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EXPERIMENTAL ANALYSIS OF A HYDRAULIC WIND TURBINE FOR SEAWATER REVERSE OSMOSIS DESALINATION PROTOTYPE

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Abstract

The integration of seawater desalination and wind energy technologies has allowed for the development of a directly wind-driven desalination system, with the potential to address freshwater scarcity issues without contributing to CO_2 emissions. The system described in this manuscript consists of a wind turbine rotor, which employs a hydraulic transmission to directly pressurise seawater into a reverse osmosis desalination plant and a Pelton turbine generator. After building and commissioning of a 44 m hydraulic wind turbine prototype in the port of Rotterdam in the Netherlands, an experimental campaign was conducted to evaluate the operational range and performance of the hydraulic system. A combination of hardware-in-the-loop tests where used to get insight into the behaviour of the integrated system. The control philosophies used for automatic operation and safety of the system are compared and discussed, as well as the system's behaviour in respon e to different wind conditions using dummy elements to replace the desalination module. Technical challenges and achievements of commissioning and testing the system are also described, along with lessons learned.

1 Wind driven seawater desalination

Fresh water scarcity issues affect many areas of the word, that need to depend on desalination plants to obtain water suitable for human consumption and agricultural purposes [1]. These plants are costly to run, primarily because they consume a significant amount of energy, which is predominantly derived from fossil fuel-based power plants [2]. The use of wind energy can reduce the CO_2 emissions related to the desalination process [3]. In particular, integrated technologies might have the potential to be cost-effective and lead the development of renewable energy-driven desalination systems to address freshwater scarcity; however the intermittent nature of the wind resource poses several technical challenges to the desalination technologies which are conventionally operated under steady conditions.

1.1. Hydraulic wind turbine for seawater desalination

The Delft Offshore Turbine (DOT) is a non-conventional hydraulic wind turbine prototype that incorporates an outfitted positive displacement high pressure pump as transmission; the hydraulic transmission can be used to provide pressurised seawater to a reverse osmosis desalination plant, avoiding, in this way, intermediate (electrical) conversion steps. The wind-driven system is composed of three primary subsystems with different functions: the hydraulic wind turbine, the electricity production subsystem and the freshwater production subsystem. During operational conditions, the angular motion from the three bladed horizontal axis rotor of the hydraulic wind turbine is transmitted through the shaft to the high-pressure pump replacing the generator in the nacelle, which pressurizes seawater and directs it to the electricity and water production subsystems. The replacement and relocation of the heavier components such as the generator and power converters to the ground level provides several benefits, among which increased accessibility and reduction of the top mass are particularly relevant in the context of offshore wind [4] [5].

The entire flow rate of the pressurised seawater can be channelled through a spear valve and a Pelton turbine generator, which comprise the electricity production subsystem. Alternatively, the pressurised seawater can simultaneously be directed to both the electricity production subsystem and the freshwater production subsystem, enabling the production of both electricity and desalinated seawater. The freshwater production subsystem comprises the seawater intake, the pre-treatment, the Reverse Osmosis (RO) desalination module and the isobaric Energy Recovery Device (ERD). The seawater intake extracts the water from the source, the pre-treatment filters it and cleans it to make it suitable for being processed by the RO membranes. In the membranes, the salts (brine) are actively separated from freshwater (permeate),

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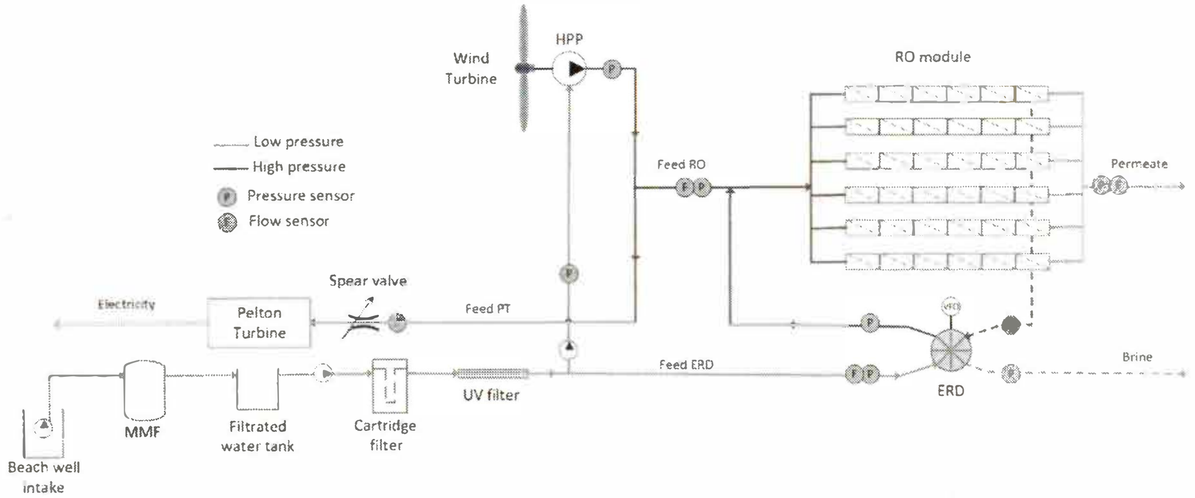

Figure 1: Simplified schematic of DOT 500 PRO hydraulic diagram. In this schematic, the main measurement points for flow (F) and pressure (P) are indicated.

by reverse osmosis mechanism through a pressure difference mechanism [6]. The ERD extracts the high residual pressure energy in the brine to reduce the power consumption needed to pressurise the seawater [7]. A more comprehensive description of the operational principles and technical aspects of the direct-driven wind turbines for reverse osmosis desalination is given in [8], [9] and [10].

A 500 kW prototype of the driven seawater desalination plant was designed and built in Rotterdam, the Netherlands, during 2021.This paper presents part of the experimental campaign results for testing the DOT driven desalination plant prototype.

2 Experimental campaign

2.1 DOT 500 PRO desalination plant prototype

A schematic with the diagram of the desalination plant is shown in Figure 1. The installation, commissioning, and testing of the system were divided into three distinct phases, which were carried out across two different locations. First, tests were conducted at the DOT B.V. workshop without the use of the physical wind turbine rotor. Instead, a simulated wind turbine rotation was created by connecting an electric motor directly to the seawater pump and utilizing hardware-in the loop to mimic the effects of the wind in real time. Afterward, the system was transported to Maasvlakte II, located in Rotterdam, the Netherlands, where further tests were conducted using the simulated wind turbine configuration. In the last phase of testing, the seawater pump was physically installed within the wind turbine, which was then connected both electrically and hydraulically to the reverse osmosis plant. Through this phased approach, it was possible to effectively evaluate the performance of the system in a controlled manner while ensuring that all necessary components were installed and operating correctly.

An overview of the experimental setup described in this paper is shown in Figure 2, where the experimental setup consists of the following parts:

1. Beach well (pump)
2. Multimedia filtration module (MMF)
3. Booster module (BO)
4. High pressure pump (HPP)
5. Hall driver
6. Pelton turbine and spear valve
7. Reverse osmosis module (RO) with flow control valve (FCV)
8. Filtrate water tank
9. Permeate water tank

Raw seawater is extracted by the beach well pump. This water is pre-treated and fed through the sand filters in the multimedia filtration (MMF) module, obtaining filtrated water. This is stored in the filtrate water tank. The filtrate water tank is used as a source for the booster module, in which the pre-treatment of the water is continued and pre-pressurized for the high pressure pump (HPP). A part of the low pressure water is also fed to the ERD in the RO module. In the full seawater desalination setup, the boost pump direct the water to hub height, where, according to the varying wind speed conditions, it is pressurized. Then, the pressurized flow of water is sent to the base of the tower and split between the desalination module and the Pelton turbine and spear valve. In the experimental setup tested in the phase described in this paper, instead, the HPP is placed at ground level and driven by the hall driver The hall driver serves as a substitute for the wind turbine. In the following tests, the HPP will be installed in the nacelle and this motor will be replaced by the wind turbine rotor. The pressure of the water is regulated by the spear valve: the spear inside the valve is used to modify the effective area of the nozzle through a linear actuator, therefore adjusting the pressure and velocity of the hydrodynamic jet provided to the Pelton turbine, that converting it into electrical energy. The water flow to the RO is regulated by the flow control valve (FCV). In the RO system the water is fed through the RO membranes to create permeate

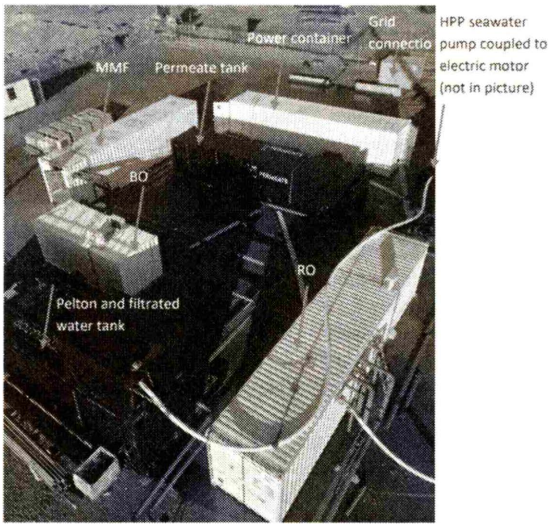

Figure 2: Aerial view of the wind driven desalination testing setup.

water. The main parameters of the prototype plant are shown in Table 1. Observe that the water utilized to operate the Pelton wheel is redirected back into the filtrated water tank, where it can be reused as feed for the membranes. Since this water has already undergone pre-treatment, it is suitable for this purpose. By choosing to recirculate this water rather than disposing of it, the size of the pre-treatment module can be reduced, resulting in a more efficient system design.

Table 1: Main dimension and rated parameters of the DOT500 PRO desalination plant prototype

Parameter	Value	Units
Rotor diameter	44	m
Wind turbine rated power	500	kW
Wind turbine rated wind speed	12	m/s
Pump rated-speed	1500	rpm
Pump nominal flow rate	145	m^3/h
RO module capacity	25	m^3/h
Number of pressure vessels	6	
Membranes per pressure vessel	36	
ERD flow rate range	21-41	m^3/h

Despite having a complete integrated system built and designed for the use of seawater as a working fluid, time constraints and complications arising from the composition of the water sourced from the beach well limited the feasibility of testing with available seawater. Instead the experiments were conducted using tap water and dummy membranes. The dummy membranes are blind flanges with an orifice connecting the high pressure and permeate lines in the reverse osmosis module, simulating the resistance provided to the water flow while permeating across real membranes. In this way, the real membranes were preserved from being clogged after few hours of operation, due to the poor source water quality. However, it is important to mention that the behaviour of real membranes cannot be entirely replicated by the dummy membranes as they cannot account for the changes in the resistance as a function of the feed concentration. In addition, since tap water was used instead of seawater, it is not possible to assess the effectiveness of the measures adopted against seawater corrosion.

2.2 Methodology

This manuscript presents steady state tests and dynamic tests. In the first case, the system is tested in steady state conditions for increasing wind speed as input in steps of 0.5m/s or 1 m/s, with values varying between 4 and 9m/s. Given the pitch angle, the corresponding rotor speed i simulated with the associated HPP rotational speed. An electric motor powered by the grid is activated and adjusted to drive the HPP which pumps pressurised water through the system. When the system is in electricity production mode only, the flow control valve is kept closed and all the water is directed to the spear valve. When the freshwater production is activated the flow control valve is opened, so that part of the flow can be directed to the RO desalination module, up to the 17% of the HPP rated flowrate. The pressure and flow are measured in different points of the system according to the schematic in Figure 1. In between each wind step, time is given to let the system reach steady state again. The tests are repeated for varying spear valve positions. An example of such a test is given in Figure 3, for a span of 20 minutes, where the following graphs are shown, from top to bottom: the simulated rotor (blue) and corresponding HPP (red) rotational speeds, next is the spear valve and flow control valve opening positions, then the measured pressures and the last graph shows the measured flow rates the system.

In the second type of tests, the system is tested in unsteady wind conditions. These dynamic tests are performed with a fully automated system and a simulated wind turbine with the so called Hardware-In-The-Loop (HITL) approach. This approach involves the integration of real hardware components, that are the desalination, the electricity production subsystem and the electromotor driving the high pressure sea water pump, with simulated elements, in this case, the rotor. The simulation model is executed in real-time, providing input signals to the physical system, which responds by producing output signals that are measured and fed back to the simulation model. In this case, a realistic wind speed profile is modelled and simulated through the software, that communicates through the PLC to get feedback over the pitch angle of the blades, and then calculates the virtual rotor rotational speed and the corresponding input to the electric motor to drive the HPP. The instrumentation system collects the required data from the physical system via pressure and flow rate sensors, which provide feedback to the software about the counteracting torque provided by the desalination and electricity production systems to the HPP in those specific wind conditions.

2.3 Numerical model description

An in-house numerical model was used to simulate the behaviour of the wind powered desalination plant when subject to the environmental loading from varying wind speed conditions in order to compare with the experimental results. The integrated dynamic model is based on physical principles for each of the main components and their interaction. The simplified aerodynamic characteristics of the rotor are defined based on its geometric features [11] and non-dimensional steady-state performance coefficients obtained by DOT B.V in a previous experimental campaign. Aero-elastic and unstable aero-dynamic effects are not taken into account in this simplified model. The fluid power transmission is represented using quasi-steady relationships for torque and volumetric flow rate. The model assumes a rigid connection and couples the pump and aerodynamic torque transmitted by the rotor through the equation of motion.
The transport mechanism of the reverse osmosis desalination is characterised using the solution-diffusion model, in combination with empirical equations that accounts for factors such as concentration polarization and the influence of temperature [12], [13]. The ERD simplified model is based on the conservation of mass principle. It is assumed that the leakages are proportional to the flow rate; in addition, the increase in concentration of the pressurized seawater flow at the exit of the ERD is considered proportional to the difference in concentration between the brine and seawater feed flow to the ERD using the overflush as an operational parameter. An auxiliary boost pump is integrated together with the ERD to compensate any pressure losses. It is assumed an ideal boost pump, either with variable speed or variable volumetric displacement, that is able to adjust the output flow to a reference value using a characteristic time constant. Regarding the Pelton turbine generator, the model takes into account the spear valve that directs the flow towards the Pelton wheel, regulated by an actuator, and described with the Bernoulli's equation for incompressible flow. Hydraulic lines and the additional pressure losses through pipes are not considered, since their impact on the system under operating condition is considered negligible.

The numerical model provided the sufficient preliminary information for designing the system and predicting its performance under various conditions. The outcomes obtained from the steady state and dynamic model were employed to propose an operational strategy first, and to design the pilot prototype and the experimental test plan. The results of the simulations provide valuable insights into the behaviour of the wind-powered desalination plant and can be later used to optimize its performance.

2.4 Theoretical control philosophy

The steady state results from the numerical model were used to identify the system settings that allow for maximum freshwater production for the prototype design and operational constraints. The potential regions of operation were identified taking into account the safe operation of the wind turbine rotor, the required electricity production to power the auxiliary equipment, and the physical and chemical constraints of the reverse osmosis process and membranes. An operational strategy was proposed within the safe operation envelope to maximize freshwater and electricity production.
The proposed operational strategy, described in detail in [9], can be summarized as follows: no water is sent to the desalination unit under osmotic pressure conditions, and all flow is used for electricity production. In this operation mode, the system is said to be in electricity production mode. The FCV is maintained in closed position, while the SV is passively controlled and held at constant opening. At lower wind speeds, the pitch angle is fixed. However, if the wind speed reaches a level such that the maximum RPM of the rotor is obtained, the rotor begins to pitch in order to maintain this maximum RPM. When osmotic pressure is reached, water production can start. To transition from electricity production only to water production too, the SV is initially closed to a smaller opening, which increases the pressure within the system and results in a lower rotor RPM. Once this is accomplished, the RO system can be started, and the FCV can be slowly opened. During water production at pressures below 40 bar, corresponding to the maximum flow allowed through the RO system, the FCV is actively controlled to regulate the flow towards the RO system. When rated pressure is reached, the FCV is fully opened and the SV is actively controlled. In this manner, the pressure and flow downstream the FCV are kept at the rated values. At this point, the desalination unit operates at a constant operating point, and electricity production increases until maximum flow rate or rotational speed is reached. Finally, when the rotor reaches its maximum rotational speed due to higher wind speeds, the blades are pitched. The consequences of this operational strategy were evaluated in the experimental campaign results, as described in the next section.

3 Results

3.1 Steady state tests results

In Figure 3 an example of the typical test and results in steady state conditions is presented. In the top subfigure, the simulated rotor rotational speed (blue) corresponding to step wise increase in the wind speed, and the consequent measured rotational speed of the HPP (red) are visualised. Due to the rigid connection between the rotor and the pump shaft, the two speeds are proportional. The selected spear valve and flow control valve positions are visualised in the second figure from the top. The values are represented as percentages, calculated considering the actual area available for the flow to pass in a specific nozzle position with respect to the total area available in case of fully open valve, i.e. a value of 0% corresponds to a fully closed value, and no flow allowed, while a 100% value corresponds to a fully open valve. It is possible to see that the SV is kept to a fixed position for the entire duration of the test, as one of the goal of these tests was to map the operating point of the system per each spear valve position.

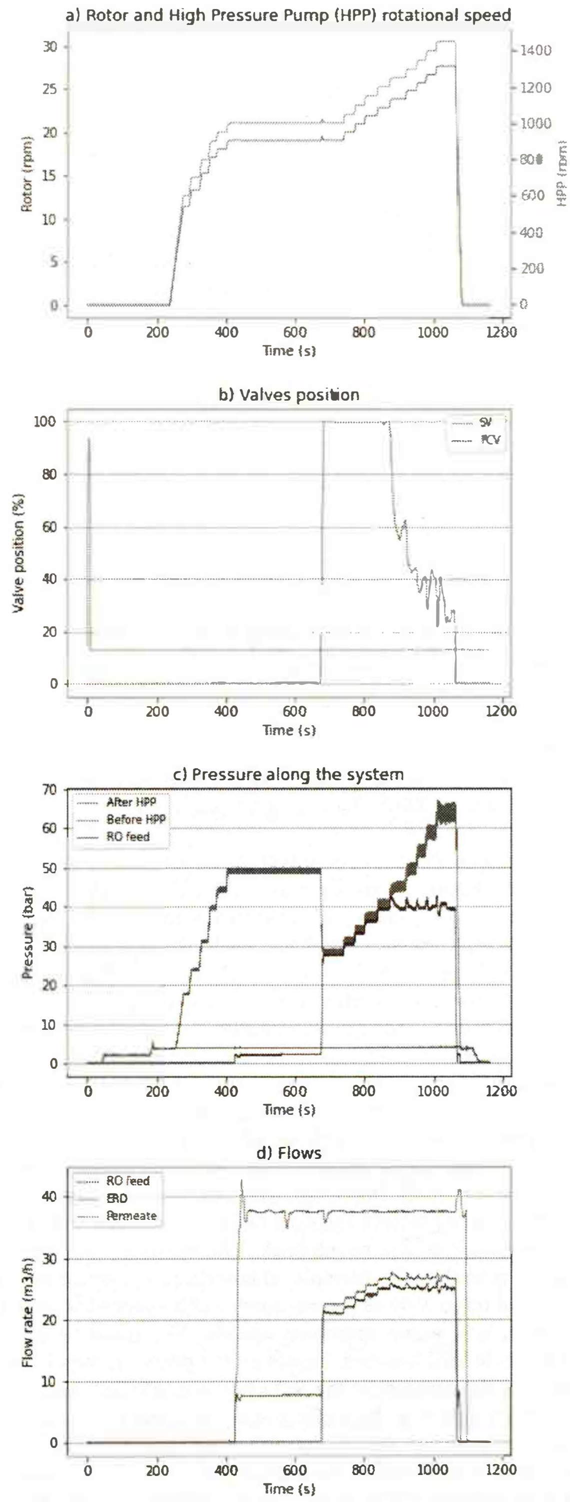

Figure 3: Steady state test example.

The FCV is kept closed for the first half of the test. This means that the system is on electricity production mode only, and the water production is not started. Therefore, the pressure in the system, measured after the HPP (in red in the third subfigure from the top) increases step wise following the increase in rotational speed of the rotor. In the same subfigure, the pressure of the water before being pressurised by the HPP (in green) and the pressure in the RO module, as measured just after the FCV valve, are also shown. After about 400s, the preparation for water production starts, so that part of the filtrated seawater coming from the boost pumps is circulated to the ERD (in green in the last subfigure). This start up procedure is necessary in order to safely start water production when the membranes will be installed. After 650 s, the FCV is finally opened and set to 100% (fully open) to enable part of the flow from the HPP to feed the RO module and start the permeate production. As a consequence, the pressure in the system drops from 50 to 30 bar. After steady state is reached, the wind speed is again increased stepwise, as it is visible from the increased rotor and HPP rotational speed. The pressure after the HPP and at the inlet of the RO module increases accordingly. The difference in between the two values is due to mainly the pressure drop in the FCV. Also the flows follow the increase. In this case, it is important to notice that theoretically, due to conservation of mass inside the system and to the presence of the ERD, the RO feed flow and the permeate should have the same values, besides few leakages and losses. However, the permeate flow results show higher values. This discrepancy is caused by the difference in the accuracy of the two flowmeters used for the measurements. After around 900 s, the maximum flow allowed to the RO module is reached, 25 m^3/h, and therefore the automatic control system is activated. Since the SV position needs to be kept fixed, the regulation of the pressure and flow of the system relies on the FCV, that is being progressively closed to maintain the pressure and the flow in the RO desalination module almost constant.

In Figure 4 the results from the steady state tests executed with a variety of spear valve openings is shown, and compared with the results from the model simulation. The figure presents the pressure as a function of the flow rate. In grey the pressure-flow curves corresponding to the aerodynamic torque on the rotor for constant wind speeds are visible. The aerodynamic torque is translated to pressure by means of the high-pressure pump with constant volumetric displacement. Similarly, the maximum torque and maximum power curve from the rotor are translated in the corresponding pump torque and pump power, shown as dashed black lines in the plot. The maximum torque delimits the region of instability for the hydraulic wind turbine. In this region, for a change in wind speed, the aerodynamic torque exerted on the rotor is not necessarily counteracted by a change in the pump torque, and an equilibrium point might not be found. In the picture, each solid coloured line represent the results from the model simulation with a fixed SV opening position, in electricity mode only. In the same colour, the markers show the experimental results with the same SV opening position; the marker is filled in case of electricity production mode only, or empty, when the RO module is active and permeate is also produced. In the first case, there is a good matching between simulated and experimental results, with the markers overlapping the solid

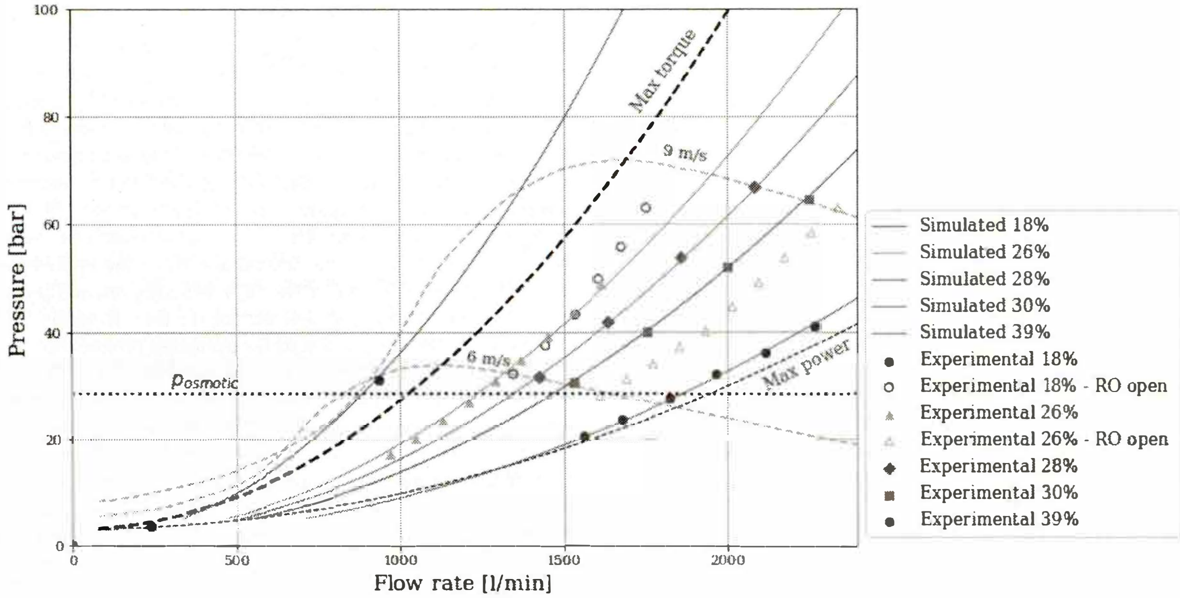

Figure 4: Comparison of static model and test results for the hydraulic resistance of the combined spear valve and RO dummy membranes. Each set of data shown in the legend corresponds to a spear valve opening position, expressed as a percentage of the available area of the fully open valve.

lines for all experimental cases. However, when the water productions starts, the results differ, with the experimental results displaying that for the same flowrate a lower pressure is measured in the system. This difference can be explained considering the fact that, in water production mode, the FCV is open, and part of the flow is diverted to the RO module. This means that a higher load is exerted on the high pressure pump, and higher flow rates are needed to reach the same pressure in the system. However, the simulation doesn't takes into account for the water production mode, and therefore this change in the line trends cannot be displayed in the figure.

3.2 Results of tests in dynamic conditions with HITL

An example of the results from the dynamic tests with a stochastic wind signal is visible in Figure 5. This test was executed with a simulated wind profile based on a real wind data, adjusted to have all ranges of operation. The wind profile used is characterised by an average wind speed of 8.2 m/s and turbulence intensity of 0.14. First, the system is started and manually set to have a constant HPP rotational speed of 900 rpm to make sure the setup is running properly. Time is given to achieve the wanted rotational speed and avoid abrupt increases in pressure in the system. During this time, the SV is kept at a fix opening position, and the FCV is close, as visible in Figure 5b. When 40 bar of pressure are reached in the system, represented by the red line in Figure 5c, flow is directed by the boost pump through the ERD and it is made circulate in within the RO module, as shown in Figure 5d. At this point, the system is ready for starting water production. Then, at around 480 s, the wind simulation is started.

In accordance with the operational strategy described in section 2.4, when water production starts, the FCV is opened. As a consequence, the pressure in the system after the HPP reduces, while there is pressure built up inside the RO module. For lower wind speeds the FCV is actively controlled to maintain the rated flow downstream. For higher wind speed, when the flow directed towards the RO module exceeds the maximum allowed of 25 m^3/h and the FCV has reached the maximum opening, the regulation of the pressure additionally relies on the active control of the SV. The SV opens to deviates more flow towards the Pelton turbine, while the pressure at the RO module is kept below rated values. Not exceeding the rated values is extremely important when the real membranes are installed, since pressure and flow rates above design values can induce failure of the membranes. The result of this type of control is visible, for example, at around 620 s, where the SV is opened up to 80% as a consequence of a sudden increase in the rotor and pump rotational speeds. The pressure in the system is indeed lowered. However, the pressure drop is such that even the pressure at the RO system is affected, causing a significant decrease. This effect is not desirable, since sudden drops in pressure inside the RO membranes might cause damages, or accelerate wear and fatigue.

Overall, despite experiencing some oscillations, the system remains stable, even though the permeate slightly exceeds the imposed constraint of 25 m^3/h. This overflow is likely because the FCV control is based on the flow measurements, while the SV controller is based on pressure measurements: flow

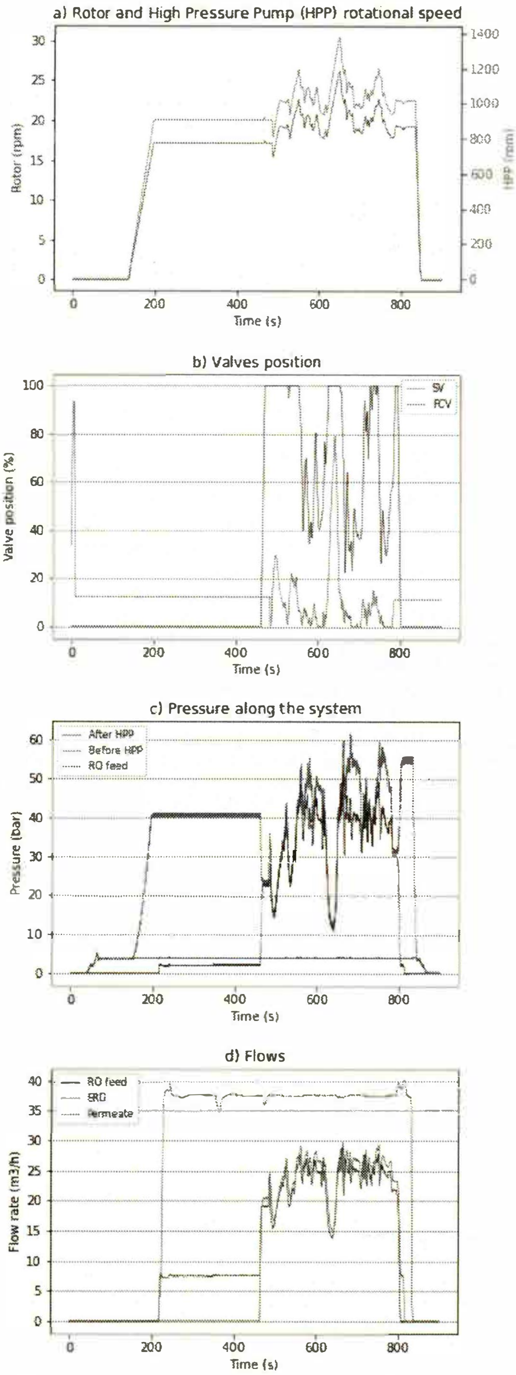

Figure 5: automated operation of the plant with a simulated wind turbine rotor with HITL.

changes are relatively slow compared to pressure reaction times, that are nearly instantaneous. For even higher wind speeds, active pitch control is activated together with SV active control. However, it was observed that the pitch control was interfering with the SV control, which is undesirable and requires further investigation.

4 Discussion of results and lessons learned

The outcomes of the experimental campaign offer significant insights into the DOT driven desalination plant, which can be used to optimize its design and performance, and to improve its operational strategy.

The steady state results show that there is agreement between the simulation and experimental data. However, the numerical model needs to be implemented in order to be able to simulate the behaviour of the system during water production. The HITL dynamic tests allowed to test the limits of the system and make sure that the operational strategy selected allows stable operations. However, there is still room for improvement, given that significant oscillations in rotor speed and system pressure have the potential to cause wear and tear on the system. A critical factor and design choice is the point in which water production is started. In fact, the starting of the RO module implies a series of operations and procedures that require time. In addition, as soon as the FCV is opened, the system perceives a decrease in the pressure, that affects the counteracting torque on the rotor. Considering that water production can only be started when osmotic pressure is reached, a decision on when to open the FCV has to be made. If the FCV is opened too early, the pressure in the system can drop below the required reverse osmosis threshold and desalination is not possible anymore. Even when this is not the case, a premature opening in cases of low wind speeds can cause a frequent starting and stopping of the system, that is neither beneficial for the desalination module, nor for the rotor, that could easily stall.

It has been seen from the tests that it is better to keep the time where it is needed to actively control the SV, FCV and pitch simultaneously to the minimum, since the controllers do affect each other, making more difficult to avoid fluctuations of pressure and flows in the system. These fluctuations can be reduced, for example, by reducing the reaction time of the FCV, making its control pressure based instead of flow based. Despite this, the operational strategy resulted effective to maintain the rotational speed and the water pressure under the maximum levels.

The use of dummy membranes was useful to be able to commission the system during simulated water production, and test the operational strategy, without risking compromising the real membranes. However, no conclusions could be made about the effectiveness and efficiency of the desalination process itself since real membranes were not tested. The installation of the membranes was not possible due to lack of time and issues with the feed water source, that resulted to be of inferior quality as expected. As a consequence, the selected pre-treatment, that is extremely location and water-source dependent, could not guarantee the required quality for the RO membranes. Dummy membranes can only provide information about the pressure and the flow related to the water production subsystem, and therefore on the corresponding load on the wind turbine. Real membranes will be integrated in the system and tested, to evaluate the effect of the operations on the water quality, after improvements to the water pre-treatment system are incorporated. Thanks to the carried tests, it was possible in a following phase to safely test the setup with the hydraulic wind turbine.

5 Conclusions and recommendation

The end result of the experimental campaign described in this paper was a fully automated DOT driven desalination plant prototype with a simulated rotor and dummy membranes. Inputs to the system were salt water from the installed beach well, and the wind as a source to power the hydraulic drive train of the wind turbine. On the output side, the setup was capable of generating electricity via the Pelton turbine, with the possibility to deliver the power back to the grid. The seawater reverse osmosis unit was ready for membrane installation, and thus to produce permeate water. Important know how related for the design, building and operation of such a complex system was gained through the experimental work. The tests provided insightful information about the limits and behaviour of the system, as well as giving a feedback on the operational strategy selection. In addition, thanks to these tests, it was possible in a later phase to test the system with the real wind turbine. Future steps will regard the testing of the full system with the integration of the membranes and seawater.

Acknowledgements

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