Final DesWEC project report

The DesWEC[1] project has been funded under the Supergen ORE Hub Flexible Fund (FF2020-1012) to investigate the integration of a reverse osmosis desalination plant with a wave energy converter. The project involves a combination of physical and numerical modelling separated into five tasks that were planned to be completed over a period of 12 months. These tasks were:

Task 1. Review of WEC PTO suitability and characteristics
Task 2. Commissioning of RO laboratory test rig
Task 3. Laboratory test programme
Task 4. Numerical modelling of wave-powered desalination systems
Task 5. Design guidelines for wave-powered desalination

Unfortunately, the commissioning of the laboratory test rig was found to be significantly more challenging than originally anticipated. Although this task has been completed, it has meant that less time was available to work on the other aspects of the project. Notwithstanding, it was possible to make some progress in all of the project tasks. In particular, sufficient progress has been made to present the results at the European Desalination Society conference, that was held in Las Palmas, Gran Canaria from 20th – 23rd June 2022. The project has also been successful in attracting further funding for wave-powered desalination linked to the commercial development of a wave-powered desalination technology by Pure Marine Gen Ltd (CASE Project A1130, Award Value £100,274). Both the test rig and the PDRA that was employed on this project are contributing to this commercial project. Further details on each of the project tasks, together with a review of the potential for further work are provided in the sections below.

Task 1: Review of WEC PTO suitability and characteristics

It has been identified that the key difference between PTO configurations is the characteristics of the RO energy recovery technology, which influences the temporal variation in the system pressure and flows. Two fundamental configurations of the energy recovery technology have been investigated for their suitability for two different types of wave energy converter (a heaving buoy and an oscillating wave surge converter). Although other configurations of energy technology technologies exist, and new technologies are being continually proposed, it is considered that the analysis of these two configurations provides an indication of how the choice of the energy recovery technology may influence the performance of the system. The variations in pressures and flow associated with each PTO configuration will influence both the quality and quantity of fresh water produced by the system. These variations are due to both the effect that these may have on the hydrodynamic performance of the wave energy converter (due to a variation in the effective PTO damping) together with the effect that it has on the performance of the RO membranes. The two configurations investigated are

- Clark pump
- Pressure exchanger – intensifier

One key difference between these two energy recovery technologies is that the Clark pump requires a low PTO pressure (~20 bar) with a larger feed flow, whilst the Pressure exchanger-intensifier requires

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[1] The name of the Project has been changed to DesWEC as deswave.com (or similar) was not available as a website, whilst deswec.com was available.

a higher PTO pressure (~50 bar) with a lower feed flow. Thus, to achieve the same PTO damping force the volume of the hydraulic pump connected to the wave energy converter must be larger when the energy recovery technology is a Clark pump compared to when it is a Pressure exchanger-intensifier to achieve the same damping force applied to the wave energy converter.

The choice of the energy recovery technology has been found to have a minimal influence on the optimal performance of the system with respect to quantity and quality (salinity) of the permeate (fresh water) production provided that the system has been appropriately designed for the particular configuration. The major impact of the choice of the energy recovery technology was on the frequency content of the feed pressure. This is shown in Figure 1 and Figure 2 for the Buoy WEC with a Pressure exchanger-intensifier and Clark pump energy recovery technology respectively. It can be seen that whilst both energy recovery technologies have a low frequency content associated with the wave groups, the Clark pump has a much higher frequency content at twice the wave frequency. Similar results were found for the OWSC wave energy converter.

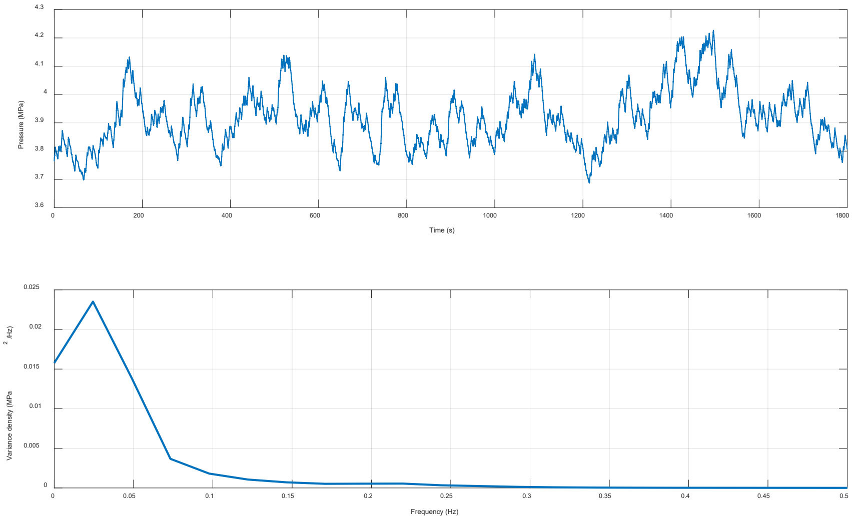

Figure 1: Pressure variations for a Buoy WEC using a Pressure exchanger-intensifier

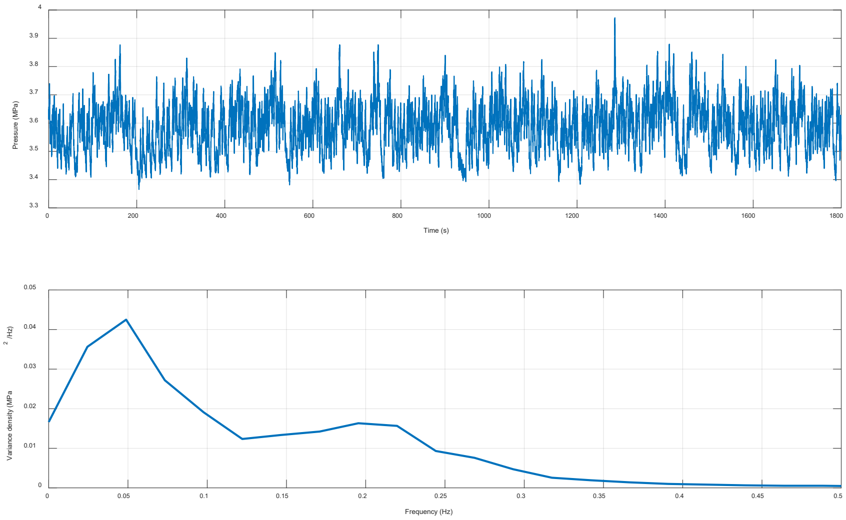

Figure 2: Pressure variations for a Buoy WEC using a Clark pump

Task 2: Commissioning of RO laboratory test rig

The commissioning of the RO laboratory test rig has now been completed, but not without the need to overcome a range of challenges.

An initial challenge during the commissioning of the test rig was encountered with the use of fresh water for preliminary commissioning. This was used to minimise the potential for damage to the membranes during these initial activities. However, water that passed through the RO membranes then had such a low salinity that the flow meter did not function since it relies on water conductivity, which was too pure for the sensor to work correctly. This unexpected sensitivity of the flow sensors to the water conductivity took a while to diagnose and means that the average production is measured through collection as well as the flow meter to provide increased confidence in the results.

A further challenge has been the control of the feed pressure with a variable feed flow. The feed pressure is controlled using a servo-activated needle valve. It had been anticipated that this valve could be controlled dynamically to maintain the target pressure. Unfortunately, this has not been completely successful due an insufficient response time of the valve, so although variations in pressure due to changes in the flow could be reduced, they could not be eliminated. This appears to be a common challenge in these types of tests as this was also the case for similar experiments undertaken by NREL as reported by Sitterley *et al.*[2]

A final challenge encountered was that the performance of the RO membranes was found to be relatively sensitive to the water temperature, which due to the closed loop design of the laboratory rig would tend to increase during a day of testing. This has been largely resolved by the inclusion of a thermostatically controlled cooling loop. The cost of the cooling loop was approximately £1,000, which was paid for through a successful application to an internal funding pool. A picture showing the full laboratory test rig, including the cooling loop is shown in Figure 1 below.

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[2] Sitterley *et al.* [2022] Performance of reverse osmosis membrane with large feed pressure Performance of reverse osmosis membrane with large feed pressure fluctuations from a wave-driven desalination system

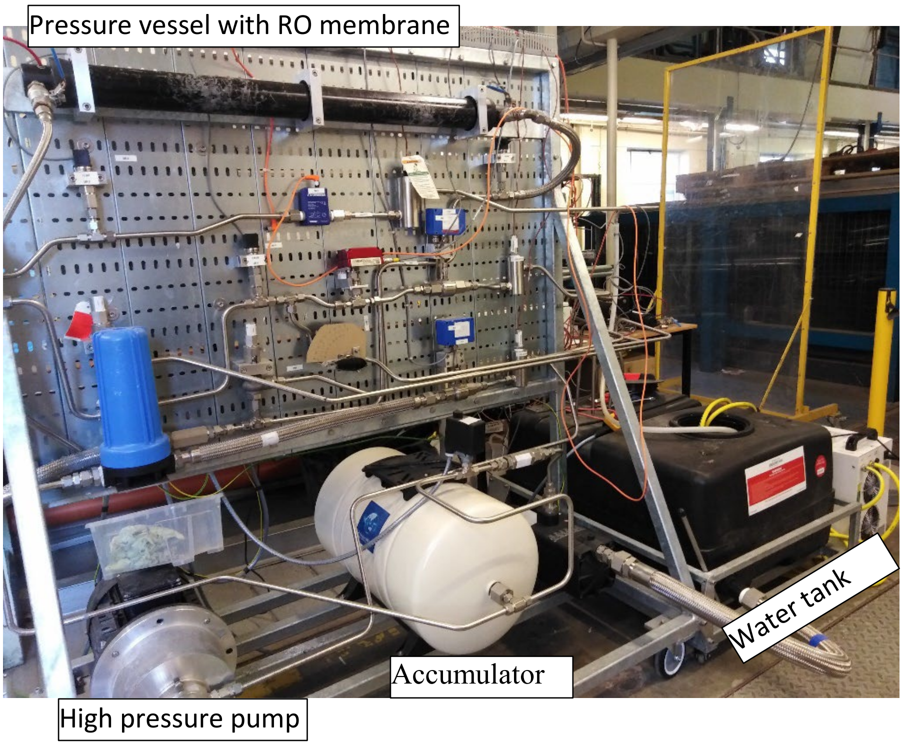


Figure 3a: Final RO laboratory test rig

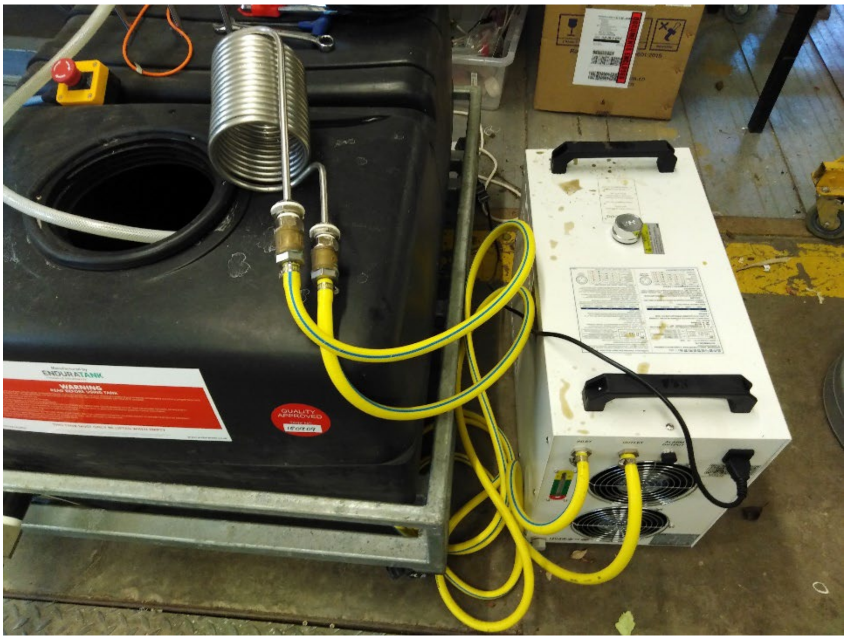


Figure 4b: The chiller with cooling circuit

Task 3: Laboratory test programme

The laboratory test programme has been completed with a range of variations in pressure and flow being investigated. The period of pressure and flow variations ranged from 5 to 60 seconds to investigate not only the effect of variations with the wave period, but also with variations due to wave groups. Indeed, the numerical modelling undertaken in Task 4 indicates that the peak of the spectral variance density for the feed pressure and flow is associated with the wave groups. This is shown in Figure 2 for a Buoy WEC with a Clark pump energy recovery device in irregular waves based on an 1800-second wave series.

The results of the laboratory test programme are summarised in the figures below. The tests are divided into three main categories:

1. Constant flow and pressure
2. Constant flow and variable pressure
3. Variable flow and constant pressure

1. Constant flow and pressure

Several tests are conducted at different constant flow and pressure. Figure 4a and 4b shows the contour maps for permeate recovery and permeate salinity. The figures indicate the operating range of feed flow and feed pressure of the experimental test rig. The feed pressure developed in the RO membrane also depends on the feed flow; as a result, there is a limitation on the feed pressure at higher feed flow rate. The permeate recovery increases with increasing the feed pressure. However, the maximum recovery occurs at low flow rate and high pressure. Similarly, the permeate salinity decreases as the feed pressure increases.

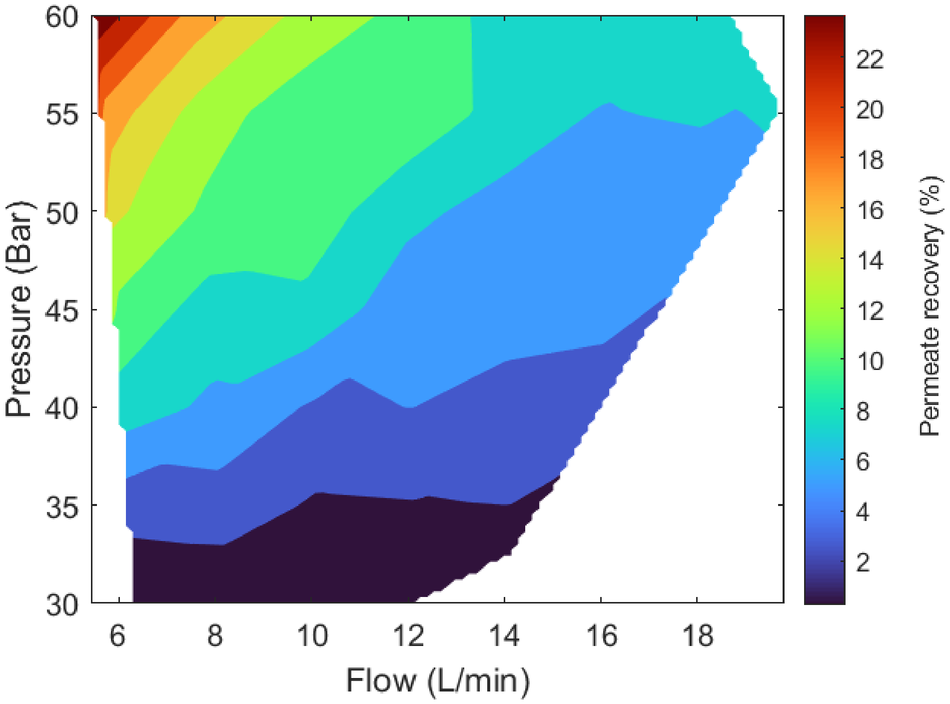


Figure 4a: Contour map permeate recovery for different feed flow and pressure

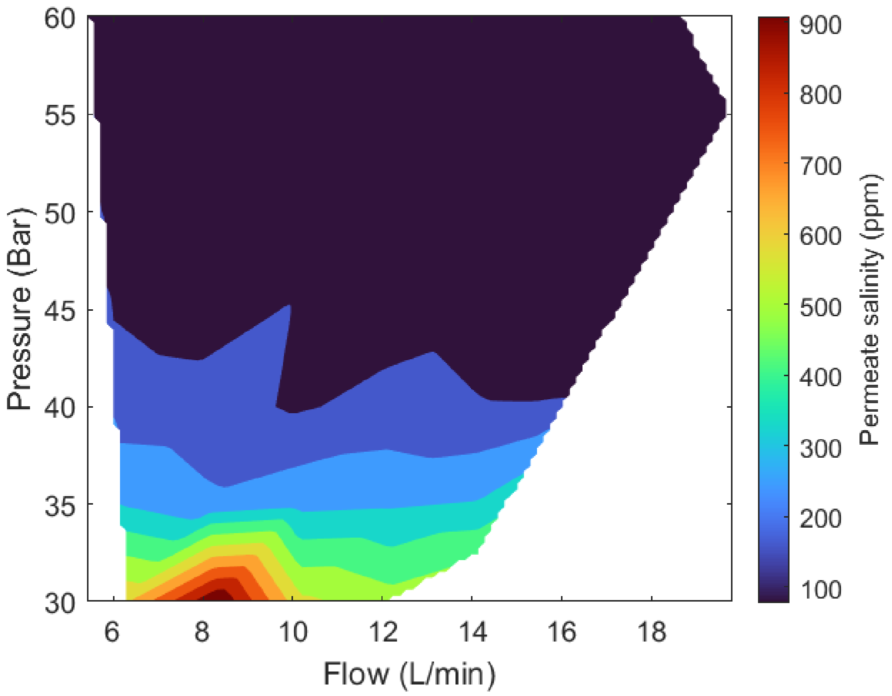


Figure 4b: Contour map permeate salinity for different feed flow and pressure

The performance of the RO membrane (FILMTEC SW30-2540) in the experimental test rig is compared with the numerical results obtained from the WAVE (Water Application and Value Engine) software developed by Dupont. For the numerical analysis, the inlet conditions and temperature values are provided same as the experimental conditions. Figure 4c shows the ratio of permeate recovery obtained from the experiment (R_{exp}) to that of the values obtained from the WAVE software (R_{num}). It is observed that the permeate recovery obtained during the experiment is less than that predicted by the numerical analysis. Similarly Figure 4d shows the ratio of permeate salinity obtained from the experiment (C_{exp}) to that of the values obtained from the WAVE software (C_{num}). In this case also, the salinity predicted by the WAVE software is higher than that obtained from the experiment, which is likely to be due to the use of “pure” salt-water, rather than actual sea-water.

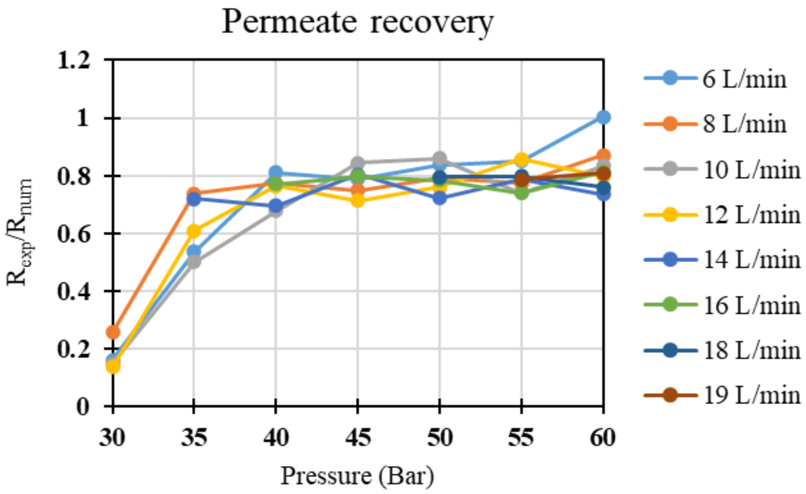


Figure 4c: Ratio of permeate recovery

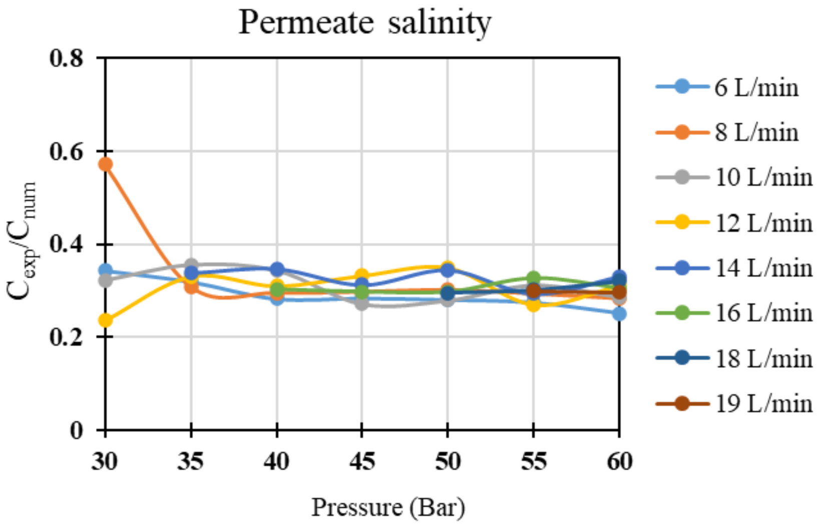


Figure 4c: Ratio of permeate salinity

2. Constant flow and variable pressure

Different tests are carried out at constant flow and variable pressure to compare the performance of the RO membrane with constant flow and pressure conditions. The tests are carried out at 4 different constant flow conditions (10 L/min, 12 L/min, 14 L/min and 16 L/min) for a sinusoidally varying pressure with a mean pressure of 50 Bar. Five different time periods of pressure variations are considered ranging from 5 to 60 sec. Figure 5a shows the ratio of permeate recovery obtained at variable pressure condition (R_{var}) to that of the constant pressure condition (R_{const}) for a fixed feed flow rate. In a similar way, the ratio of permeate salinity for two conditions (C_{var}/C_{const}) is plotted in Figure 5b.

It can be observed that the change in feed flow rate changes the permeate recovery as well as the permeate salinity. However, there is no significant effect of the time period of pressure variation on the permeate production.

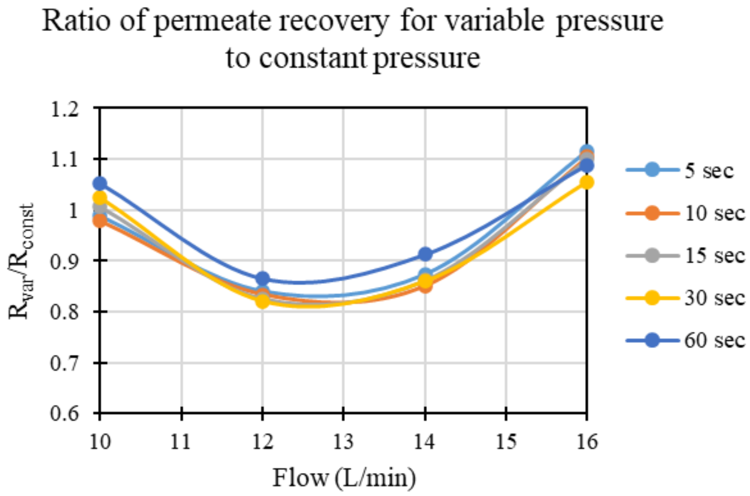


Figure 5a: Ratio of permeate recovery for two different conditions

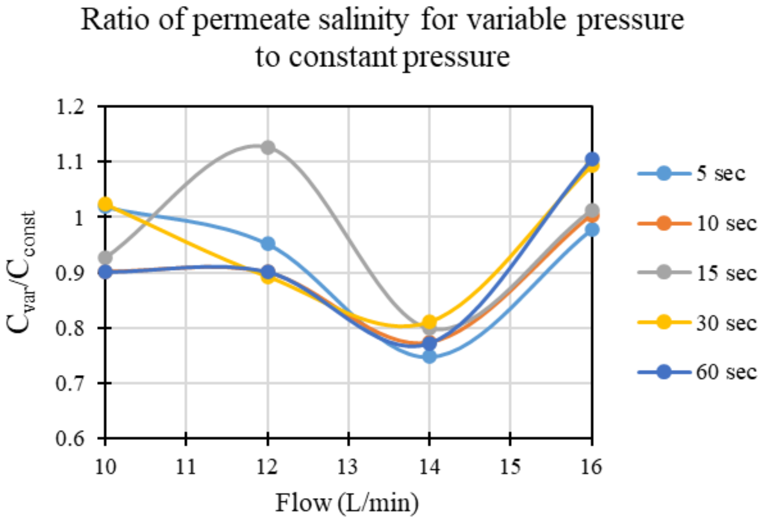
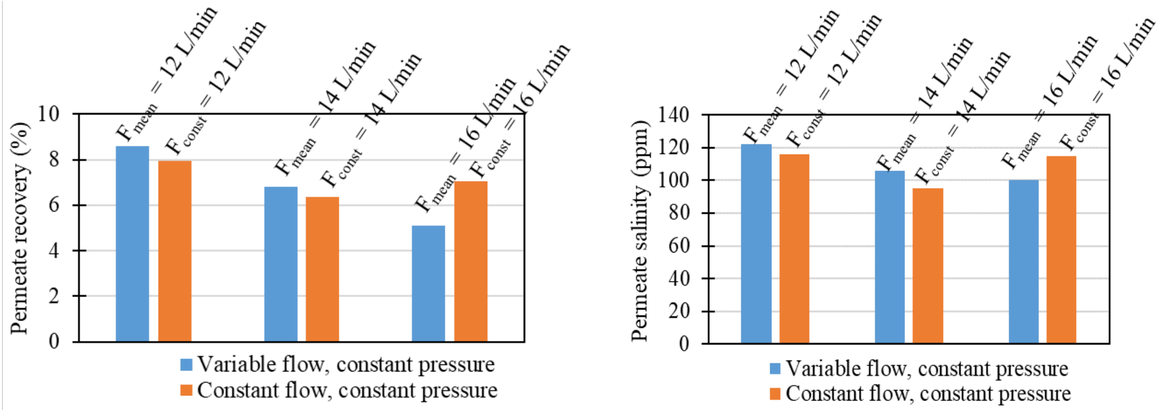


Figure 5a: Ratio of permeate salinity for two different conditions

3. Variable flow and constant pressure

Some experiments are conducted to compare the RO membrane performance when the feed flow varies sinusoidally while the feed pressure remains constant. An actuator needle valve is used at the exit of the RO membrane to control the pressure. Ideally, the actuator changes the position of the needle valve based on the flow condition to keep the pressure constant. However, some variation in pressure exists due to time lag in the pressure sensor and the actuator needle valve. Two different tests are conducted: (a) Sinusoidal flow when mean flow (F_{mean}) varies but time period (T_p) remains constant (b) sinusoidal flow when time period (T_p) varies but mean flow (F_{mean}) remains constant. The results are then compared with the constant flow and pressure conditions.

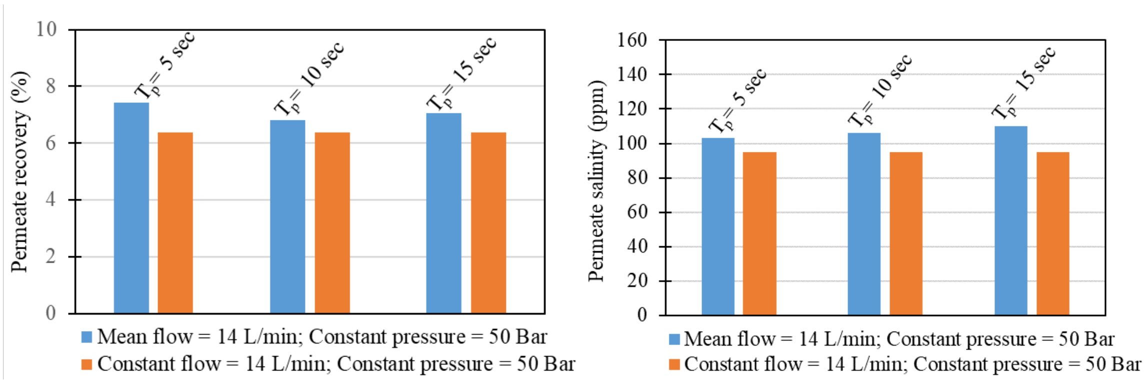
Figure 6 shows the results of sinusoidal flow with constant T_p of 10 second and mean flow varying from 12 to 16 L/min. The feed pressure is set at 50 Bar. The results are compared with constant flow (F_{const}) and constant pressure (50 Bar) conditions. It can be observed that for variable flow conditions, the permeate recovery and permeate salinity are slightly higher than constant flow condition for F_{mean} = 12 and 14 L/min. At higher F_{mean} the permeate recovery and salinity is higher than that of constant flow condition.



(a) (b)

Figure 6 Comparison of (a) permeate recovery and (b) permeate salinity for two conditions: variable flow (same T_p, varying F_{mean}) - constant pressure and constant flow - constant pressure

Figure 7 shows the RO membrane performance for sinusoidal flow with constant mean flow (F_{mean}) of 14 L/min, while the time period (T_p) varies from 5 sec to 15 sec. It can be observed that the sinusoidally varying flow produces slightly higher permeate recovery and permeate salinity compared to constant flow condition. However, the change in time period does not have any significant effect on the permeate production for the time periods considered in the experiment.



(a) (b)

Figure 6 Comparison of (a) permeate recovery and (b) permeate salinity for two conditions: variable flow (varying T_p, same F_{mean}) - constant pressure and constant flow - constant pressure

Task 4: Numerical modelling of wave-powered desalination systems

The numerical modelling the wave-powered desalination systems was completed using WEC-Sim, which is a dedicated 'wave-to-wire' wave energy converter modelling tool that is based on Matlab/Simulink. The top-level WEC-Sim model is essentially the same for both wave energy converter as both extract energy from a single oscillating mode (heave for the Buoy and surge for the OWSC) and is shown in Figure 5. The five blocks shown include a *Global Reference Frame* against which the *Buoy* can react to extract power through the *pto*. The *Buoy PTO* block converts the force and response of the *Buoy* to the *RO* block. The water production is calculated within the *RO* block, which is shown in Figure 6. The numerical model developed here is used for the review of WEC PTO suitability and characteristics, described in Task 1.

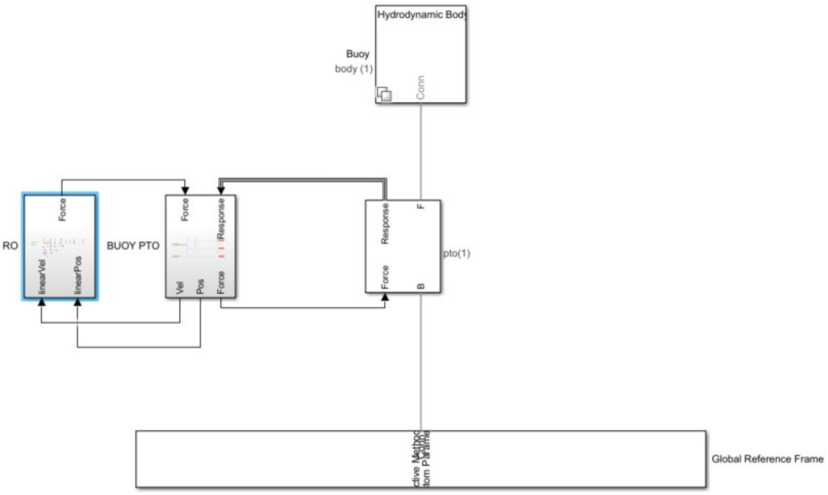


Figure 5: Top-level WEC-Sim model

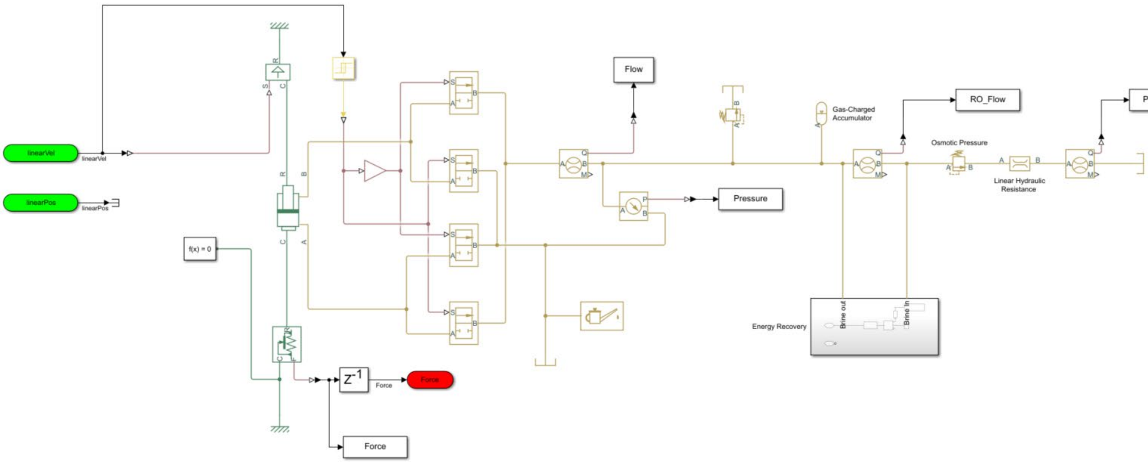


Figure 6: *RO* block of WEC-Sim model

Task 5: Design guidelines for wave-powered desalination

The results of the numerical modelling of the wave-powered desalination system indicates that the Pressure Exchanger-intensifier is better suited as the energy recovery technology for a directly-driven wave energy converter desalination plant when compared to the Clark pump. This is because the Pressure Exchanger-intensifier shows minimal fluctuations in the pressure and flow at twice the wave frequency, whilst there is a clear variation in the pressure and flow when the Clark pump is used. This is illustrated in Figure 1 and Figure 2 for a Buoy WEC with the two different types of energy recovery technologies. This greater suitability of the pressure exchanger-intensifier is true of both types of wave energy converter investigated.

Notwithstanding that the pressure exchanger-intensifier is the preferred energy recover technology for both wave energy converters considered, the performance of the system was different for each wave energy technology, and also varied with the sea-state and dimensions of the wave energy converter. Thus, as with conventional PTOs used in electricity-producing wave energy converters, it is necessary to design the PTO, including the number of membranes and size of the energy recovery technology based on the incident wave climate and the response of the wave energy converter in this wave climate.

The performance of the wave-powered desalination plant can be optimised by varying the effective size of the pump driven by the wave energy converter as well as the number of connected RO membranes within the desalination plant. Because the water pressure is largely driven by the requirements of the RO process, modification of the effective pump size enables the equivalent damping coefficient to be adjusted to match the optimal conditions for the incident sea-state. The effective size of the wave-drive pump could be changed by connecting / disconnecting individual water hydraulic pumps. The number of connected RO membranes needs to be controlled so that the pressure required for the RO process is achieved. If too many RO membranes are connected, then the pressure may be insufficient to overcome the osmotic pressure of the seawater and so no water will be desalinated. Conversely, if too few RO membranes are connected then the pressure may become excessive, and energy will be lost as the pressure relief valve discharges energy to avoid the pressure exceeding the rating of the RO membrane pressure vessels.

The experimental investigation into the performance of the RO membranes in variable flow is that fluctuations in the pressure and flow can cause an increase in the recovery ratio, but with an associated increase in the salinity of the permeate, although not such a large increase in salinity that the water is not potable (<500 ppm). However, it would appear that typically the salinity increases more than the recovery ratio indicating that the fluctuations result in a greater volume of salt passing through the RO membrane. This additional salt flux needs to be accounted for in the sizing and design of the RO plant to ensure that the permeate will always produce water of an acceptable quality.

Other developments and further work

Since the initial proposal of the DesWEC project there has been an increase in interest in wave-powered desalination. In particular, the US DoE developed the challenge entitled the Waves2Water prize, where competitors were invited to develop wave-powered desalination system that would be suitable for disaster relief. This prize attracted twenty entries, which demonstrates the interest in wave-powered desalination, and was won by Oneka, a Canadian company that is focused on wave-powered desalination. A review of the proposals and their statements indicates that many entries had not fully considered the requirements and implications of coupling a variable power source such as wave energy to a desalination system that works most efficiently with a constant power supply. However, the Waves2Water prize has identified this as a critical area of development and the need for projects such as DesWEC that can help to understand how this can be done most efficiently and economically.

The award of funding for an industry-led project through the Centre for Advanced Sustainable Energy (CASE Project A1130, Award Value £100,274) at QUB provides the opportunity for funding further investigation into wave-powered desalination. This funding enables the PDRA employed on this SuperGen Flexible Fund award to continue working in this area. Whilst progress has been made within the DesWEC project in the design of wave-powered desalination plant, further investigation is required to fully understand the implications of the variations in RO feed pressure and flow on the performance of the RO membranes both in the short and long term. The industry-led project will build directly on the work undertaken in this project, with a focus on the use of the laboratory test rig to assess the potential of the technology being developed by Pure Marine Gen Ltd.

The results of the DesWEC project, were presented at the European Desalination Society conference, where interest in the work done at QUB was shown by a wave energy converter developer that attended the conference and are planning to develop a wave-powered desalination technology. Discussions are on-going with this company to assess where further investigations may be focused and identify the potential for collaboration.

Discussions are also on-going with the University of Minnesota to investigate the impact that batch desalination technologies may have on the viability of wave-powered desalination. The current potential source of funding for this research is the US-Ireland grant, which would be a tri-partite collaboration between QUB, University of Minnesota and Maynooth University. In this collaborative project, QUB would research how batch desalination technology may be linked together, the University of Minnesota would research the design of the hydraulic components and Maynooth University would investigate the control requirements.

Finally, one of the Indian universities involved in the US DoE Waves2Water and actively working in the wave powered desalination has also shown further interest in developing a joint proposal under the UK India and Education Research Initiative (UKIERI). Further initiatives will be taken in this regard depending on content of the next call for the UKIERI funding.