that potentially impact sensitive costal environments, they are sited at wastewater treatment plants that discharge into the ocean or other sources of saline water and are effective in a comprehensive environmental management and design role. Electricity can then be generated from the mixing of the treatment plants outfall and seawater while providing a high level of additional treatment and environmental protection. In the state of California alone, 1,350 million gallons per day of treated municipal wastewater is discharged into the Pacific Ocean. Using PRO this represents about a 26 megawatt resource. In addition to the electricity produced, the PRO also provides tertiary treatment of the wastewater treatment plant's outfall. It is comparable to treatment with reverse osmosis membranes. The combination of PRO and tertiary treatment (PRO/TT) provides the mutual benefit of sustainable power production and advanced wastewater treatment. This is particularly important in locations where regulation is requiring treatment plants to tertiary treat wastewater. PRO/TT can be used to offset the cost of providing treatment by generating electricity that can be sold for profit or used to help power the treatment plant.

Keywords: Forward osmosis; Pressure retarded osmosis; Osmotic power; Osmotic wastewater treatment; Water/power nexus

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1. Study background and team

This study is the result of a Google/NASA ARC collaboration on forward osmosis based power generation and simultaneous wastewater treatment, and is a spin-off of space life support research. NASA has been supporting FO research and development since 1993 [2]. This research has contributed to the development of some of the first viable FO membrane processes.

Another important collaborator in this research is Hydration Technology Innovations LLC (HTI). HTI is one of the original commercial developers of FO. NASA has been intermittently collaborating with HTI since 1993. HTI now markets a number of commercial FO based water treatment products and provided the membrane used in this test program, and is an integral member of this research team.

This research group is not the only organization currently researching PRO. There are several university and private organizations conducting ongoing research in this field. One of the most notable of these is the Norwegian company, Statkraft Inc. In November of 2009 Statkraft commissioned the first PRO pilot demonstration plant in Tofte, Norway. This unit combines river and seawater to produce electricity. NASA representatives from this research group were among those attending the commissioning of this facility and are actively supportive of this work as well.

2. Osmotic power theory

Osmotic power utilizes the osmotic pressure difference between a high total dissolved solids (TDS) water (i.e. saltwater) and a low TDS water (freshwater) to generate a hydrostatic pressure difference between the two water streams. This pressure difference is then harvested to generate power. The hydrostatic pressure difference is generated across a semi-permeable membrane by allowing forward osmosis water flux to occur through the membrane. The passive resistance the membrane applies to the water flux is then available as hydrostatic pressure (referred to as hydrostatic head). This hydrostatic head is then used to drive a conventional water turbine to generate mechanical power that is then transferred via the turbine shaft to an electrical generator for electrical power production.

Power output from any hydrostatic source is given by the following relationship [3]:

$$W_p = \eta(\lambda QH/1000) \tag{1}$$

where η is the pump/turbine efficiency; λ is the inverse of the water density (N/m^3); Q is the quantity of the water passed through the turbine (m^3/s); H is the hydrostatic head (pressure) difference across the turbine (m of equivalent water column height).

Turbine efficiency is determined by water turbine type, but can be assumed to be in the range of 50–90% for lower pressure turbines.

Total osmotic potential can also be calculated, and will vary with total dissolved solids (TDS) concentration and ionic species (type of salt ions) in the water [4]. The osmotic pressure, π, can be calculated using the following relationship [5]:

$$\pi = iMRT \tag{2}$$

where i is a dimensionless factor related to the disassociation of the solute molecule. For most non-electrolytes solutes it is equal to 1. For most ionic compounds it is equal to the number of discrete ions in a formula unit of the substance. M is the molarity of the solution (moles/L); R is the gas constant 8.314472 (L kPa·mol^{-1}·K^{-1}); T is the temperature (K).

Using these methods and a 35 g/l as NaCl approximation for seawater TDS gives a total osmotic pressure of 2.8 MPa (or 410psi) for seawater.

Total flow is referred to as flux in the context of membrane system design. It can be measured directly or calculated. Flux across the membrane is given by [6]:

$$F_w = A_c\left(\Delta\pi - \Delta P\right) \tag{3}$$

In this relationship, F_w is the total water flow across the membrane (l/m^2 h), A_c is the membrane flux resistance constant (L/m^2 h atm), $\Delta\pi$ is the osmotic pressure (atm), and ΔP is the opposing hydrostatic pressure (atm). It should be noted that A_c is not in fact a constant even in pressure driven reverse osmosis (RO), and becomes particularly variable in diffusion-mediated processes (i.e. FO). For this reason empirical determination of F_w for specific input waters (fresh/wastewaters) and draw solutions (saltwaters) is recommended and justifies the portable test stand approach to this research.

Actual power density targets (i.e. expected W/m^2 values for membrane performance) depend strongly on the specific process application input water, both on the saltwater and freshwater side of the membrane. Municipal wastewater to seawater contactor theoretical values are approximated using the following relationship [7]:

$$W = F_w\left(\Delta\pi - \Delta P\right) \tag{4}$$

where F_w is the volumetric water flux (L/m^2 s); $\Delta\pi$ is the osmotic pressure (N/m^2), ΔP is the opposing hydrostatic pressure (N/m^2).

3. Wastewater treatment

Several important possibilities present themselves when one moves from the large-scale hydropower arena to the micro-power wastewater cogeneration frame of reference. First, the act of using a membrane to do FO is a form of water treatment even if it is also generating power simultaneously. If used as a tertiary treatment to a wastewater treatment plant outfall at an ocean or estuary, the membrane is as selective as it would be operating in a reverse osmosis, or more accurately based on membrane selectivity ultrafiltration (UF) treatment mode. This means essentially, high levels of rejection of solids, bacteria, viruses, inorganics, and metals as well as partial rejection of organics, depending on the species. If the much smaller reject brine is pond or wetland treated then the entire wastewater stream can receive high levels of tertiary treatment while generating osmotic power.

Many wastewater treatment facilities in sensitive brackish water environments are required to perform advanced treatment prior to discharge. Using a forward osmosis membrane at the discharge point could provide highly advanced tertiary treatment capable of meeting stringent discharge standards, while generating a portion of the power required to operate the rest of the wastewater treatment process.

The same cogeneration principle could be used in more highly contaminated water at industrial facilities. Currently many facilities use evaporation basins for the sequestration and concentration of inorganic industrial wastes. These ponds are required to evaporate and concentrate these wastes to a manageable high solids product. If the input system to such ponds was carefully managed, osmotic power could be harvested from these ponds as they received more dilute industrial wastes to concentrate. Because the TDS concentration in these evaporation ponds is so much higher than natural seawater, this process could generate far higher power densities than seawater applications.

4. Experimental apparatus and methods

The experimental apparatus was developed around the use of a small custom built cross flow filtration membrane contactor and two re-circulating fluid streams. The feed, which was composed of treated sewage (secondary effluent), was re-circulated on one side of the membrane and seawater on the other. The osmotic potential difference between these two fluids causes water to flux across the membrane from the feed and into the seawater. This continues until the osmotic pressure difference between the seawater and secondary effluent equalizes. As water moves across the membrane it is contained so as to increases the hydrostatic pressure of the seawater. This pressurized seawater is then used as the energy source for the PRO process.

In these tests, the feed was composed of secondary treated wastewater from a local treatment facility. Seawater was approximated with a NaCl solution of 35 g/L, to maintain analytical consistency as actual bay water TDS near the location of the selected wastewater source varies slightly over time. The testing was designed to determined power densities and membrane performance that is achievable from secondarily treated wastewater. Bench scale values for membrane element performance in terms of output pressure $\Delta\pi$ (osmotic pressure) and water flow across the membrane per unit area (F_w in l/m^2h) as a function of time were measured. Feed conductivity (EC) and hydraulic pressures were also measured. Because this is a simplified batch testing system, EC measurement is required to track the effects of dilution of the saltwater draw solution over the length of any given test run. Dilution allowed should be limited to the actual variability noted for the source saltwater being tested (as determined by previous environmental monitoring), and can be tracted for each pressure and flux measurement.

The experimental apparatus consisted of a membrane contactor, two pumps to re-circulate the feed and seawater through the contactor, a pressure reservoir to hold the seawater at pressure, a scale to measure the flux of water, and a back pressure valve to pressurize the seawater side and simulate a hydraulic turbine. A flow diagram of the experimental apparatus is shown in Fig. 1 and a picture of the test stand is provided in Fig. 2.

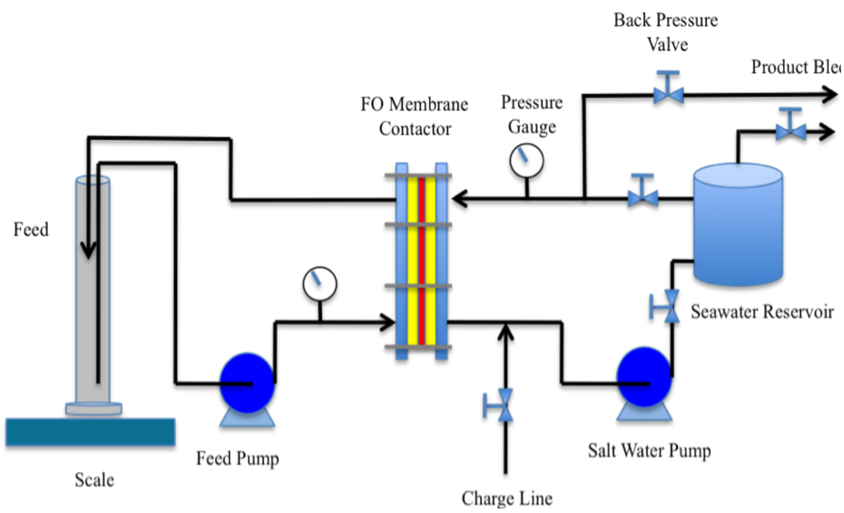

Fig. 1. PRO\TT flow diagram.

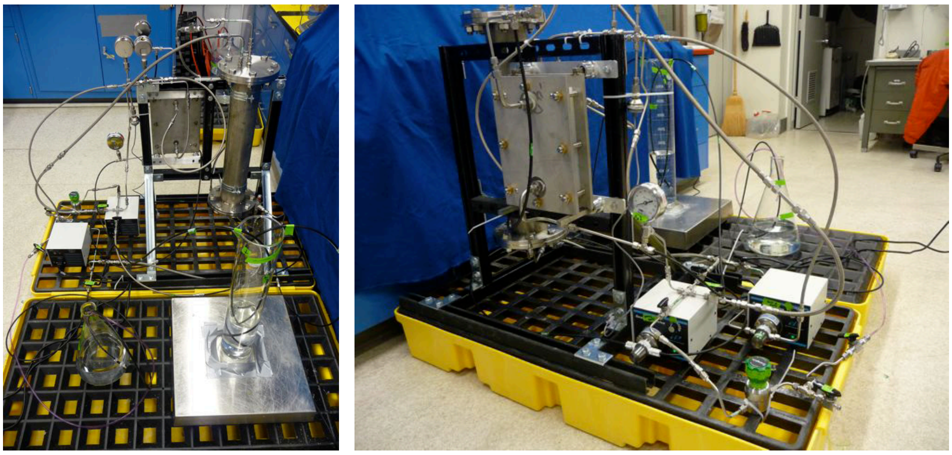

Fig. 2. FO power membrane test rig.

The feed was placed in a 4 L graduated cylinder, and the cylinder was placed on a scale. A feed pump (Cole Parmer, 75211-10 and Micropump, 81808) re-circulated the feed from the graduated cylinder to custom built membrane test cell, with a 31 in^2 (0.02 m^2) membrane area, and then back to the graduated cylinder. The simulated seawater was re-circulated by a salt water pump (Cole Parmer, 07003-4 and 7521-10) from the membrane test cell to a pressurized 5.5 L seawater reservoir and back to the test cell. The pressure of the seawater solution was measured by a dial indicator pressure gauge (Ashcrioft, 8964). A bleed was taken from the re-circulating seawater stream through the backpressure regulator (Swagelock KPRIGRB412A2000). The product of this back pressure regulator is the product of the PRO/TT.

Secondary treated wastewater was collected from the Watsonville, California wastewater treatment plant and transported to NASA Ames Research Center. The wastewater was refrigerated and stored until use. No further pretreatment or sample preservation was performed on the wastewater. Wastewater was used within 5 days of collection.

The membrane used in the test was a custom prepared HTI forward osmosis membrane. This is a special membrane developed specifically for NASA and is not identical to commercial available off the shelf elements. The membrane was placed active layer facing the feed and was sealed with a series of o-rings in the test cell.

The following procedure was used to run the PRO experimental apparatus as shown (Figs. 1 and 2).

Procedure to fill saltwater tank:

1. Verify that valve to pressure tank is in open position
2. Close the tank output valve and open valve to the charge line
3. Turn the saltwater side pump on
4. Draw saltwater into seawater tank until tank is filled and saltwater overflows through open valve
5. Turn pump off and close overflow valve and other valves including the feed line valve

Procedure to fill wastewater tank:

1. Fill wastewater tank (graduated cylinder) to 4 L and place on scale
2. Insert wastewater pick up line and return line in the wastewater flow liter vessel
3. Zero out weight on scale
4. Turn on feed pump and set back pressure speed to 10 psi
5. Verify saltwater loop uptake line and pressure release line are closed and that the product line valve is opened but the pressure regulator valve is closed

Start test:

1. Start saltwater loop line pump
2. Verify that it is set to 10 psi
3. Watch pressure gage on input side of the element (saltwater line)
4. Watch and record every 10 psi increase on salt and pressure tank side until desired operating pressure for run is achieved (Note: This is necessitated as practical equipment operations matter due to a small amount of air entrainment in the apparatus that tends to be present during start up. Recording this data provides an accurate measurement of dead volume filled at startup)
5. Set back pressure regulator valve by opening until pressure decreases slightly
6. When back pressure release valve releases at desired pressure, record start time
7. Measure weight, flow rate and EC every hour for five to six hours (Conductivity Instrument used by inserting EC probe in samples of water. YSI 3200 model number 3200-115V)

4. Results

The operating conditions of the test system are shown in Table 1. Again, the feed is secondary treated municipal wastewater from the Watsonville, CA. wastewater treatment facility. The seawater is a simulant using a pure reagent grade NaCl solution for analytic consistency. Data is provided from a total of 5 different runs. Each run is 6 h long. The system was operated in batch mode, meaning the feed was re-circulated through a feed tank and no new feed was added during a run. As a result the feed was concentrated during the length of the experiment, and the feed conductivity approximately doubles during a run (Fig. 3).

The seawater was also re-circulated through a seawater tank and its composition also changed during the run. A small amount of the salts from the seawater leak back across the FO membrane into the feed, thus slightly reducing the seawater salinity during the run. In addition, a bleed was taken from the seawater side during the test by the back pressure valve. This bleed contains salts that when removed act to dilute the seawater. As a result, during a run the osmotic potential of the feed increases and that of the seawater decreases. Thus the osmotic potential difference between them decreases. As it decreases, the flux of water through the membrane and the resulting power density also decrease. Operating values are given in Table 1.

There is change in power density of the membrane as a function of run time. The power density decreases by about 40% during a run. Most data shows good agreement, with a standard deviation of 0.02 W/m^2. The data at the last data set, at 5 h, shows increased variability, with a standard deviation of 0.06 W/m^2. It is not known why this variability exists but experimental issues are suspected. Membrane fouling is not indicated as hour 5 data shows random trends rather than sequential decrease as a result of exposure to the feed.

The power density during each run ranged from as high as 0.89 W/m^2 at the start of the run down to 0.20W/m^2 at the end, with an average of 0.23 W/m^2. Water was produced at an average of 3.6 L/m^2 h. The total water recovery ratio achieved in 6 h was 15%.

Table 1
Experimental operating ranges and values

Pressure (psi)	62 ± 2
Feed initial volume (L)	4 ± 0.1
OA initial volume (L)	5.5 ± 0.1
Feed	
Flow (L/h)	108 ± 12
Salinity input (mS)	1.85
Salinity output (mS)	39.56
OA	
Flow (L/min)	51 ± 9
Salinity start (mS/cm)	48 ± 0.1
Salinity end (mS/cm)	2.43 ± 1.1
Product flow (L/h)	0.13 to 0.06
Water flux	
Range (L/m^2 h)	7.3 to 1.6
Average (L/m^2 h)	3.6
Power density	
Range (W/m^2)	0.89 to 0.4
Average (W/m^2)	0.87
Power density (Wh/gal)	0.23 ± 0.01

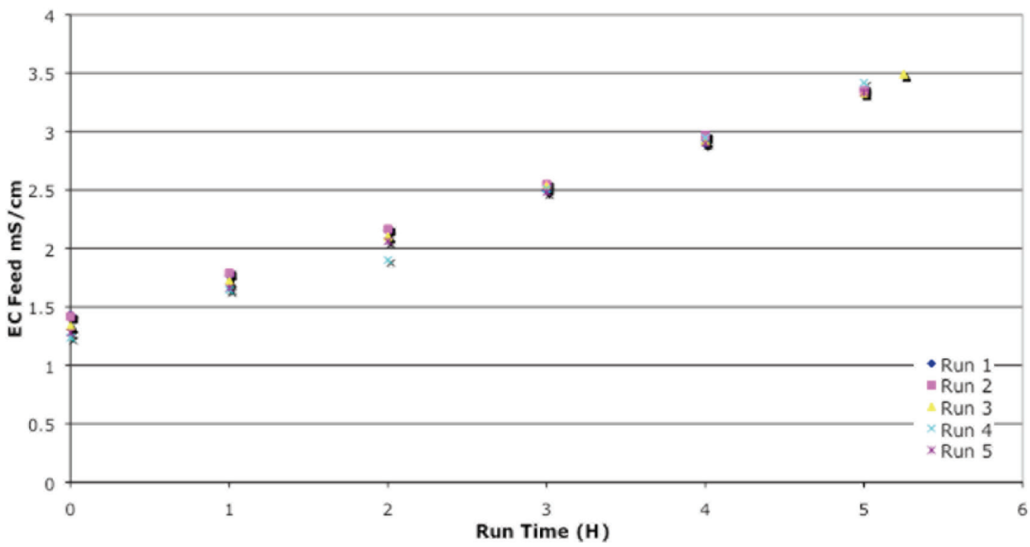

Fig. 3. Electrical conductivity of feed as a function of time.

4. Conclusion

These experiments have shown that the PRO/TT process is conceptually feasible. Secondary treated municipal wastewater was treated using the process. PRO/TT testing at 62 psi gave initial membrane power densities of up to 0.89 W/m^2 and end of batch run power densities of 0.4 W/m^2 when using secondary effluent and simulated seawater. This indicates an average volumetric power density of 0.06 W-h/L when projecting power potential in terms of input flow. This value of 0.06 W-h/L equates to about 0.23 W-h/gal. This is the power density of the membrane only and neglects the inefficacy of the membrane and of generating electricity or pumping input power requirements to flow both the saltwater and wastewater water through the system.

Actual power densities will be a function of process design. For instance, operating at a high water recovery ratio counter intuitively produced volumetric power densities on the order of 0.125 W-h/L while operating at low water recovery ratios produced densities closer to 0.06 W-h/L. In addition, most proposed commercial PRO system designs (there are in fact no truly commercially viable operational PRO systems at this time) operate in a continuous flow mode. The system tested was operated in batch mode. Extrapolating variable batch operating data to a continuous flow system is problematic. For simplicity, it is assumed that the average of the batch data is the expected performance of the system. However, a more thorough assessment of the data may make more sense for a given system design operating at a constant recovery ratio.

As some initial reporting on this project is available and states potentially much higher membrane power densities, some clarification on the projection of these values is warranted. As stated in the results, the power density during each run ranged from as high as 0.89 W/m^2 at the start of the run down to 0.20 W/m^2 at the end, with an average of 0.23 W/m^2. Water was produced at an average of 3.6 L/m^2 h. The total water recovery ratio achieved in 6 h was 15%. However, some initial findings were reported at high values for flux (14.7 L/m^{2}h) resulting in power density (1.78 W/m^2) and watts per gallon projections (0.46 Wh/gal) being equally inflated. The difference in these figures is simple but critically important in understanding the results of this and other studies relating to membrane power density and flux.

The difference in these figures is simply the application of a 50% effective membrane area reduction factor based on support mesh in the element in early reporting. This produces a higher projected performance value for the membrane in the remaining area. Retrospective examination of the data resulted in the removal of the effective membrane area correction factor. The researchers believe the values reported here are much closer to actual expected performance of elements in engineering and economic analysis.

But this also points out how large a discrepancy can result between laboratory membrane efficacy research projections, which are directed at the removal of all shape factors to projecting membrane flux, and testing for actual fieldable membrane element engineering projections. It also demonstrates the potential for greatly over estimating membrane performance by applying shape factors that are overly aggressive and not reflective of real elements anyway. We endeavor here to be as transparent as possible to remove any ambiguity in using our results to do engineering projections, thus we take no projected element inefficacy correction into account, and leave such analysis up to the designer using our values. With this in mind, the reader can be assured that the membrane performance projected here is highly conservative.

5. Disscussion

The membrane power density ranged from 0.89 to 0.2 W/m^2 during this test. Power densities reported in the literature using freshwater as a feed range from as high as 4–0.11 W/m^2 [8–11]. Low-pressure power densities range from 2.3 to 0.11 W/m^2 [7]. Thus the results of this testing are within the range of expected low pressure values.

The 0.06 W-h/L (0.23 W-h/gal) volumetric power density can be used to estimate the size of a PRO/TT plant. For example, a large municipal sewage treatment plant, such as the San Jose/Santa Clara plant, produces as much as 167,000,000 gal/d of effluent. This equates to about 1.6 MW of potential energy. At $0.10/kW-h this has a value of $1.4 M/y.

This value does not take into account the cost of building or operating a PRO/TT plant. Also, the projected effects of parasitic losses on overall power production are still poorly documented and are hard to develop without full scale membrane elements and plumbing pilots (see future work). It merely indicates the level cogeneration return values for assessing the feasibility of the plant. However, when assessed using a multiple pay back approach that also benefits from increased treatment performance and compliance to more stringent discharge standards, some models for application of this technology may be currently feasible. However, this will require both future assessment of this data using site specific and targeted economic modeling, as well as longer term testing of the membranes on specific effluents.

6. Future work

The results of this testing have shown that the treatment of secondary treated municipal wastewater using the PRO/TT process is possible. The next logical step is to develop the process to a level appropriate to evaluate its feasibility under more realistic operational conditions. The work covered in this report has been conducted as a bench scale feasibility test to evaluate potential power densities and membrane operability that is achievable for osmotic power from wastewater. The next step in the development of the technology is the construction of a continuous flow prototype that can be operated for longer durations and at scale to determine operational parameters such as actual power (i.e. parasitic losses), cleaning and pretreatment requirements, operational costs, and membrane life.

This system would then be a prototype for a larger scale project that would construct a pilot scale technology demonstration project at a local wastewater treatment facility. This pilot scale test would be used to define the economics of the PRO/TT process. Two potential sites and municipal partners have been identified and preliminary discussions are on going.

Abbreviations

DOC — Direct osmotic concentration
ELS — Exploration life support
FO — Forward osmosis
OA — Osmotic agent
PRO — Pressure retarded osmosis
PRO/TT — Pressure retarded osmosis/tertiary treatment
RTD — Rapid technology development
SBIR — Small Business Initiative Research (grant)
TDS — Total dissolved solids
TOC — Total organic carbon

Symbols

F_w — Volumetric water flux, L/m^2 s
H — Hydrostatic head (pressure) difference across the turbine (m of equivalent water column height)
i — A dimensionless factor related to the disassociation of the solute molecule. For most non-electrolytes solutes it is equal to 1. For most ionic compounds it is equal to the number of discrete ions in a formula unit of the substance.
M — Molarity of the solution, moles/L
Q — Quantity of the water passed through the turbine, m^3/s
R — Gas constant 8.314472 L · kPa · mol^{-1} · K^{-1}
T — Temperature, K
ΔP — Opposing hydrostatic pressure, N/m^2
$\Delta\pi$ — Osmotic pressure, N/m2
η — Pump/turbine efficiency, %
λ — Inverse of the water density, N/m^3

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