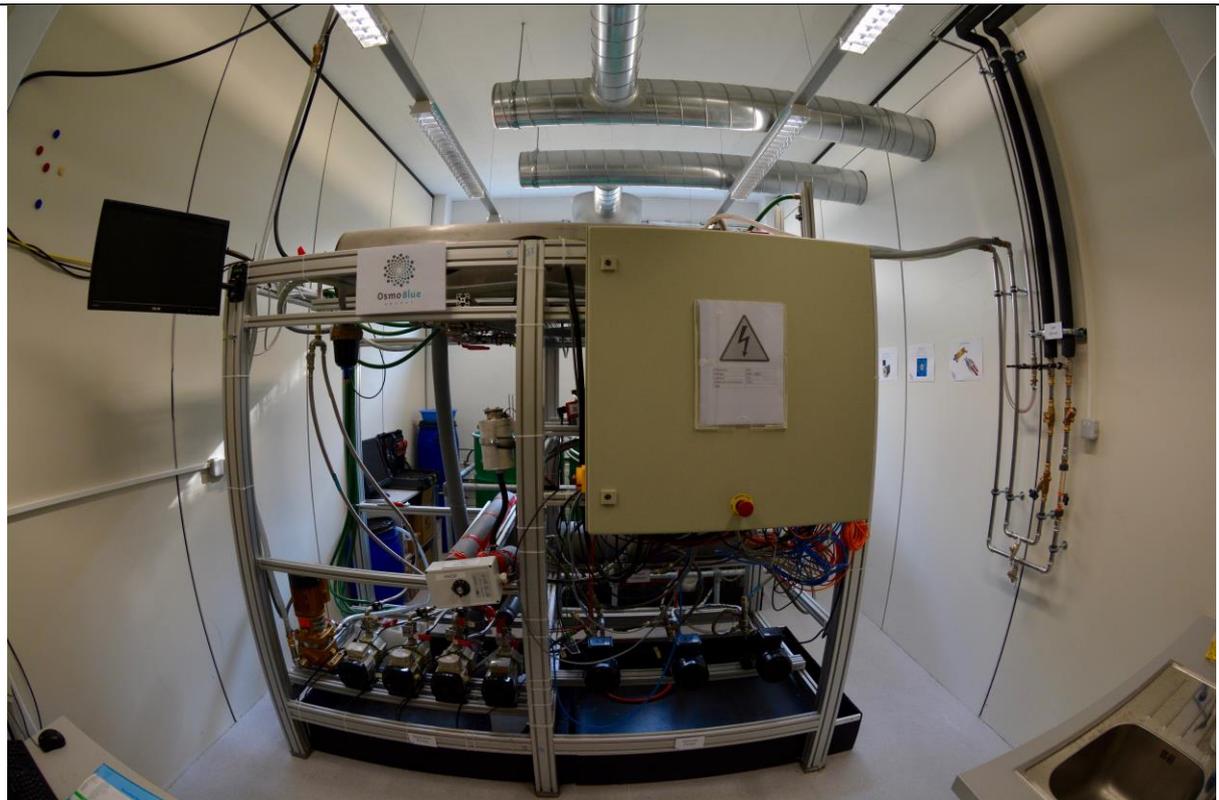




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Osmotic Heat Engine to Recycle Low-Temperature Industrial Waste Heat





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Zusammenfassung

Die positive Energiebilanz des osmotischen Wärmekraftmaschine von OsmoBlue wurde validiert. Hitze bei 80° C wurde verwendet, um einen Konzentrationsgradienten zwischen zwei Lösungen zu erzeugen, die wiederum einen osmotischen Fluss durch eine Membran induziert. Dieser Prozess, der in einem geschlossenen Regelkreis betrieben werden kann, hat netto ein elektrisches Äquivalent von einigen Watt erzeugt. Experimente wurden ausgeführt, um die Leistungserzeugung der Wärmekraftmaschine bei verschiedenen Konzentrationen des osmotischen Mittels, bei verschiedenen Strömungsgeschwindigkeiten und bei unterschiedlichen Hydraulikdrücken zu charakterisieren. Parallel zu diesen Experimenten entwickelten wir ein numerisches Modell, das erlaubt, die Betriebsbedingungen vorherzusagen und zu optimieren, um die osmotische Strömung durch die Membran zu verbessern. Entscheidend war, dass das Projekt geholfen hat, die relevanten Schlüsselparameter zu identifizieren, um die Motorleistung zu verbessern, resp. anzuheben und die Kosten zu reduzieren. Die Ergebnisse zeigen, dass die Qualität der Regeneration des osmotischen Gradienten nach der Energieerzeugung wesentlich ist, um eine gute [osmotische] Nettoleistung zu erhalten.

Résumé

Le bilan énergétique positif du moteur thermique osmotique OsmoBlue a été validé. De la chaleur à 80°C a été utilisée pour générer un gradient de concentration entre deux solutions, qui ont induit un flux osmotique à travers une membrane. Ce procédé, qui peut fonctionner en boucle fermée, a permis de produire un équivalent de quelques Watt électriques nets. Des expériences ont été réalisées pour caractériser la génération de puissance de la machine thermique à différentes concentrations d'agent osmotique, différents débits et pressions hydrauliques. Parallèlement à ces expériences, nous avons développé un modèle numérique qui a permis de prédire et d'optimiser les conditions opératoires afin d'améliorer le flux osmotique à travers la membrane. Plus important encore, ce projet nous a permis d'identifier les paramètres clés qui doivent être améliorés afin d'améliorer la performance de la machine et son coût. Les résultats montrent que la qualité de la régénération du gradient osmotique après la production d'énergie est indispensable pour obtenir une bonne puissance nette.

Abstract

The positive energy balance of OsmoBlue's osmotic heat engine has been validated. Heat at 80°C was used to generate a gradient of concentration between two solutions, that induced an osmotic flow through a membrane. This process, that can be run in a close-loop, provided an equivalent net electricity of a few Watt. Experiments have been performed to fully characterize the power generation unit of the engine, testing different operating conditions: osmotic agent concentration, hydraulic pressure applied and flow rates. In parallel to the experiments, we developed a numerical model that allowed to predict and optimize the operating conditions to enhance the osmotic flow through the membrane. Most importantly, this project helped us identify the key parameters that need to be improved in order to enhance the engine's performance and reduce its cost. The results show that the quality of the re-generation of osmotic gradient after power generation is essential to obtain a good osmotic net power.



Table of Content

Zusammenfassung	3
Résumé	3
Abstract	3
1. Context	5
2. Project Objectives	5
3. Framework	5
4. Concept – Description of the Installation	6
4.1. Osmotic Heat Engine (OHE)	6
4.2. Lab prototype	7
5. Procedures and Methods	8
5.1. Membrane selection.....	8
5.2. Osmotic flow measurements and protocols	8
6. Results	9
6.1. Osmotic flow optimization	9
6.2. Osmotic power generation: Characterization and Optimization of the PRO process.....	9
6.3. Numerical simulation.....	11
6.4. Prototype validation in closed-loop configuration	11
6.5. Economical validation	13
6.5.1. Target market	13
6.5.2. Cost calculation	13
7. Discussion	15
8. Conclusions	16
9. Perspectives and Next Steps	16
10. List of abbreviations	17



1. Context

OsmoBlue is a startup company, founded in 2013, developing an innovative heat engine to recycle low-temperature (<150°C) industrial waste heat. The OsmoBlue system is a hydraulic circuit based on the natural phenomenon of osmosis; built at different scales the potential is there to produce from hundreds of kW to several MW of electricity.

Early in 2013, OsmoBlue developed and validated a numerical model defining the osmotic heat engine specificities with a positive energy balance.

Early 2015, a lab-prototype had been assembled and tested. In this first version of the prototype, standard and commercially available equipments were used (such as pumps, valves, heat exchangers, tanks), except for the custom-made osmotic membrane.

While this engine gave initial results, the performance was limited due to the small size and poor performance of the custom-made membrane module. The objective of this project was to implement a commercial-size module to validate the energy balance of the prototype.

2. Project Objectives

The objective of this project was the production of a few watt of electricity to validate the positive energy balance of this lab-prototype. The osmotic membrane and the membrane module are key elements in order to optimize its performance. A boiler provides the heat to the engine. In parallel to the technological progress, the economical validation of the final product was assessed at different operating conditions (temperature, power capacity).

Thanks to this lab-prototype validation, OsmoBlue will be ready to establish industrial partnerships. This represents a key step towards realization of a pilot unit in the field and commercialization of OsmoBlue's technology.

3. Framework

In this project, OsmoBlue partnered with the company Kera-Coat, based in Spain. Kera-Coat has a strong expertise on conception, design and fabrication of condensers. Kera-Coat develops an innovative technology for flue gases condensation, using coatings resisting to corrosion. Kera-Coat brought a valuable input on the design, choice, cost estimate and cost study of the condenser and engine's implementation.



4. Concept – Description of the Installation

4.1. Osmotic Heat Engine (OHE)

Osmosis is a natural phenomenon observed when two solutions of different salt concentrations are flown on each side of a semipermeable membrane. An osmotic flow is naturally induced and permeates through the membrane, from the low-concentrated to the highly concentrated solution. The osmotic pressure difference between the two solutions, $\Delta\pi$, expressed in bar can be measured with an osmometer.

Instead of using salt (sodium chloride), commonly used as an osmotic agent, OsmoBlue develops and synthesizes its own osmotic agent. This osmotic agent presents the following properties: i) higher osmotic power than seawater (up to 80 bar); ii) thermal properties allowing its re-concentration at low-temperature heat (30-250°C). OsmoBlue's strength lies in the development of innovative thermally sensitive osmotic agents. OsmoBlue developed a first osmotic agent, thermally sensitive from 40 up to 70°C, that has been used in this prototype validation.

OsmoBlue's system is a hydraulic circuit made of standard industrial equipment (pumps, heat exchangers, turbine, membrane). Two solutions of different osmotic agent concentrations (draw solution = high concentration, feed solution = low concentration) are pumped on each side of a semipermeable membrane. The mechanical energy of the resulting osmotic flow through the membrane is turned into electrical energy through a water turbine. This process is called Pressure Retarded Osmosis (PRO). After osmosis, the gradient of concentration is regenerated using low-temperature heat. The closed-loop process constitutes what is called an Osmotic Heat Engine (OHE).

The figure below describes the process of the OHE. The Feed and Draw pumps are used to pump the Feed and Draw solutions on each side of the membrane. We flow the Draw solution at a higher pressure (High Pressure, HP) than the Feed solution (Low Pressure, LP), resulting in a hydraulic pressure (ΔP) across the membrane. The hydraulic pressure is equal to half of the osmotic pressure difference ($\Delta\pi$) between the draw and feed solutions. This leads to a maximized power generated, as described in the literature¹.

The use of a Pressure exchanger (PX), a passive mechanical device used to recover energy from a pressurized flow, helps reduce the osmotic process' pump consumption. This way, instead of using a high-pressure pump for the draw solution, we use a pressure exchanger to pressurize the entering draw solution. The pump PX is a circulating pump, directing part of the membrane outlet high-pressure flow into the pressure exchanger. This high pressure is transferred to the entering draw solution. The pressure exchanger has a very high efficiency of up to 95%.

After osmosis, the draw solution has been diluted and the gradient of concentration needs to be re-generated. The osmotic agent is thermosensitive. Heating up the Mix solution results in the re-concentration of the osmotic agent in one part of the solution. The highly concentrated part of the liquid constitutes the draw solution and the low concentrated part the feed, which are sent to two separate tanks. Before sending them to the tanks, Feed and Draw solutions are cooled down to ambient temperature; the temperature at which the osmotic process is performed.

¹ "Pressure retarded osmosis: From the vision of Sidney Loeb to the first prototype installation - Review" Achili et al., *Desalination* 261 (2010) 205–211; doi:10.1016/j.desal.2010.06.017

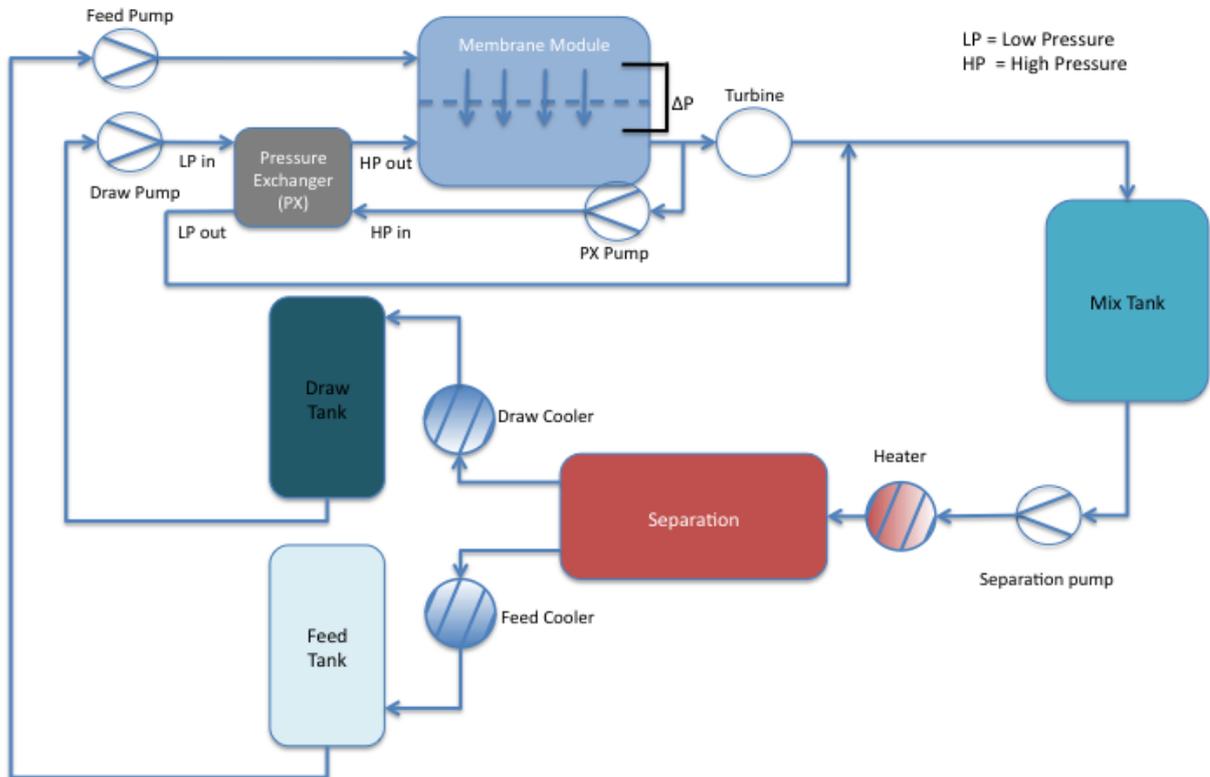


Figure 1: Simplified process flow diagram of the Osmotic Heat Engine. Feed and Draw solutions are flown on both sides of a semipermeable membrane. The mechanical energy of the osmotic flow induced through the membrane is converted into electricity by a water turbine. After osmosis, the mixed solutions are heated up. Thanks to its thermosensitive nature, the osmotic agent is reconcentrated, and the gradient of concentration between feed and draw solutions is regenerated. The solutions are cooled down back to ambient temperature before performing osmosis again.

At this prototype scale, we did not implement a water turbine. In the present setup, the turbine has been replaced by a regulation valve mimicking the pressure drop through the turbine. Measurement of the flow rate and pressure are used to calculate the turbine power production, assuming a turbine efficiency of 90% (efficiency of a Pelton turbine).

4.2. Lab prototype

OsmoBlue's osmotic heat engine lab prototype is made of standard industrial equipment. In the framework of this project, we implemented a new and larger membrane module to validate the positive energy balance of the system.

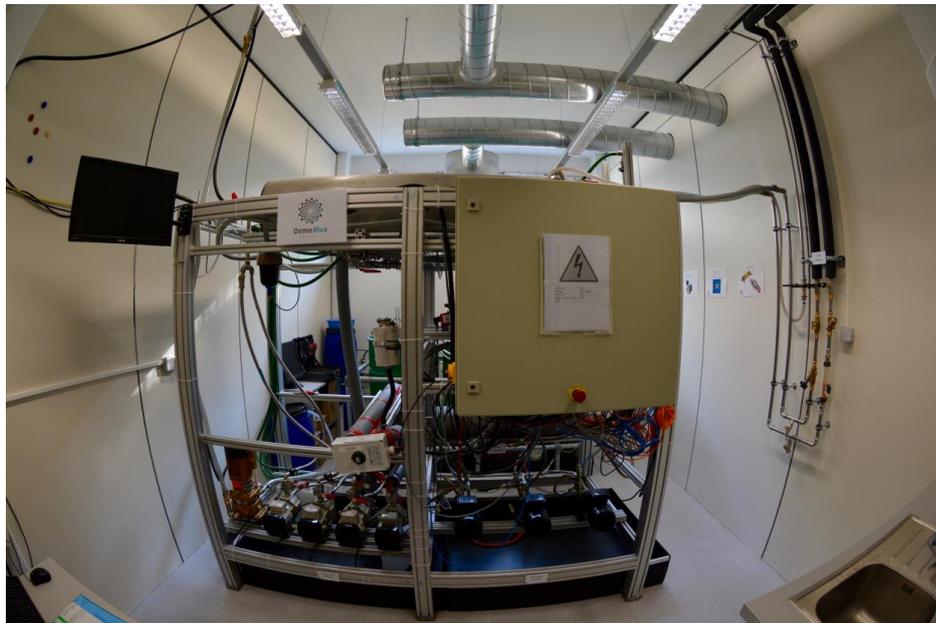


Figure 2: Picture of the osmotic heat engine lab prototype at OsmoBlue's facilities.

5. Procedures and Methods

5.1. Membrane selection

In the lab prototype of OsmoBlue's osmotic heat engine we have implemented a large size membrane module (60 m² of membrane area) that can support high hydraulic pressures up to 40 bar. Cellulose acetate membranes have been chosen for their good chemical stability and their wide availability in commercial membrane modules.

5.2. Osmotic flow measurements and protocols

The engine is controlled by several flow, pressure and temperature sensors along the circuit. The data is monitored through a control software. We installed some more accurate flow sensors at the outlet and inlets of the membrane for a better measurement of the osmotic flow. The pumps are controlled by the software through frequency controllers. The circuit contains different paths controlled by manual 3-way valves. After several tests, a protocol, a starting procedure and a membrane rinsing procedure have been put in place to run the engine.



6. Results

6.1. Osmotic flow optimization

At the bench scale, we performed tests on small membrane samples. These experiments aimed at enhancing the osmotic flow through the membrane. Membrane surface modification by adjustment of the pH solution, as well as vibration of the membrane to enhance the flow mass transfer failed at improving the permeate flow through the membrane. Therefore, we are focusing our efforts on other ways to improve the osmotic flow by:

1. Screening and testing stronger osmotic agents presenting higher osmotic power (higher than 80 bar). OsmoBlue identified several osmotic agents that have osmotic pressure up to 170 bar, resulting in a gain of a factor of 2 in osmotic flow.
2. Screening highly permeable membranes developed by different membrane companies. Although they are still at development stage, membranes with carbon nanotubes hold a high potential. OsmoBlue is in contact with different companies that will provide samples to be tested.

6.2. Osmotic power generation: Characterization and Optimization of the PRO process

We first characterized the PRO process with the newly installed commercial-size membrane module. At the prototype scale, we measured the osmotic flow for different concentrations of osmotic agent in the draw solution. These measurements and trends were consistent with the theoretical results described in the literature for the PRO process. Indeed, as expected, the higher the concentration in our draw solution, the higher the osmotic flow and power produced. For each draw solution concentration, an optimum hydraulic pressure needs to be applied across the membrane, to maximize the net power produced. The newly installed membrane module and osmoblue's osmotic agent lead to a good osmotic flow (up to 5L/min at 20 bar) and an associated Equivalent Net PRO power of 140 W for 25% of osmotic agent in the draw solution.

The osmotic flow has been experimentally measured for each data point in figure 3 and 4. The gross power turbinized has been calculated: $\text{Gross power} = \text{Osmotic flow} \times \Delta P \times \text{Turbine efficiency (90\%)}$. The Equivalent Net PRO Power represented here, corresponds to the gross power, minus the energy consumption of the draw, feed and PX pumps. We do not consider the electric consumption of the separation pump, as we are here only performing the characterization of the PRO process (see characterization of the full cycle operation in paragraph 6.4).

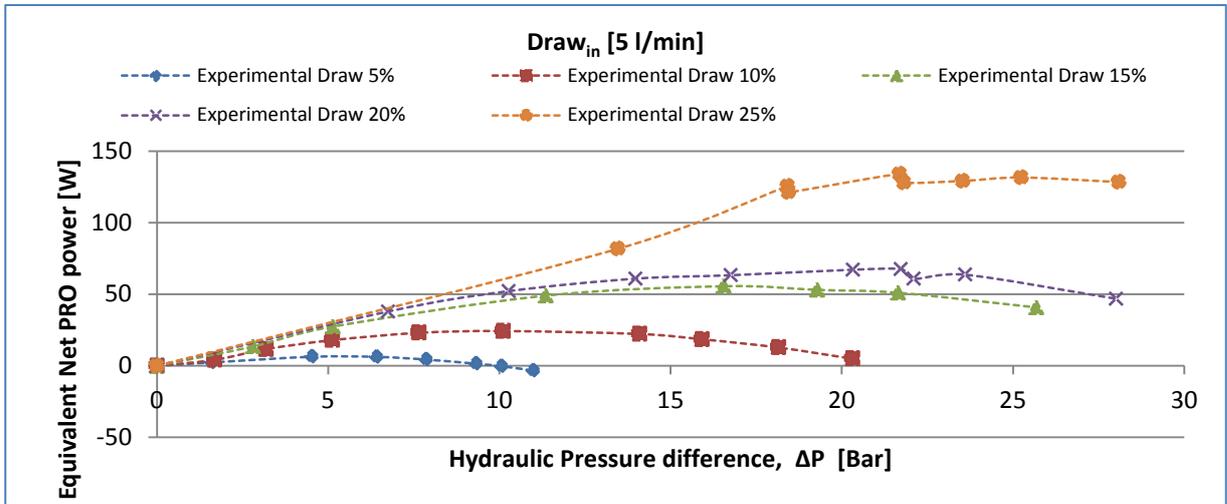


Figure 3: Equivalent net PRO power for draw solutions containing 5, 10 15 20 and 25% of osmotic agent, as a function of the hydraulic pressure ΔP applied across the membrane. For a hydraulic pressure beyond 20 bar, the pressure exchanger, limited in size, became unstable. Therefore, the data points beyond 20 bar of hydraulic pressure should be taken with care.

Our experiments also showed that the non-purity of the feed solution greatly affects the osmotic flow. For feed solutions containing 0.5% and 4.5% of osmotic agent, the net power is reduced by 27% and 74% respectively. Therefore, the quality of reconcentration of the osmotic solutions will be key in optimizing the engine performance.

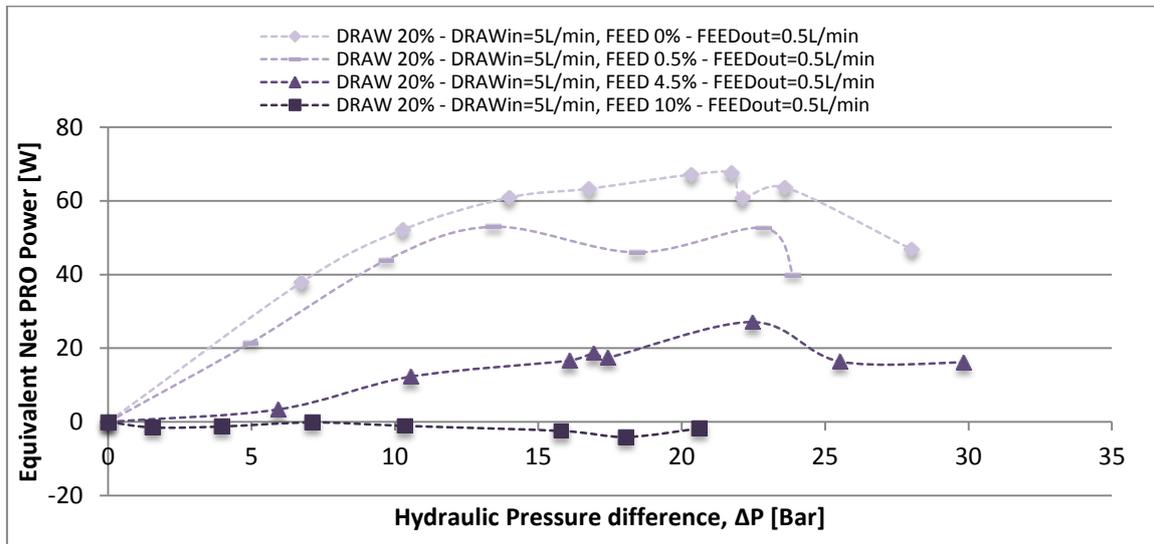


Figure 4: Equivalent net PRO power for draw solutions containing 20% of osmotic agent, against pure, 0.5%, 4.5% and 10% feed solutions, as a function of the hydraulic pressure ΔP applied across the membrane. For a hydraulic pressure beyond 20 bar, the pressure exchanger, limited in size, became unstable. Therefore, the data points beyond 20 bar of hydraulic pressure should be taken with care.



6.3. Numerical simulation

In parallel to the experimental results, OsmoBlue developed a numerical model to predict the performance and osmotic flow through the membrane module. With this model, we were able to estimate how to properly adjust the flow rates on each side of the membrane in order to enhance the mass transfer, a major limiting factor for a good osmotic flow.

The simulations also lead to a better understanding of the importance of the feed/draw ratio. We measured the net and gross power for different feed/draw ratios, finding the optimum around 40% for a given draw and feed concentrations of 19.6% and 1.2% respectively.

The model confirms the importance of the feed purity to obtain a good osmotic flow, as observed in our experiments. A rise from 0% to 1.2% of osmotic agent concentration into the feed leads to a decrease of the osmotic pressure difference of only 1.2 bar but affect the osmotic power by up to 37.4%.

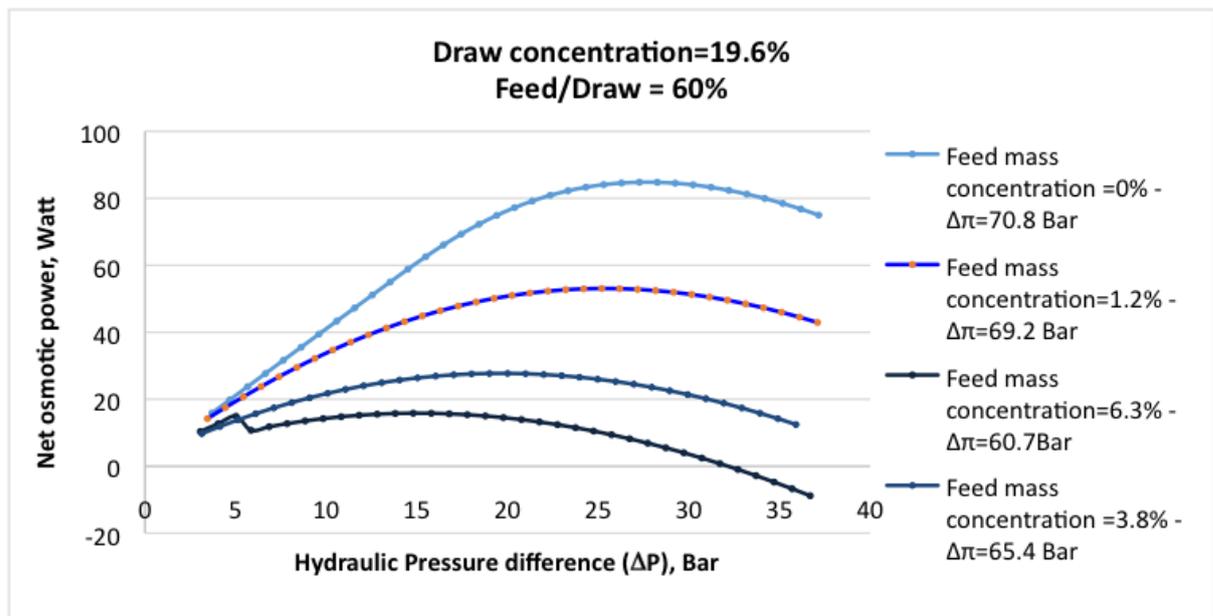


Figure 5: Numerical simulation showing the influence of the feed osmotic agent concentration on the net osmotic power, as a function of the hydraulic pressure ΔP applied across the membrane. For each curve, we set the draw concentration at 19.6% of osmotic agent. The feed solution varies between 0 and 6.3% of osmotic agent, resulting in a variation in the osmotic pressure difference ($\Delta\pi$), between feed and draw solutions, ranging from 70.8 to 60.7 bar. (The peak at 5 bar on the dark blue curve is due an artifact of the model).

6.4. Prototype validation in closed-loop configuration

After characterization of the membrane module with different solutions and operating conditions, we performed tests in a closed-loop (osmotic power generation followed by heat harvesting for separation), validating the positive energy balance of the system (see histograms in figure 6). As for the PRO experiments described in the paragraph 6.2, we calculated the gross power generated by the turbine based on the osmotic flow measured for a hydraulic pressure of 10 bar. We subtracted the electrical



consumption of the feed, draw and PX pumps, as well as the electrical consumption needed to flow the solutions into the thermal separation unit (see Separation pump in the schematic fig. 1). In the full loop experiment conducted we converted 2.53 kW thermal energy at 80°C into the equivalent of 3.43 W net electric power. The remaining heat was cooled using cooling water at 12°C. The thermal equivalent net efficiency obtained is 0.14% for a Carnot Efficiency of 19.26%.

The main limiting factor in the performance of the engine is the non-purity of the feed solution. We performed further tests, analyzing the composition of the solutions after separation, and by performing osmotic flow measurements. A better regulation, physico-chemical analyses along the circuit and stabilization of the process led to some improvements. But ultimately, we believe that significant improvements will be achieved using a more performing chemistry. In parallel to this project, OsmoBlue is pursuing development of the osmotic agent. OsmoBlue has identified and tested at the bench scale an osmotic agent with much higher osmotic pressure up to 170 bar.

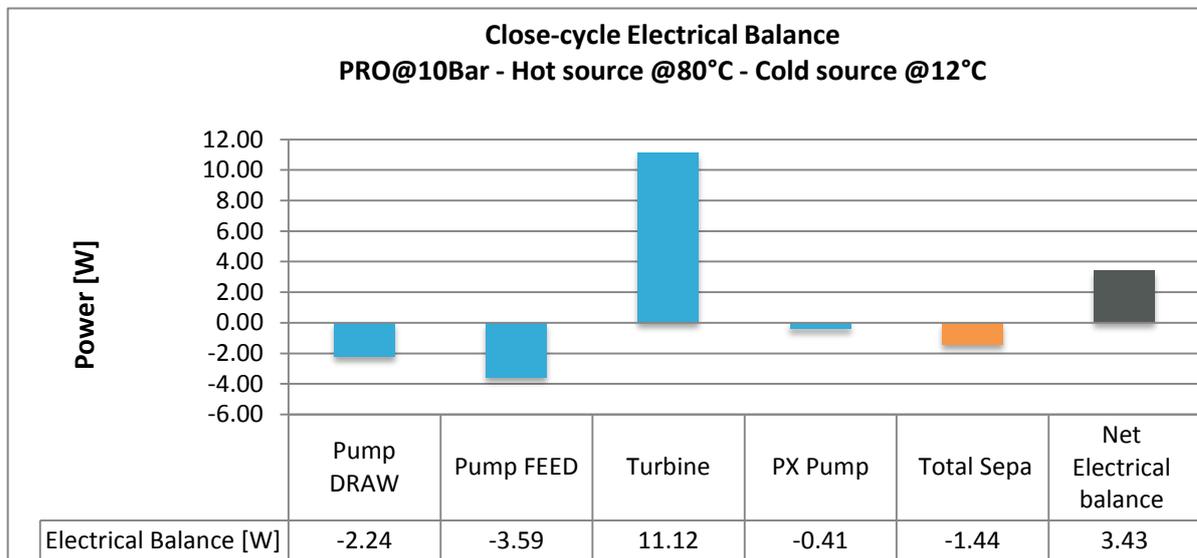


Figure 6: Electrical balance of the Osmotic Heat Engine. The electrical consumption of the Draw, Feed and PX pump is indicated, as well as the electrical consumption of the separation pump ("Total Sepa"). We indicated the equivalent gross power that could be produced with a water turbine in this setup, and the resulting equivalent net electrical balance.

For these experiments, we were limited by some experimental constraints preventing us from working at higher pressure. Indeed, the pressure exchanger used here is custom-made for OsmoBlue, as no commercial pressure exchanger exists for low flow rates below 20 L/min. It was unstable beyond 20 bar, rendering the experiment less reliable. Moreover, the reconcentration process requires heating up a large volume of solution that we need to cool down after reconcentration. We have therefore designed a heat recovery system, to recycle up to 90% of the heat entering the system. By removing the experimental constraints, and having a better heat recovery system in the reconcentration process, we calculated that we could today reach a performance of 0.66% thermal efficiency. This corresponds to 3% of the Carnot Efficiency, which is at the defined temperature equal to 19.26%.



6.5. Economical validation

6.5.1. Target market

Biomass plants burn wood waste to produce electricity. These industries are looking for solutions to value the excess of heat at low-temperature ($< 150^{\circ}\text{C}$). This market is attractive for its high electricity prices at which the heat can be valued (0,22 CHF/kWh compare to 0,8-0,15 CHF/kWh in other industries). It is a growing market with already 2'200 plants worldwide and 165 new plants built each year².

6.5.2. Cost calculation

Past studies showed that industries require 3 to 5 years Return on Investment (ROI) for the majority of innovation projects in the energy sector. The main factors influencing this ROI for the Osmotic Heat Engine (OHE) are:

- The application, the implementation location and the Cost of Electricity (CoE) associated.
- The equipment choice, size and cost.
- The process design and the performance linked to chemistry.
- The availability of a free-of-charge cold source will also be key, and should not be neglected when selecting the end-user's plant.

We developed numerical tools to cost each osmotic engine previously sized based on cost assumptions verified by experts in the field. For each equipment, we estimated the equipment cost and its installation cost. Cost analysis shows that membrane and heat exchangers are the main costing parts in terms of equipment and installation costs. Through our experiments and our numerical simulations, we have defined two different engine performances, that we call P1.5 and P4:

- The first one is called P1.5 considered as « Today's Performance ». It is based on the performance projection that we can obtain with today's Osmotic agent solutions demonstrated in our prototype and described in the paragraph 6.4. In other words, we designed a scale-up machine based on our prototype without the prototype technical constraints (e.g. Pressure limit, continuous operation and other small scale constraints).
- The second case scenario, called P4, considered as « Targeted Performance ». After investigating various parameters of the technology we identified, through a sensitivity analysis, the main impacting ones and our control over them. We fixed reasonable assumptions concerning the performance that we could potentially achieve in the future with further R&D effort. We considered the use of a new osmotic agent, with higher osmotic power (up to 170 bar and a corresponding hydraulic pressure of 80 bar applied across the membrane) and allowing a higher feed purity (with less than 1% impurities). In parallel to this project we have already identified several osmotic agents having high osmotic pressures of 170 bar. These osmotic agents have been tested at bench scale, showing an increase in osmotic flow by a factor of 2. The numerical model of our membrane module confirms that we could gain a factor of 2 in the osmotic flow for a hydraulic pressure of 80 bar. In other words, we designed a machine based on the performance we are targeting, working at higher pressure with a new osmotic agent.

² <http://www.altenergymag.com/news/2012/10/18/electricity-generation-from-biomass-continues-to-boom-worldwide/26766>



Performance		$\Delta\pi$ [bar]	Feed impurities	Osmotic flow [kg/m ² .s]	ΔP [bar]	Ratio Feed /Mix	Delta of tempera- ture $T_{Sep} - T_{PRO}$
P1.5	P1.5 - Today's Performance: with current osmotic agent (Agent 1), (from the results presented in paragraph 6.4)	80	6%	4.16E-04	24	30%	80°C - 25°C = 55°C
P4	P4 - Targeted Performance: with a hypothetical Agent 2 having higher osmotic power of 170 bar, and presenting a higher feed quality after thermal separation.	170	1%	8.52E-04	80	29%	80°C - 25°C = 55°C

For these two performances P1.5 and P4, we calculated with our numerical models the OHE efficiency, the engine costs and return on investment, as shown in the histograms below. These results have to be taken with care as they are based on numerical models, but they give a good idea of the trends to follow and the importance of acting both on the feed purity and increase in operating pressure.

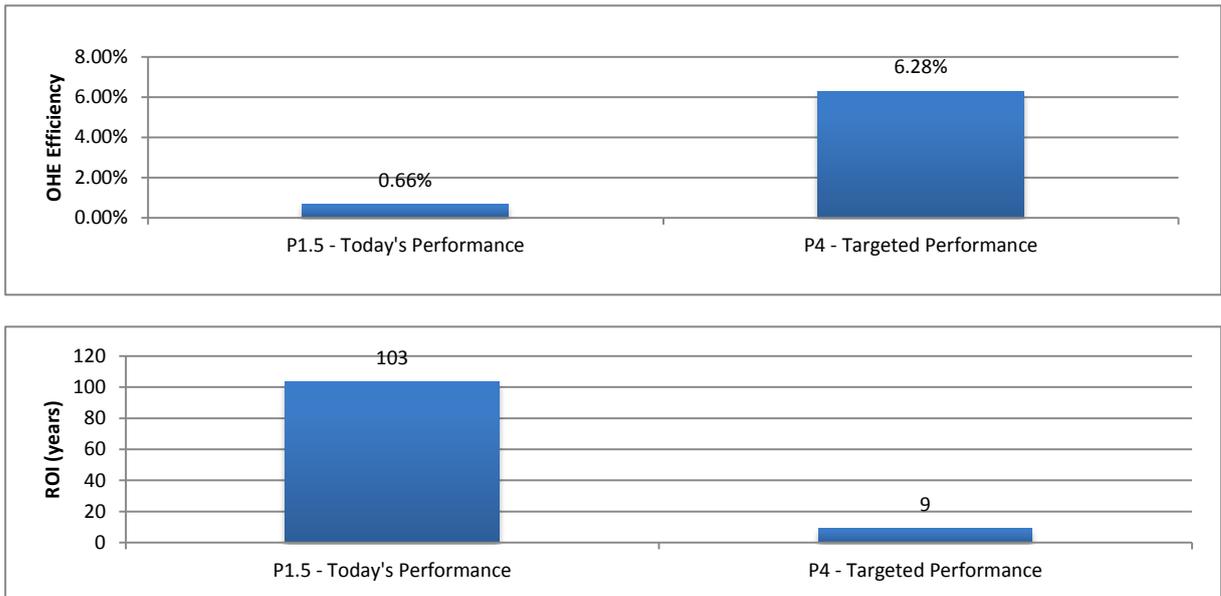


Figure 7: OHE efficiency and Return on investment estimated for the performances called P1.5 and P4, corresponding to today's and tomorrow's performances, respectively. For the return on investment, we have assumed an electricity price of 0.22 CHF/kWh and we also assumed that the engine runs for 8'000 hours per year.

If the performance of the next generation of osmotic agent evolves as we are targeting (i.e. increasing by a factor of 2 the osmotic power and reducing the impurities of the feed solution below 1%), we will be able to maximize the energy density (W/m²) and divide by 10 the current ROI.

We represented below the costs repartition for the equipments and the installation for the performances P1.5 and P4. The membranes account for the largest part of the equipment cost. One other important cost comes from the installation of the Heat Exchangers. Improving the efficiency of the engine



helps to reduce the size of the heat exchanger and therefore the cost of installation. Further discussion with heat exchanger manufacturers will help to refine this cost. We can see that increasing the energy density from P1.5 to P4 allowed us to reduce the part of the membrane costs.

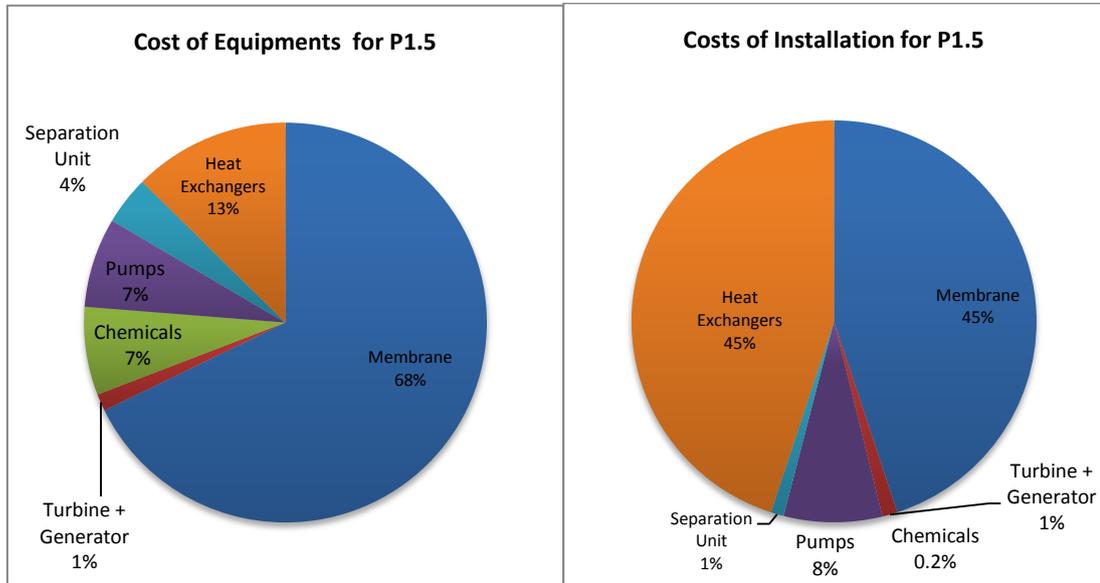


Figure 8: Repartition of Equipment Costs and Installation Costs for OHE at a Performance P1.5

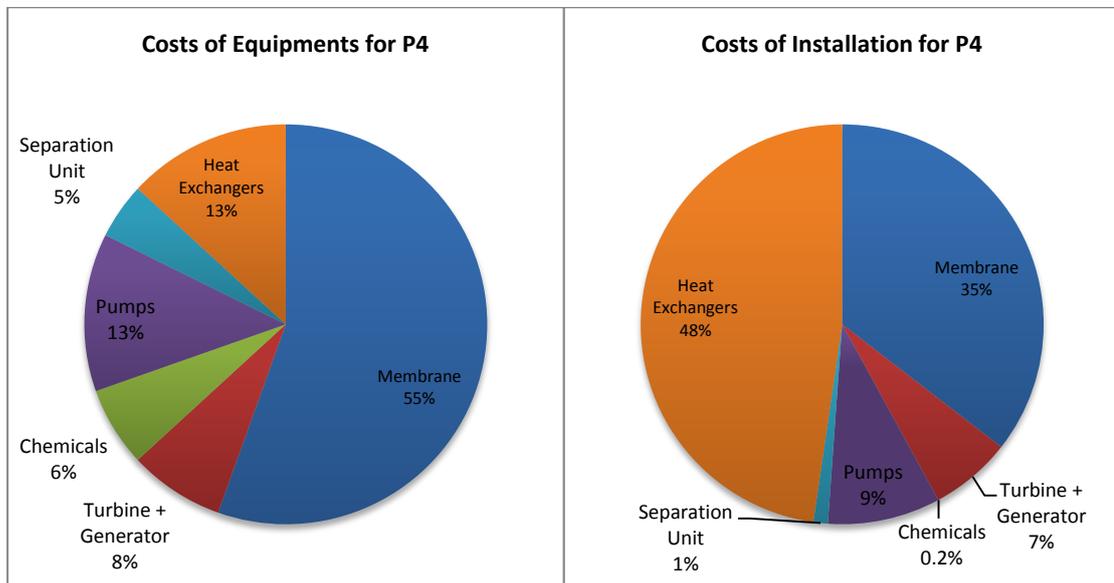


Figure 9: Repartition of Equipment Costs and Installation Costs for OHE at a Performance P4.

7. Discussion

Thanks to our economical study, we now understand which physical/chemical parameters are crucial in order to have the biggest impact on the cost and performance of the OHE. We concluded that with



new osmotic solutions, presenting a higher osmotic power and a better feed purity after thermal re-concentration, we could gain significantly in terms of engine efficiency and ROI.

We developed a powerful PRO model that helps us to design and select the next generation osmotic agent and predict accurately its PRO performance. We can vary many process parameters to optimize the condition to maximize Net PRO power output. Through our experiments, as well as our numerical models, we can observe the impact of the quality of the separation on the PRO side. We already selected promising osmotic agents for PRO having the appropriate features leading to high PRO net Power density (i.e. working with higher osmotic power up to 170 bar and hydraulic pressure across the membrane at 80 bar).

Today, the main cost comes from the cost of the membranes. By enhancing the energy density per square meter we will decrease the number of modules needed. In addition to a work on the chemistry of the next generation of osmotic agent, working on the interaction between membrane and osmotic agent will greatly improve performance. Reducing the membrane cost and the membrane pressure vessel (housing of the membrane cartridge that is today as expensive as the membrane itself) is key to have a viable OHE. If the market of membrane follows the same trend, as experts in the field expect it, we could lower the ROI of the OHE further, below 3 years. Looking at the past, the membrane cost was reduced by a factor 9 in the last 15 years and their performance multiplied by 4. OsmoBlue will continue working in close collaboration with membrane vendors.

8. Conclusions

We successfully validated the positive energy balance of our prototype Osmotic Heat Engine. We performed osmosis, and were able to regenerate the gradient of concentration of the solutions using heat at 80°C, provided by a boiler. The energy balance was calculated based on the osmotic flow measured and the electrical pumps consumption (In this setup, the turbine was replaced by a regulation valve mimicking the pressure drop across a water turbine).

In parallel to experimental results, we performed performance and economical studies based on numerical models developed by the OsmoBlue team. With current performance we cannot yet achieve 3 years ROI. Membranes and Heat exchangers account for more than 60% of the equipment costs. And according to our estimates, installation costs account for 2/3 of the total engine cost. We can also conclude that if the performance evolves, using osmotic agents with higher osmotic power (170 bar) and an improved thermal separation leading to a higher feed purity (less than 1% osmotic agent in the feed solution) we could significantly reduce the return on investment. When combined with the market evolution forecast, we believe that we could achieve a profitable OHE with 3 years ROI in a reasonable timeframe.

9. Perspectives and Next Steps

The learning obtained through this project, will be used to optimize the engine performance. We will implement a new osmotic agent that has been identified by the OsmoBlue team, in a project conducted in parallel to this one. An enhanced version of this prototype will be validated before scale-up of the engine in a plant.



10. List of abbreviations

OHE	Osmotic Heat Engine
PRO	Pressure Retarded Osmosis