

Experimental Study for Pressure Exchanger Applied to Brackish Water

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To cite this article:

Sameh Hassan Elbana, Radwan Mostafa Kamal, Ahmed Farouk Abdel Gawad. Experimental Study for Pressure Exchanger Applied to Brackish Water. *American Journal of Mechanical and Industrial Engineering*. Vol. 3, No. 1, 2018, pp. 15-26.

doi: 10.11648/j.ajmie.20180301.12

Received: February 25, 2018; **Accepted:** March 19, 2018; **Published:** April 11, 2018

Abstract: Over the last ten years, reverse osmosis (RO) desalination technique became the most common and popular technology to desalinate brackish and seawater due to its low cost and simplicity. Great efforts have been conducted to reduce the energy consumption in reverse osmosis plants. One of the most efficient techniques is the pressure exchanger (PX) which utilizes the high pressure existing in waste concentrate to pressurize a part of feed brackish or seawater. The present research deals only with a pressure exchanger for brackish water. Such PX was manufactured specifically for the present work from simple materials such as cast iron and plastics to match brackish water technical and financial conditions. Results showed that PX for brackish water has a lower hydraulic efficiency than PX for seawater application. The present ultimate hydraulic efficiency is 25.6% compared to 95% for seawater PX manufactured by ERI (the single manufacturer in the Globe) with a higher mixing rate.

Keywords: Desalination, Reverse Osmosis, Energy Recovery Devices, Pressure Exchanger, Brackish Water

1. Introduction

1.1. Background

Energy consumption is a key factor which influences the cost of freshwater production in reverse osmosis (RO) process. Nowadays, there are many energy recovery devices and all of them are focused on recouping the concentrate pressure by transferring hydraulic energy to power generation [4].

Typically, the application of energy recovery is much less common in brackish water RO systems, primarily because of the relatively low-feed pressure and low-flow rate of the membrane reject stream. The fear is energy recovery devices can also potentially limit the flexibility of a brackish RO process because of efficiency losses or flow-rate constraints encountered during off-peak operation.

Recently, low-cost isobaric energy recovery devices moved to the front for brackish RO applications. These devices provide greater energy-savings payback and greater operational flexibility than was previously achievable. They also have the potential to reduce the overall capital costs of

an installation since they can be less expensive than the high-pressure pump capacity which is necessary in their absence [1].

Energy recovery devices (ERDs) types for brackish applications are mainly centrifugal devices, such as turbochargers, as well as rare isobaric devices such as the brackish water PX Pressure Exchangers [9]. PX is the device that transfers the pressure of the high-pressure fluid stream to a low-pressure fluid stream working on the principle of direct contact positive displacement. Stable efficiency (97-98) % over a wide range of recoveries and lack of traditional seals make PX more efficient than any other devices. In RO system, pressure exchangers are used as energy recovery devices (ERDs). As can be seen in Figure 1, high-pressure concentrate from the membranes {C} is directed {3} to the ERD {D}. The ERD uses this high-pressure concentrate stream to pressurize the low-pressure brackish water stream into the highest-pressure brackish water stream created by the high-pressure pump {A}. This combined stream feeds the membranes {C}.

The concentrate leaves the ERD at low pressure {5}, expelled by the incoming feed water flow {1}. Pressure exchangers save energy in these systems by reducing the load on the high-pressure pump. Stable efficiency (97-98) % over a wide range of recoveries and lack of traditional seals make it more efficient than any other devices.

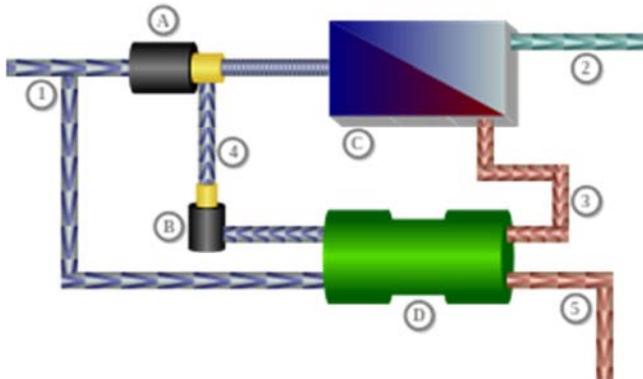


Figure 1. The circuit of pressure exchanger.

1.2. Literature Review

PX from Energy Recovery Inc. (ERI) “the only

Table 1. Energy efficiency and advantages/disadvantages of PX device, Guirguis (2011).

Type	Class	Maximum Efficiency	Advantages	Disadvantages
PX	Hydraulically driven pumping in parallel	98%	1-Core built of ceramic selected to be the ideal material for its toughness, corrosion resistance and dimensional stability withstanding the harshest saline environments Unlike turbines no transformational losses occur in a PX device 2-Stable efficiency over wide range of recoveries 3-Lack of traditional seals and bearings.	1-High capital cost. 2-Booster pump is needed. 3-Complexity of design, operation and maintenance. 4-Mixing, lubrication, over flush, high pressure differential, low pressure differential.

Guirguis (2011) explained various energy recovery devices such as the Francis turbine, Pelton wheel, turbocharger, recuperator, DWEER and Pressure Exchanger, used in seawater reverse osmosis (SWRO) desalination plants along with case studies associated with each of them. Special focus was given to the energy efficiency and costs associated with these devices as shown for PX in table 1.

Yihui (2011) had studied the mixing process and the effects of RPE parameters on the liquid piston by 3D model, which described the dynamics mixing more accurately and closer to the real operation conditions. It was found that the effective control of mixing rate in the ducts of rotor is very important to the stable operation of SWRO [12].

This paper deals with the performance of a local-made pressure exchanger that was fabricated from cast iron and plastics, and its effect on the overall performance of brackish water pumping process.

2. PX Geometry Model

2.1. Components of PX

The pressure exchanger (PX) main parts are shown in Figure (2) as follows:

manufacturer of PX in the world” is the most efficient and reliable energy recovery solution on the market for desalination. This award-winning family of products is unmatched in the industry and has been widely adopted around the world for seawater desalination projects, both large and small. It has main advantages for seawater usage [3] as follows:

1. Designed for any size reverse osmosis desalination plant.
2. Efficiency of 98%.
3. Scalable solution for the customers who need premium performance energy recovery with a larger unit capacity.
4. Lowest lifecycle cost of any energy recovery device on the market.

MacHarg and McClellan (2004) studied how to reduce energy cost in brackish water RO system and found that PX can significantly lower the costs of brackish water RO applications. PX significantly reduces flow through the main pump resulting in lower energy consumption and operating costs. Since ERI [3] is a unique manufacturer in such important area [1].

- a-Rotor (made from plastics).
- b- Two end cabs (made from plastics).
- c- Shell (made from cast iron).
- d- Two end covers (made from cast iron).

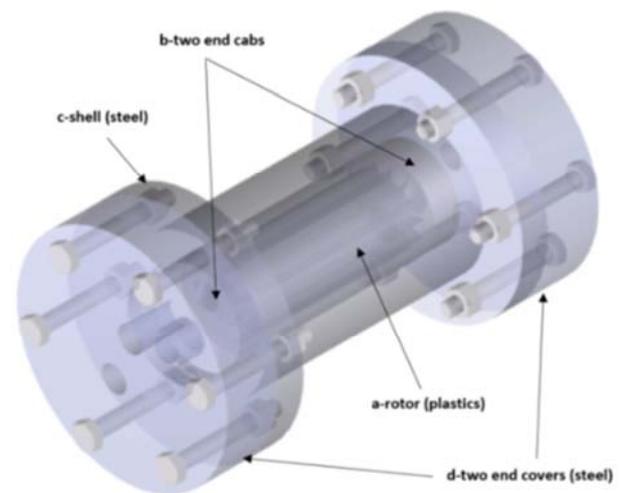


Figure 2. Assembly of pressure exchanger.

2.1.1. Rotor (A)

This device uses a cylindrical rotor, Figure (3), with

longitudinal ducts parallel to its longitudinal axis. The rotor spins inside a shell between two end covers. The rotor in PX was made from plastics using 3D printing technology with density filling 100% to rise its stress resistant. Rotating rod of 5 mm that was made from steel diameter is hinged to rotor and is extended outside the shell in order to measure the revolutions per minutes RPM.

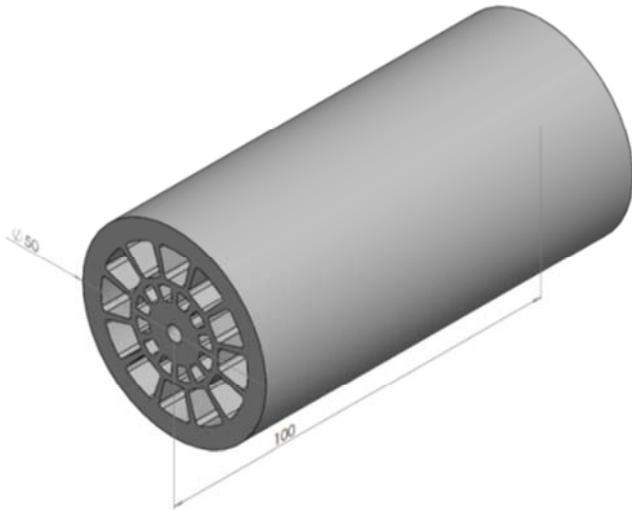


Figure 3. Rotor configuration, Dimensions in mm.

2.1.2. Two End Cabs (B)

These two end cabs were used to direct water to enter and exit the slots of the rotor with angle of attack =30° to rotate the rotor inside the shell. PX of the energy recovery Inc. [3] has a small angle of attack but for the low-cost PX a bigger angle of attack was needed to overcome the high-friction force between the rotor (plastics) and the shell (cast iron) and that was urgent to increase the number of revolutions of the rotor and reduce the mixing rate. The two cabs were made from plastics using 3D printing technology and also with density filling 100% to rise its stress resistant, Figures 4 and 5.

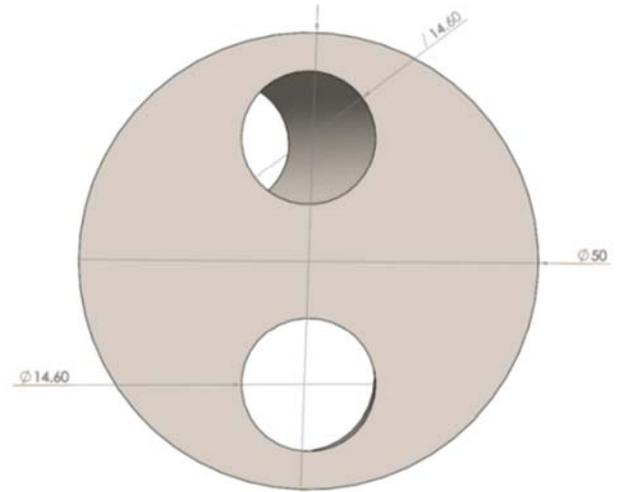


Figure 5. End cab front view in mm.

2.1.3. Shell (c)

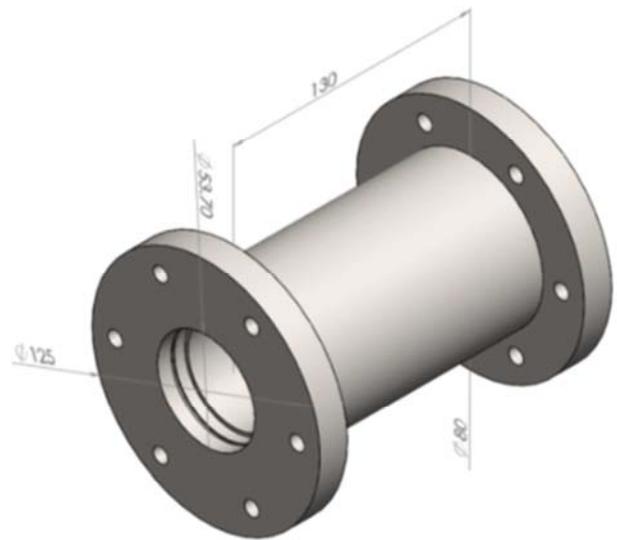


Figure 6. Shell isometric, Dimensions in mm.

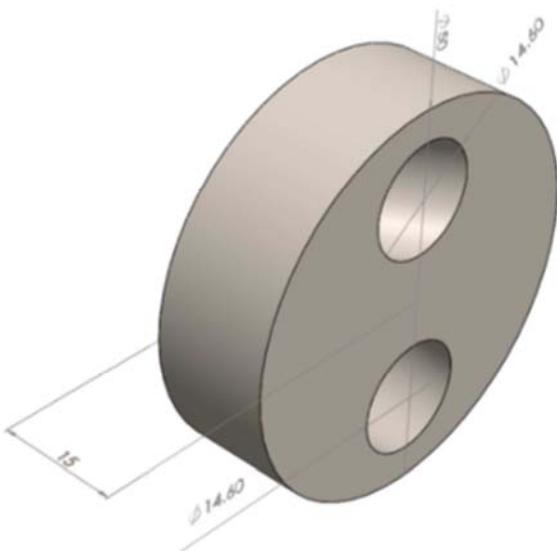


Figure 4. End cab dimension in mm.

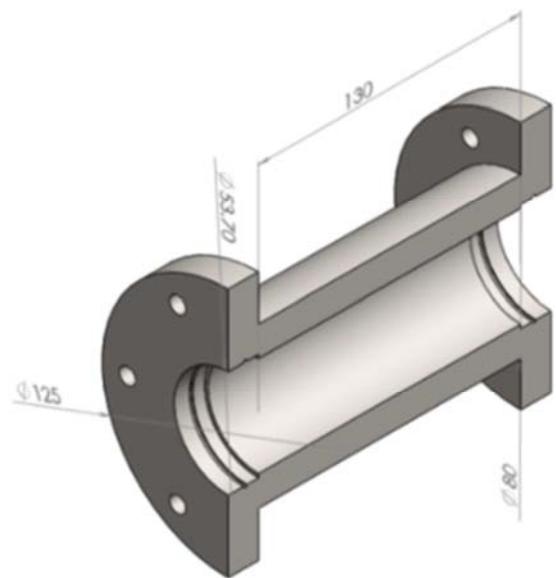


Figure 7. Shell section view.

Stationary enclosure of all the previous parts was made from cast iron. Its internal surface was lubricated to ease rotation, see Figures. 6 and 7.

2.1.4. Two End Covers (D)

The two end covers enclosed the shell from both sides. Each end cover included an O-ring with a suitable size to prevent leakage and was used to isolate the high-pressure stream from mixing with the low-pressure stream, see Figure 8.

Figure 9 shows the main parts of PX after manufacturing before the assembly procedure.

2.2. Assembly of PX

To assemble PX from the parts (components) that are shown in figure 9, the following steps are to be followed:

1- Put small amount of mineral oil inside the shell then put the rotor inside the shell, see figure 10 and 11.

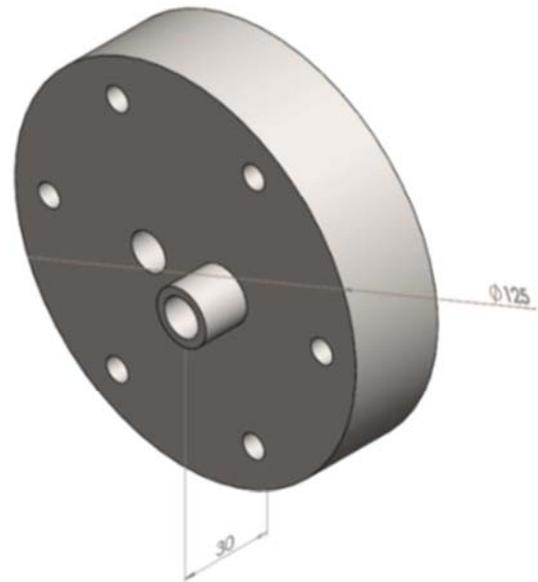


Figure 8. End cover isometric, Dimensions in mm.

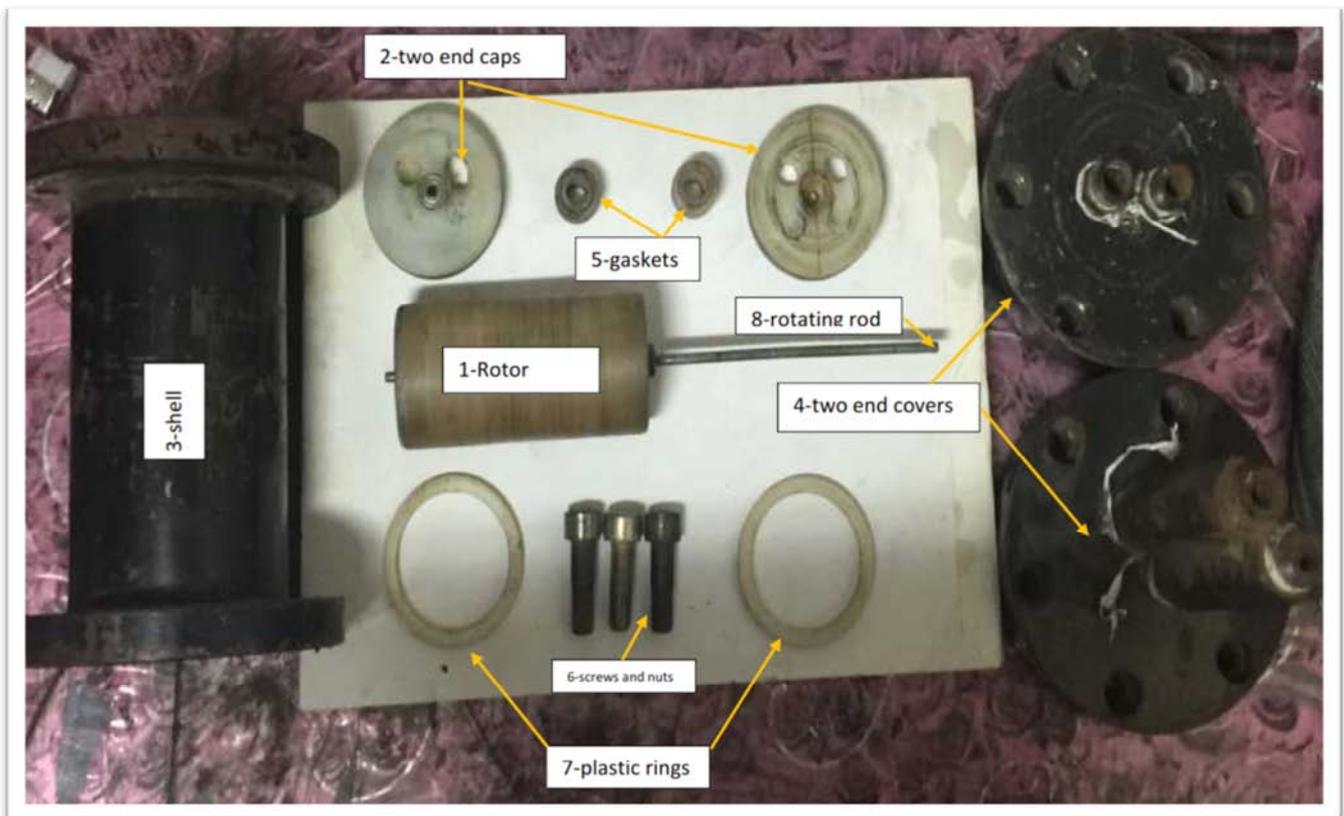


Figure 9. Main parts of PX after manufacturing.



Figure 10. Rotor inside shell, front view.



Figure 11. Rotor inside shell, rear view.

2- Assemble the two cabs against the rotor from both sides and assure the flow direction of the flow through the cabs, see Figures 12 and 13.



Figure 12. Shell after assembling the two.



Figure 13. Shell after assembling the two cabs (closer view).

3- Plug the oil seal and then assemble both the end covers, see Figure 14.

4- Tight the screws and nuts, see Figure 15.

5- The final PX assembly is shown in Figure 15.



Figure 14. The assembly of the two covers.



Figure 15. PX assembly.

3. Experimental Work

The present PX was tested on BWRO capacity of 1.5 m³/hr, see figures 16 and 17. The following are the main components of the test rig:

- 1- Storage feed water tank 1 m³.
 - 2- Low-pressure pump to overcome filter pressure loss 0.5 kW.
 - 3- Sand and carbon filters.
 - 4- Cartridge filter 5 μm.
 - 5- High-pressure pump
- The high-pressure pump supplies the pressure needed to

push water through the membrane, even so the membrane rejects the flow of salt through it. Typical pressures for brackish water range from 225 to 376 psi (15.5 to 26 bars). This requires a large amount of energy. When, energy recovery is used, part of the high-pressure pump's work is done by the energy recovery device, reducing the system energy inputs. The high-pressure pump rated power is 1.5kW.

- 6- Membrane assembly.
- 7- Energy recovery (present locally-manufactural PX).
- 8- Measurements devices and control panel.

The test rig contains many gauges to measure flowrates and pressures after each filter and pump in the circuit, see Figure 18.

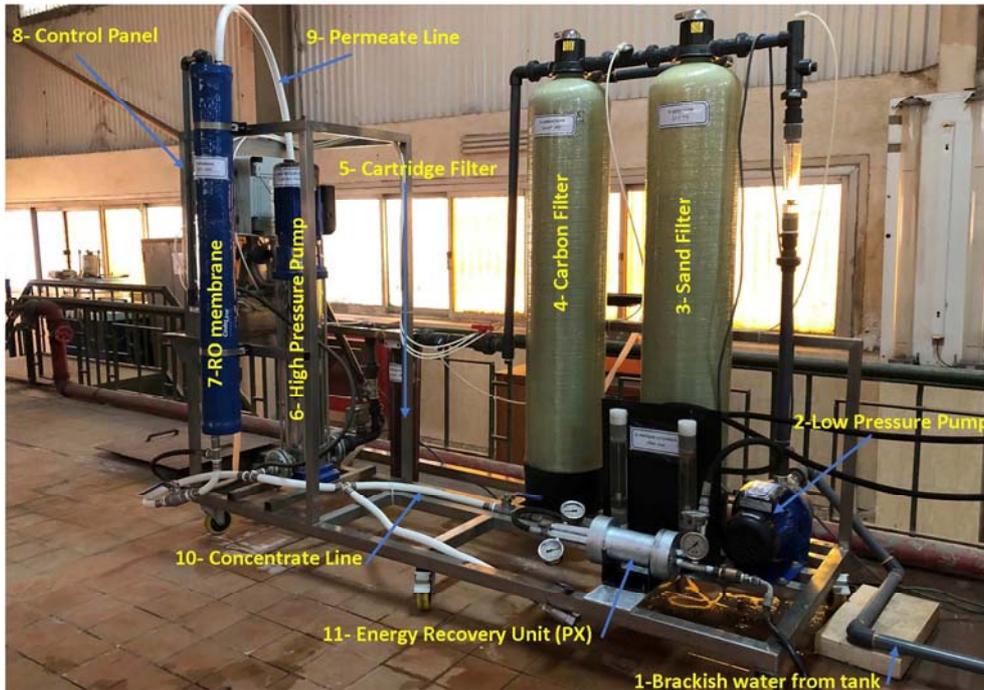


Figure 16. Brackish water RO unit.

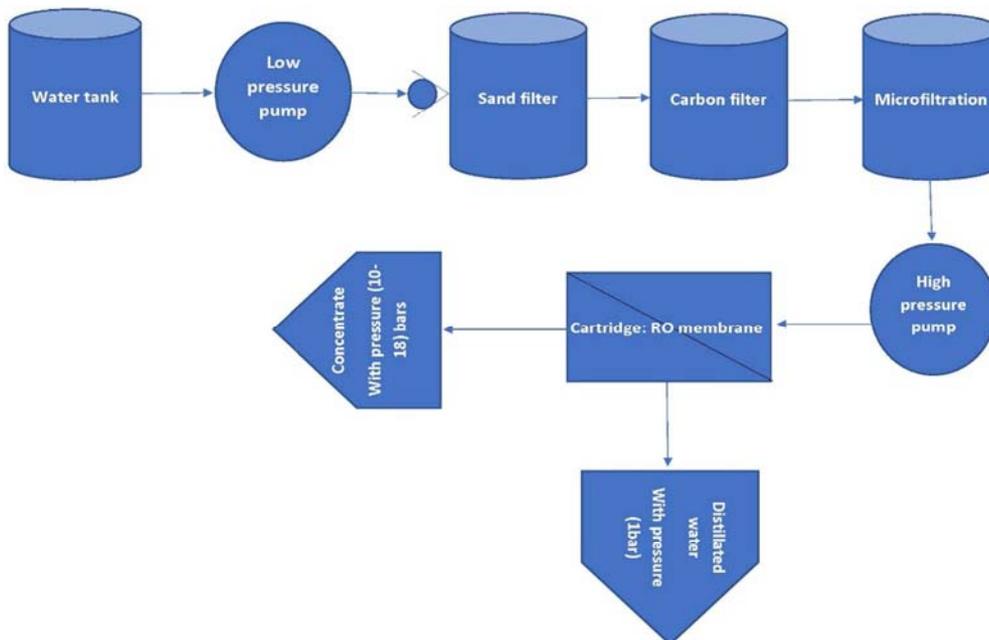


Figure 17. The Brackish water RO unit without PX (schematic presentation).

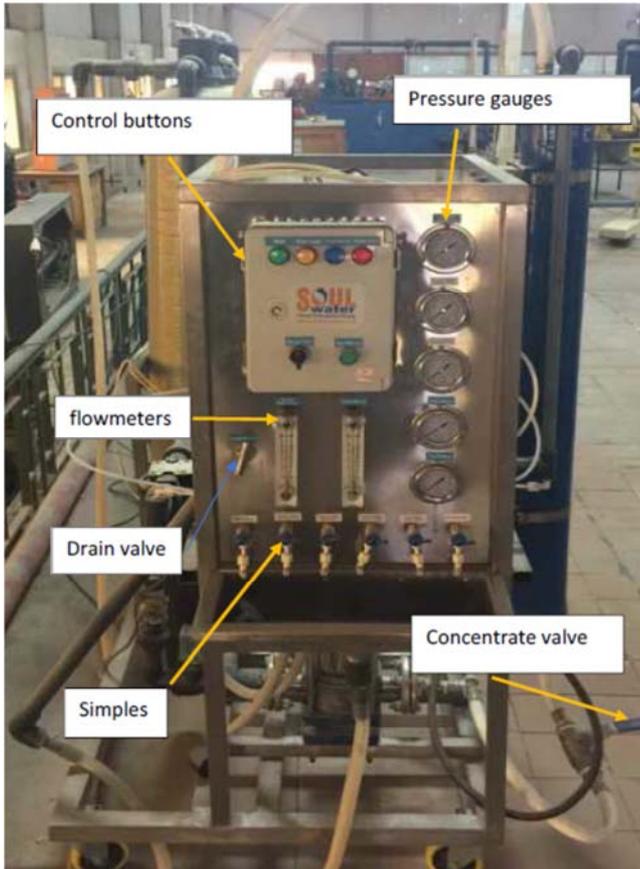


Figure 18. Control panel of BWRO unit.

The RO unit maximum pressure in the test rig is 18 bars at flowrate of 1.5 m³/hr. The locally-manufacturing PX was tested at many pressures from 10-17 bars at various flow rates. The test was focused on the following:

1- The flow across the PX:

Solidworks software was used to study the flow streamlines and the variation of pressure inside PX.

2- The number of revolutions RPM:

With the aid of a tachometer and the rotational speed of the main rotating rod can be measured.

3- The mixing rates:

Flowmeters at each port of PX were used to measure the flow, hence, mixing rates between both sides can be measured.

4- Performance curve:

After measuring the pressures (by using pressure gauges at every port) and the flow rates (by using flowmeters at every port), performance curves of both sides, i.e., turbine side (the high-pressure side) and pump side (the low-pressure side) can be drawn, then, the best operating point for the PX can be estimated.

5- The hydraulic efficiency of PX:

The ratio of the hydraulic power delivered at the turbine side to the hydraulic power reached to the pump side.

$$Efficiency(\eta) = \frac{power\ out}{power\ in}$$

6- Material effect on PX operation

4. Experiment Procedure

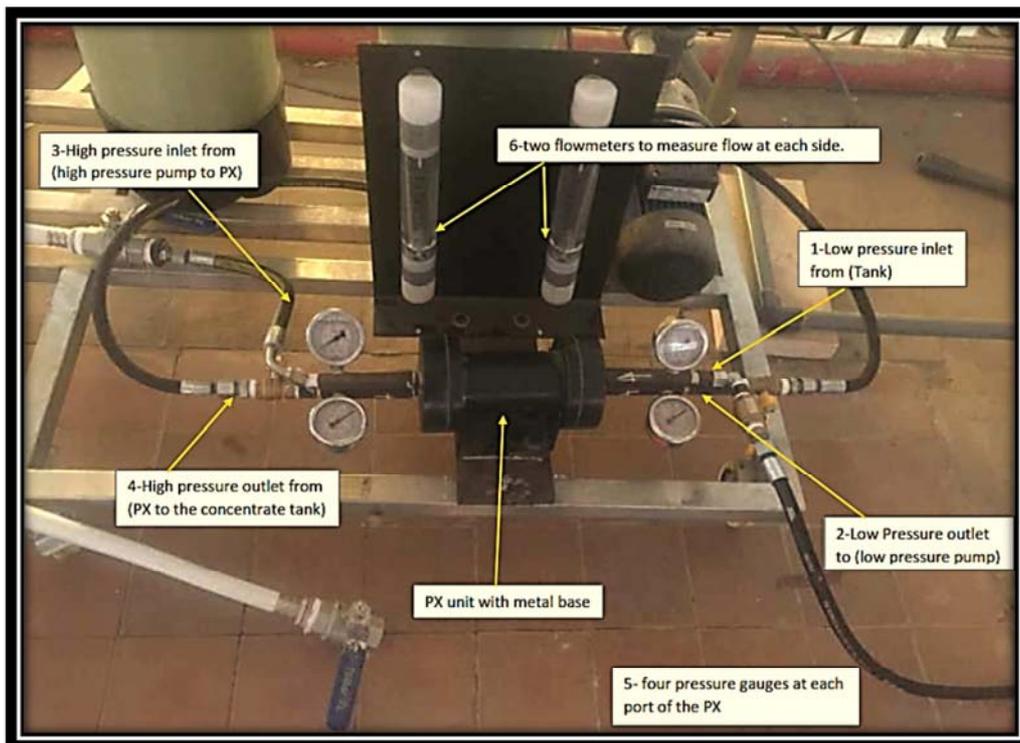


Figure 19. Operation of PX.

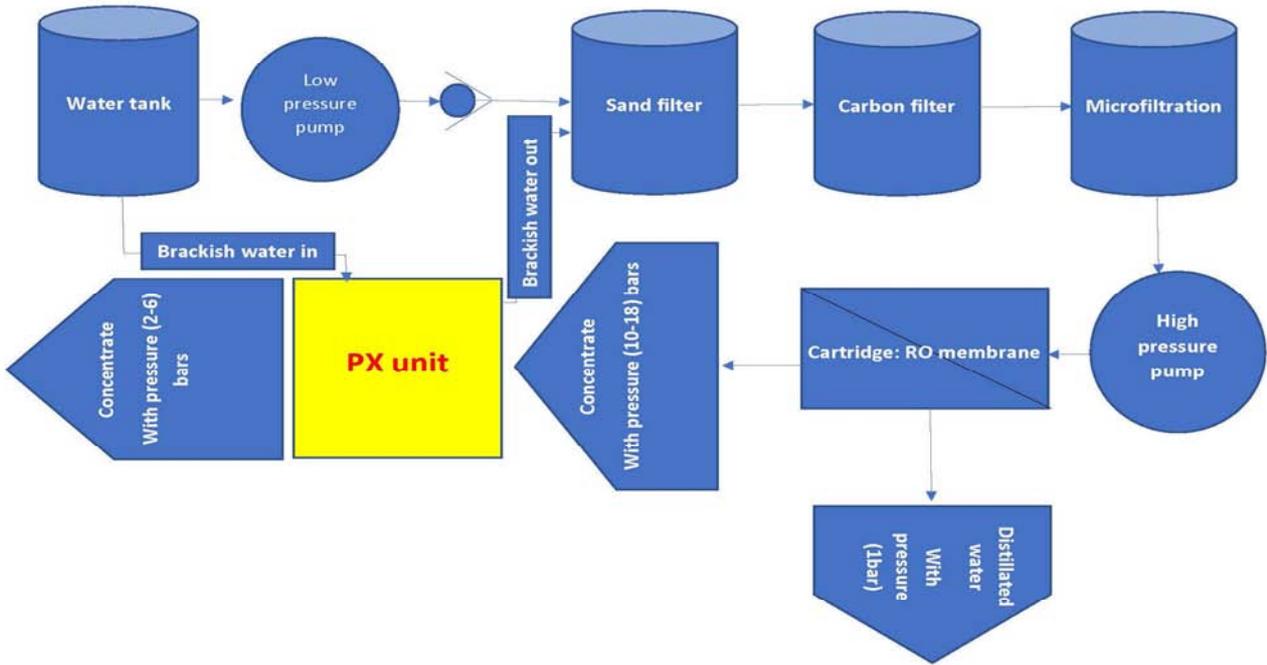


Figure 20. Schematic diagram of PX unit.

The experimental procedure must achieve the protection of PX as well as low and high pumps and reach the stable conditions. The experimental procedure of the present work consisted of the following steps:

- 1- Make sure that the tank is full of test water.
- 2- Start the low-pressure pump.
- 3- Open all valves in the experimental unit.
- 4- Wait about 15 minutes to permit water filling all RO unit pipes and filters (steady state operation).
- 5- Push the button on the cartridge filter to push the air out of the circuit.
- 6- Check all pipes and valves for leakage.
- 7- Stand PX on its metal base at the right position.
- 8- Use screws to fasten PX to its metal base.
- 9- Begin to connect hoses using the wrench but not tight them well.
- 10- Close the drain valve, then, it is safe to operate the

high-pressure pump.

11- Now, water is filling all hoses, so, begin to open the drain valve slowly.

12- Use wrench to tight all connectors of PX connector.

13- Now, use valves now to control the amount of water to PX.

14- Wait 15 minutes for the circuit to reach steady state, then, begin to take readings, see Figures 19 and 20.

5. Results and Discussion

PX can be modeled as a system consist of a pump and a turbine working together and matching together. It is required to find the best matching point between them to give the best hydraulic efficiency and low mixing rate.

Figure 21 shows the main parameters of the experimental results that will be discussed in the present section.

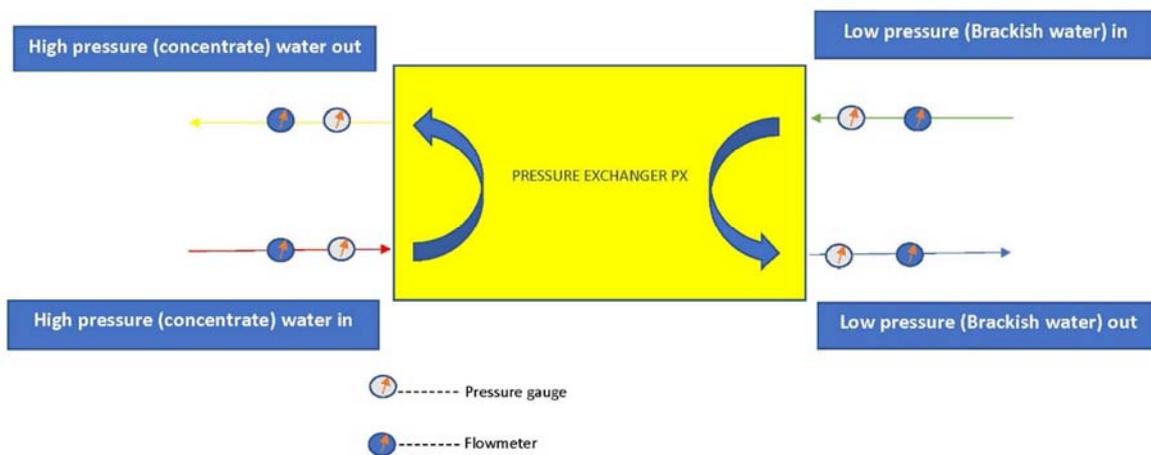


Figure 21. Main parameters of the experimental results.

5.1. Results of PX at the High-Pressure Side (Turbine Side)

The concentrate that left RO assembly drives PX. The more pressure inlet to the rotor, the more RPM was introduced. The high-pressure side can be modeled as turbine with performance curve of relation between head $(H) = \frac{\Delta p}{\rho g}$ and flowrate Q1. See table 2 and Figure 22.

Table 2. High-pressure side results.

	N (R. P. M)	P1 (bars)	Q1 (m ³ /s)	P2 (bars)	Q2 (m ³ /s)	Power in = (P1-P2) XQ1
1	700	17	3.5x10 ⁻⁴	7.85	3.1x10 ⁻⁴	320.25
2	670	15.7	4.2x10 ⁻⁴	6.4	3.7x10 ⁻⁴	390.6
3	490	14.8	5x10 ⁻⁴	5.3	4.4x10 ⁻⁴	475
4	440	11.4	5.9x10 ⁻⁴	1.8	5.25x10 ⁻⁴	566.4
5	310	10.6	6.1x10 ⁻⁴	0.9	5.3x10 ⁻⁴	591.7

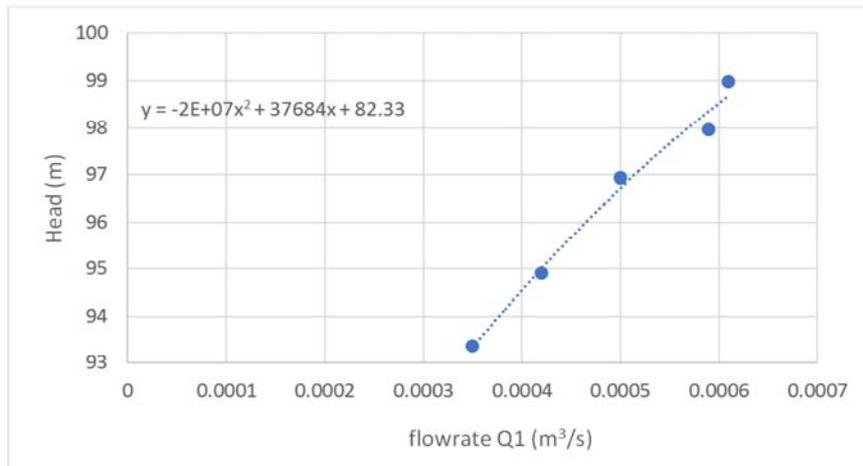


Figure 22. High pressure side results.

From the previous results, the governing equation between the head and the discharge across the high-pressure side is:

$$\text{Head} = -2 \times 10^7 Q^2 + 37684Q + 82.33 \quad (1)$$

5.2. Results of PX for the Low-Pressure Side (Pump side)

The rotating motion of the rotor helps brackish water to enter PX. The low-pressure side acts like a pump with

suction and delivery ports. The more rotation speed is the more amount of brackish water can be delivered. The low-pressure side can be modeled as a pump with performance curve of relation between head $(H) = \frac{\Delta p}{\rho g}$ and flowrates Q4, see table 3 and Figure 23. From the previous results, the governing equation between the head and discharge across the low-pressure side is:

$$\text{Head} = 7 \times 10^7 Q^2 - 54809Q + 51.938 \quad (2)$$

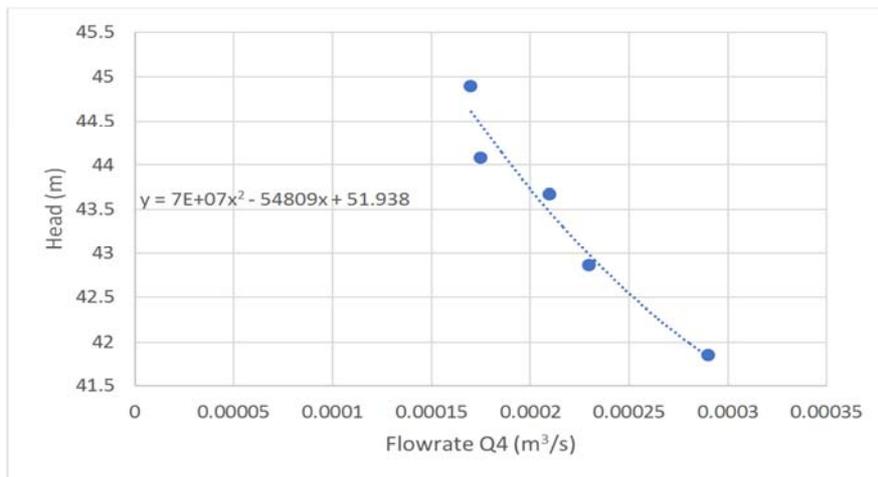


Figure 23. Low-pressure side results.

Table 3. Low-pressure side results.

	N (R. P. M)	P3 (bars)	Q3 (m ³ /s)	P4 (bars)	Q4 (m ³ /s)	Power out (P3-P4) XQ (W)
1	700	0.6	2x10 ⁻⁴	4.7	2.9x10 ⁻⁴	82 w
2	670	0.6	1.8x10 ⁻⁴	4.8	2.3x10 ⁻⁴	75.6 w
3	490	0.6	1.5x10 ⁻⁴	4.88	2.1x10 ⁻⁴	64.2 w
4	440	0.7	1.1x10 ⁻⁴	5.02	1.75x10 ⁻⁴	47.52 w
5	310	0.75	0.9x10 ⁻⁴	5.15	1.7x10 ⁻⁴	39.6 w

5.3. Best Operating Point of PX

PX can be modeled as a system of pump and turbine. So, it is required to obtain the best operating point of both pump and turbine system at which the highest possible efficiency exists.

Solution of equations 1, 2 together shows the best operating point of the system that corresponds to a head of 68.59 m and the flow rate of 8.6x10⁻⁴ m³/s.

5.4. The Mixing Rate of PX

Pressure increase in the high-pressure side leads to more

rotational speed and less mixing rate. Also, in order to increase RPM, it is desired to increase the angle of attack of the high-pressure side. The angle of attack in the present PX design is 30°. See table 4 and Figure 24

Table 4. Relation between RPM and mixing rate.

	N (R. P. M)	Mixing rate Q1-Q2
1	700	0.4x10 ⁻⁴
2	670	0.5x10 ⁻⁴
3	490	0.6x10 ⁻⁴
4	440	0.65x10 ⁻⁴
5	310	0.8x10 ⁻⁴

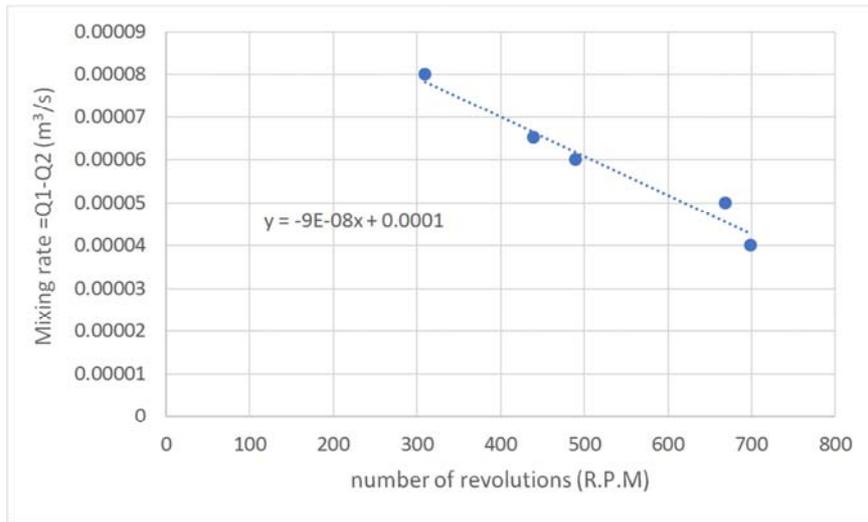


Figure 24. Relation between RPM and mixing rate.

The equation governing mixing rate of PX and R. P. M is:

$$\text{Mixing rate} = -9 \times 10^{-8} N + 0.0001 \quad (3)$$

5.5. The Hydraulic Efficiency of PX

The hydraulic efficiency of PX can be expressed as the ratio of power delivered to the low-pressure side to the power generated from the high-pressure side and can be calculated from equation:

$$\text{Efficiency}(\eta) = \frac{\text{power out}}{\text{power in}} \quad (4)$$

The results are illustrated in Table 5 and Figure 25. The relation between the hydraulic efficiency of PX and R. P. M is:

$$\text{Efficiency} = 8 \times 10^{-5} N^2 - 0.0346N + 9.8568 \quad (5)$$

Table 5. Relation between efficiency and R. P. M efficiency.

No.	N (R. P. M)	Efficiency (η)
1	700	25.6
2	670	19.35
3	490	13.5
4	440	8.4
5	310	6.7

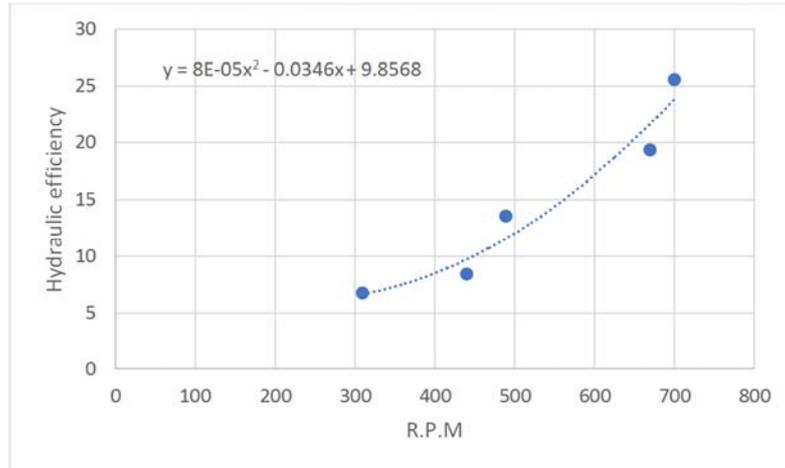


Figure 25. Relation between efficiency and R. P. M.

6. Conclusion

The desired PX that made only from plastics and cast iron in order to decrease the energy consumption of BWRO was tested. It was made from very low-cost materials to commensurate with the total capital cost of BWRO.

There is no local manufactured pressure exchanger for both brackish or sea water associated with BWRO & SWRO plants which are widely used in Egyptian market. The present model is considered as the first research hand to localize such efficient technology in Egypt.

The Higher rotor speed is, the less mixing rate between the concentrate and brackish water. Although, the test included only the efficiency of power transfer from the high-pressure

stream to the low-pressure stream neglecting the mixing rate, it is important to take it in consideration.

The first test of the pressure exchanger is acceptable but it is needed to take into consideration the mixing rate. The mixing rate is higher than PX from ERI because of friction and lower number of revolutions. Maximum hydraulic efficiency of PX reached 25.6 and can be increased in the future work with changing the manufacturing materials and using better insulating material to reduce mixing rate.

Local manufacturing of PX can reduce 85% from ERI prices and this is needed urgently because the brackish water reverse osmosis is the hope of the future generation in Egypt and many countries in the middle east.

Nomenclature

Symbols

H	Pressure Head (m)
N	Number of Revolutions (R. P. M)
P_i	Pressure at different locations $i=(1, 2, 3, 4)$ (bars)
Q_m	Flowrates at different locations $m=(1, 2, 3, 4)$ (m^3/s)

Greek letters

θ	Angle of Attack
η	Hydraulic Efficiency

Abbreviations

BWRO	Brackish Water Reverse Osmosis
ERD	Energy Recovery Devices
ERI	Energy Recovery Incorporation
PX	Pressure Exchanger
RO	Reverse Osmosis
SWRO	Seawater Reverse Osmosis

Units

mm	millimeter
μm	micrometer
m^3	Cubic meter
R. P. M	Revolutions per minute
psi	pound per square inch (pressure unit)
bars	Pressure unit
kW	Kilowatt

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