Analyzing the effect of the hot water temperature on different OTEC processes

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Abstract

The ocean thermal energy conversion or OTEC has a large potential for providing energy to humanity at least in tropical zones. it is often considered as a technology which will provide a constant energy in contrary to other renewable energy such as wind or waves. Different processes can be developed to extract this energy and generate electricity but all of them use the surface hot water as the hot source. However this temperature is subject to change.

This study addresses the effect of the hot water temperature change and mainly its decrease on different processes that could be used to convert the thermal energy in electricity. A slight decrease of this temperature of 0.25°C can reduce the net power produced by more than 10%. Controls on different parameters can be implemented on these processes. They will allow to almost cancel the temperature effects but these controls must be very sensitive to very small temperature changes.

1 Introduction

The upper layers of the tropical oceans are a vast reservoir of warm water that is held at almost constant temperature all year-round by a balance between the absorption of heat from the sun and the loss of heat by mainly evaporation and convection.

A practical and economical technology for converting even 0.01 % of this absorbed solar energy into electricity could have a profound impact on world energy availability and economics.

The technology called ocean thermal energy conversion (OTEC) fulfills the technical and economic requirements for productive use of the solar energy continually absorbed by the oceans.

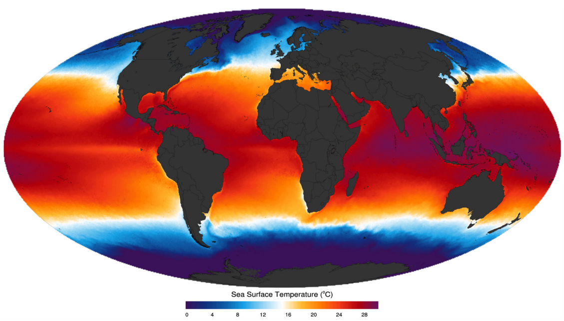

Figure 1: Modis (Moderate Resolution Imaging Spectroradiometer) measurement of the surface sea temperature [i]

Various renowned parties estimate the amount of energy that can be practically harvested to be in the order of 3 to 5 terawatts (1 terawatt is 10^{12} watts) of base load power generation, without affecting the temperature of the ocean or the world's environment. That's about twice the world global electricity demand. The oceans are thus a vast renewable resource, with the potential to contribute to the future energy mix offering a sustainable electricity production method.

However the technology could be viable primarily only in equatorial areas where the year-round temperature differential between the upper water layers and the deep ones of the ocean is at least 25°C.

First attempt to develop OTEC started in early twentieth century. In 1970 a plant was built on the island of Nauru (Japan) by the Tokyo Electric Power Company and produced 120 kW of Electricity [*ii*]. In 1974, The U.S. established the Natural Energy Laboratory of Hawaii Authority (NELHA) at Keahole Point on the Kona coast of Hawaii. In 1979 a plant was built on this site and produced for three months a small amount of electricity. In 1993, a 250 kW open-cycle OTEC pilot plant was constructed by the National Energy Laboratory of Hawaii (then called NELH) and the Pacific International Center for High Technology Research. The plant operated for six years and produced a record amount of 255 kW of energy [*iii*]. In 2002, India tested a 1 MW floating OTEC pilot plant near Tamil Nadu. The plant was ultimately unsuccessful due to a failure of the deep sea cold water pipe [*iv*].

One can ask why such a slow industrial development while there is such a large resource and demand. Furthermore OTEC is one of the few renewable energy which is said to be nearly constant all year-round. The fact is that the temperature differential between the cold bottom sea water and the hot surface one is not very important. If we take a temperature of 4.5°C at bottom and 28°C at top the Carnot efficiency is not greater than 8%. This is the upper limit which cannot be reached. Different losses and thermal discontinuities make that in practical the raw efficiency is around 3.5 to 4.0%. Furthermore an important part of the electricity generated is use to activate different pumps and finally the net efficiency is around 2.5 to 3%.

As a consequence of such a low efficiency the flow rates of the heating, cooling and working fluids much be high to very high inducing very large equipment and thus very large investment (CAPEX). Just to give some figures, flow rates of more than 10000 kg/s of water for producing 5 megawatts must be achieved and therefore to minimize pressure drops in pipes their diameter must be over 5 meters. If for an onshore installation it is possible to lay such huge pipes on the terrain slope, for a floating offshore installation these pipes could be submitted to vessel or waves movement increasing their stresses and fatigue. Designing and manufacturing such pipes is a real challenge. Furthermore the cold and hot fluid is sea water which is highly corrosive and the hot sea water will generate bio fouling in pipes and heat exchangers. All these technical difficulties can be one among others explanation of the very slow development of OTEC.

2 Base Cycle

2.1 Constants of the cycle

Different thermodynamic cycles can be used for OTEC. In this paper we will consider only the closed cycles and more precisely the Rankine one.

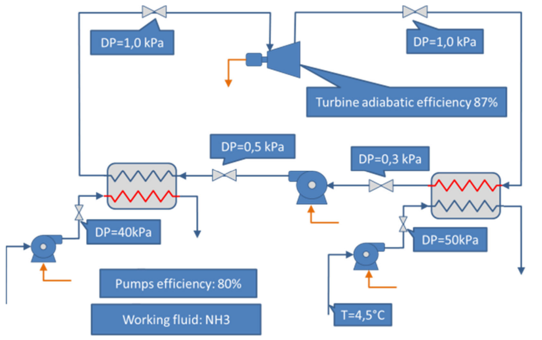

Figure 2: Rankine process main constant parameters

The working fluid is vaporized in the evaporator by exchanging heat with the hot water pumped near the ocean surface. Then its pressure is decreased by passing through the turbine which generates mechanical power. This mechanical power is transformed in electricity by the electric generator. At the exhaust of the turbine, the working fluid is brought back to the liquid state through the condenser by exchanging cold with the cold water pumped deep in the ocean. Finally the working fluid pressure is increased to its original value with the help of the working fluid pump. Besides the four main equipment of the Rankine cycle namely the evaporator, the turbine, the condenser and the pump, there are at least two other essential equipment which need to be powered: the hot and cold water pumps. Finally some pipes are necessary to link all these equipment which generate pressure drops that are shown as valves in figure 2. Pressure drops include the ones of the piping and of the heat exchangers. In the simulations hereunder the pressure drops will stay constant and independent of the flow rates.

2.2 Choice of parameters

For the purpose of the paper we will design a base case which 5 MW of electricity generated by the turbine. Somme parameters of this design are displayed in figures 2 and 3.

For the base case the hot sea water temperature is set to 28°C and the cold one to 4.5°C.

The working fluid must be in liquid phase at the working fluid pump entry to prevent damage by bubbles in the liquid. The working fluid must be in the vapor phase at the turbine entry to prevent damage of the blades by droplets. Taking into account the temperature of the hot and cold sea water, one of the best choice as working fluid is ammonia. Its high latent value compared to the others fluid allows to minimize its flow rate.

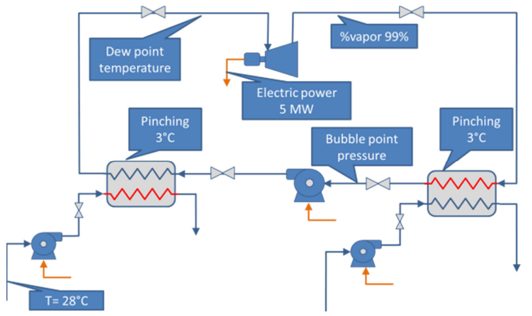

Figure 3: Chosen Rankine process parameters for base case

The pinching temperature of the two heat exchanger is set to 3°C. The pinching temperature is defined as the minimum temperature difference between the hot fluid and the cold one. The temperature at the turbine entrance is set such as the vaporized ammonia is just at the dew point temperature taking into account its pressure at this point of the cycle.

To compare the different options of the Rankine process we will define:

- The raw efficiency : it is equal to the raw power generated by the turbine divided by the evaporator duty
- The net electrical power: it is the electrical power generated at the turbine less the power consumption of the pumps
- The net efficiency: it is equal to the net power generated by the process divided by the evaporator duty

2.3 Choice of the thermodynamic model

The choice of a proper thermodynamic model is necessary to perform realistic simulations. Here we will focus on the thermodynamic models validity that we can find in the process simulator ASPEN HYSYS for the pure compound: ammonia. We propose for this study the use of the PR-Twu thermodynamic model [*iv*] which is based on the Peng-Robinson equation of state, described below:

$$P = \frac{RT}{v-b} - \frac{a}{v^2 + 2vb - b^2}$$

P is the pressure, R the ideal gas constant, T the temperature, v the molar volume. This equation of state uses two parameters: the co-volume b and the attractive term $a(T)$:

$$b = \Omega_b \frac{RT_c}{P_c}$$

$$a(T) = \Omega_a \frac{R^2 T_c^2}{P_c} \alpha(T_r)$$

These parameters are function of critical parameters and temperature. The characteristic of the PR-Twu model is that the attractive term does not depend of the acentric factor as in the classical version. Indeed, for the PR-Twu model, the alpha function of the temperature is defined as :

$$\alpha(T_r) = T_r^{C_3(C_2-1)} \exp[C_1(1-T_r^{C_2 C_3})]$$

where T_r is the reduced temperature (i.e. T/T_C) and C_1, C_2 et C_3 are empirical pure compounds parameters. This choice is justified in order to obtain vapor pressure with lower deviations.

To check the performance of the equation of state, we have tested the PR-Twu model on ammonia properties : saturation pressure, enthalpy of vaporization, heat capacity at constant pressure, density and molar volume. A comparison between the values obtained from the model to values issued from the literature (the DIPPR [*v*] for the liquid phase and the NIST [*vi*] for the vapor phase) is summarized in the table 1:

Table 1: Comparison between thermodynamic model PR-Twu and experimental values for NH3

Properties	Temperature range (°C)	Average deviations to
Saturation pressure	0-100	0.41
Enthalpy of vaporization	0-100	3,56
Liquid heat capacity	0-40 40-100	1.89 12.98
Liquid density	0-100	0.62
Vapor density	0-100	4.37
Liquid molar volume	0-100	0.61
Vapor molar volume	0-100	4.58

The contrasts are the most important for the heat capacity and they increase with temperature.
On the operating temperature range: [0 - 40°C], the differences are below 2 %, as shown in figure 4:

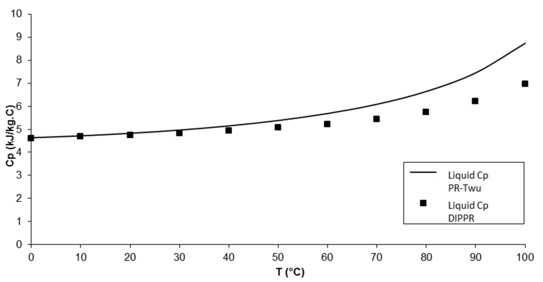

Figure 4: NH3 heat capacities (kJ/kg.°C) obtained experimentally and from model

For the other properties, we obtain a good restitution. The use of the PR-Twu basic thermodynamic model, without optimization of the parameters, is so the most convenient for this study.

2.4 Design of the process

Using the above values the process is designed for generating 5MW of electricity by the turbine. For this base case the pressure of ammonia at the entrance of the evaporator has been chosen rather low:

- Ammonia pressure at the entrance of the evaporator: 825 kPa
- Ammonia flow rate: 284.5 kg/s
- Hot water flow rate: 13210 kg/s
- Cold water flow rate: 12770 kg/s

The performances of this base case are as follows:

- Raw power: 5 MW
- Raw efficiency: 1.41%
- Net power: 3.4 MW
- Net efficiency: 0.96%

2.5 Sensitivity analysis

A parameter which might be subject to change is the hot sea water temperature. In fact this one is more sensitive to seasonal or meteorological conditions than the cold sea temperature. Even in tropical zones the surface sea temperature is also subject to seasonal change. The Figure 5 shows an example of the variation of the sea surface temperature. It has been measured during an El Niño anomaly in the Pacific ocean. In this example (figure 5) large change of surface sea temperature over 0.5°C can be spot in the other oceans under the tropics.

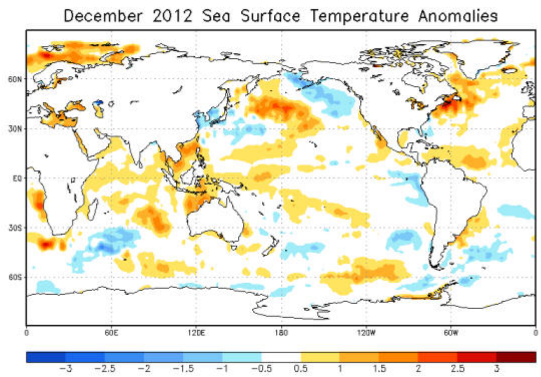

Figure 5: Surface sea temperature as recorded during an El Niño event

The cold sea water temperature is pumped from deep in the ocean at depth larger than 1000 meters. It is known that in most of the case it stays constant all year-round.

Therefore only the effect of the decrease or increase of 0.5 °C of the hot sea water is studied below.

When the temperature of hot sea water decreases the temperature of ammonia at the exhaust of the evaporator decreases to keep the 3°C of pinching temperature in this heat exchanger. In fact this value is a constant in relation with the technology used for the heat exchanger. The temperature of ammonia at the exhaust of the evaporator has been set to the dew point one. If it decreases, it drops below the dew point temperature. If nothing is done, ammonia will not be fully vaporized and droplets will flow with the vapor stream up to the turbine entrance. The presence of droplets at the entrance of the turbine will damage its blades.

Actions must be undertaken to keep the vapor exempt of droplets at the entrance of the turbine. The first one is to include a demister in front of the turbine to catch the droplets. The three other ones are to include controls on some process parameters in order to keep ammonia at dew point or over and thus prevent the formation of droplets in front of the turbine. These controls could be:

1. Decrease the pressure of ammonia at the entrance of the evaporator
2. Decrease ammonia flow rate
3. Increase hot water flow rate

A demister is a device for withdrawing droplets in a stream. In our case the demister will be set in front of the turbine and the liquid extracted is sent back at the entrance of the condenser. For comparison purpose we will consider that the presence of the demister does not add any extra pressure drop in the Rankine cycle and thus will not change the performances of the process.

The figure 6 shows the influence of the presence of a demister or the consequences of controlling the three parameters on the process raw and net efficiency and on the net electrical power produced. With the demister a 12% loss of net power is expected. The most efficient control is an increase of the hot water flow rate which allows to produce only 1.8% less of net power but with an increase of the hot water flow rate equal to 8.9%.

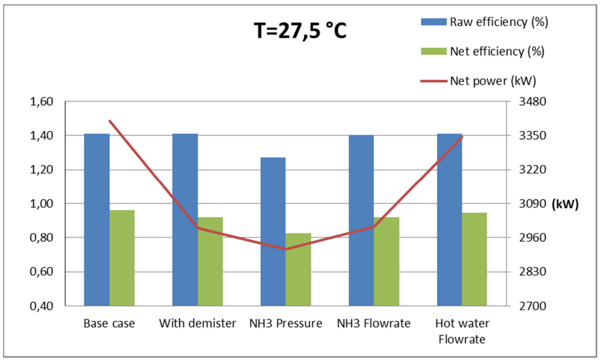

Figure 6: Effect of a hot water temperature decrease and controls to counteract

Regarding the very slight diminution of the hot water temperature (-1.8%) there is a need of a large increase of the hot water flow rate from 13210 kg/s up to 14380 kg/s (see table 2).

Table 2: Variation to achieve on controlled parameters

	Hot water temperature	NH3 Pressure	NH3 Flowrate	Hot water Flowrate
Variation (%)	-1,79%	1,46%	-8,22%	8,86%

On the other hand if the hot sea water temperature increases, the temperature of ammonia at the exhaust of the evaporator cannot increase. In fact and due to the chosen heat exchangers technology, the temperature at the exhaust of the evaporator is settled by the ammonia pressure and thus the temperature cannot change. Therefore for this base case the increase of temperature of the hot water as no effect on the process. However one can try to catch the extra energy provided by the extra heat brought by the hot sea water stream by:

1. Increase the pressure of ammonia at the entrance of the evaporator by changing the evaporator heat exchanger technology
2. Increase the ammonia flow rate
3. Decrease the hot water flow rate

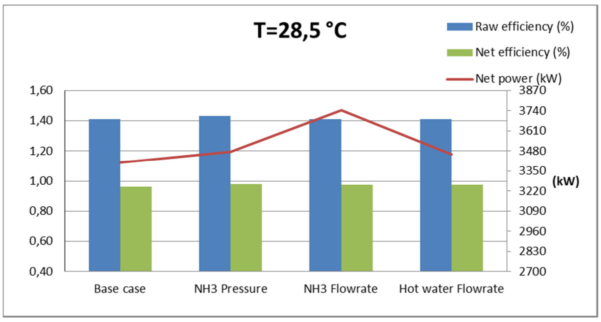

Figure 7: Effect of the hot sea water temperature increase and controls to take advantage

The most efficient parameter to control is the change of the ammonia flow rate which allows to produce 9.95% more of net electrical power. It must be increased from 284.5 up to 308.1 kg/s namely 8.3% regarding a very slight increase of the hot water temperature (see table 3).

Table 3: Variation to achieve on controlled parameters for the base case

	Hot water temperature	NH3 Pressure	NH3 Flowrate	Hot water Flowrate
Variation (%)	1,79%	4,82%	8,30%	-7,65%

Regarding the cold water flow rate and when changing the ammonia flow rate, it is necessary to change its value from 12770 kg/s up to 13840 kg/s or by 8.4 %. This is not very good solution. Firstly there is a need to control two parameters at a time: ammonia flow rate and cold water one. Secondly to allow an increase of the cold water flow rate without increasing the pressure drop in the pipe raising the cold water from the deep ocean. This pipe must be designed with a diameter larger than necessary with potential impacts on the floater size and costs.

As the increase of the hot water temperature as no effect on the process for this base case, one can design it for the lowest temperature that can be expected on the site. However, the process will be under designed and will not benefit from the highest temperature. Control can be set on ammonia or hot water flow rate but as shown above, these control must be very sensitive to slight change of the hot water temperature to keep the process running safely.

3 Enhancing the process

When designing the base case, very conservative options have been taken on the equipment, their performances and on some parameters. Thus the base case net efficiency is rather low. Hereunder we will study at first three following options separately and then together:

1. Having a temperature of the ammonia at the exit of the evaporator higher than the dew point one
2. Reducing the pinching temperature in the heat exchangers
3. Allowing the percent of liquid at the exit of the turbine to be lower than 99%

All the options are linked to technological choices: the two first ones to heat exchanger technology, the last one to turbine one.

Upon the different types of heat exchangers one can make the difference between kettle ones (shell and tube boiling outside the bundle) which do not allow to reach a working fluid temperature higher than the dew point one at a given pressure and other technologies of heat exchangers. For the later ones the plate type heat exchangers allow to have a counter current between the two fluids and thus to get a lower pinching temperature than the shell and tube heat exchanger technology.

3.1 Temperature above the dew point one

At 825 kPa the dew point temperature of ammonia is equal to 18.91°C according to the chosen thermodynamic model. For the purpose of this particular case we will keep the pinching temperature equal to 3°C but we will raise the temperature of ammonia at the evaporator exhaust so that it stays 0.25°C lower than the hot sea water temperature at the evaporator exhaust. Doing so the ammonia temperature at the turbine entrance is increased. In consequences the pressure at its exhaust can be reduced to keep the 99% vapor content at the turbine exhaust. This allows to generate extra net electrical power up to 5357 kW or 57.32% more (see table 4).

3.2 Reduced pinching temperature

The evaporator and condenser pinching temperature have been set to 3°C for the base case. With more effective heat exchanger technology such as plate type ones the pinching temperature can be reduced. Here the value of 2°C is chosen. Doing so the hot water and cold water flow rates can be reduced and 200 kW more of net electrical power can be produced or an increase of 6.16% (table 4). In order to reduce the pinching temperature, we need to increase the surface of the heat exchanger and the better way seems to use compact like plate technology.

3.3 Higher liquid content at the turbine exhaust

In the base case a conservative value equal to 0.01% of liquid content at the turbine exhaust have been chosen. We study the effects of increasing this value to 0.02% or having a 98% of vapor content at the turbine exhaust.

Ammonia flow rate and pressure are kept constant and also the heat exchangers pinching temperature. To reach a 98% vapor content the pressure at the turbine exhaust must be reduced to 584 kPa. This has no effect on the hot water heat exchanger but a tremendous one on the cold water one. To keep the 3°C pinching temperature of the condenser, the cold water flow rate must be increased up to 77500 kg/s whereas it was 12770 kg/s. A way to reduce the cold water flow rate in that case is to increase the ammonia pressure at the turbine entrance. If we increase it from 825 kPa in the base case up to 875 kPa the cold water flow should be equal to 28600 kg/s to keep the condenser pinching temperature equal to 3°C. In that later case the net electrical power produced is equal to 7355 kW and the net efficiency is 2.05%.

However and for this particular study of the effect of the liquid content at the turbine exhaust we don't want to change many given parameters at the same time so we will keep ammonia pressure constant. Thus the net power is increased up to 4558 kW or 33.8% more. As shown in table 4 there is a large difference between the raw and net efficiency due to the very high electric power necessary to run the cold water pump.

Table 4: Gain in raw and net efficiency and net power when changing some Rankine process parameters

	Raw efficiency (%)	Net power (kW)	Net efficiency (%)
Base case	1,41	3405	0,96
Temperature above dew point	2,09	5357	1,49
Pinching temperature at 2°C	1,41	3615	1,02
Liquid content = 2%	2,88	4558	1,26

Table 5 : Effect on hot and cold water flow rate when changing some Rankine process parameters

	NH3 temperature at turbine entrance	NH3 pressure at turbine entrance (kPa)	NH3 pressure at turbine exhaust (kPa)	Hot water flow rate (kg/s)	Cold water flow rate (kg/s)
Base case	18,89	824	700	13210	12770
Temperature above dew point	21,48	824	645	13260	20900
Pinching temperature at 2°C	18,89	824	700	11350	11025
Liquid content = 2%	18,89	824	585	13200	77500

These three enhancements of the Rankine process allow a large increase of the net electrical power produced without little or no effect of the sea water flow rates except in the third case. In all cases, more net electrical power can be produced. However it must be noticed that in the case of an increased liquid content at the exhaust of the turbine the cold water flow rate (77500 kg/s) is not acceptable (table 5).

3.4 Effect of the hot sea water reduction on these options

We will check only the case of a reduction of the hot sea water temperature form 28 °C down to 27.5 °C (-1.8%). The previous study has shown that the hot sea water temperature decrease is the most critical for the process and its equipment.

If one checks the process performances with the three options described above against a hot water temperature reduction one notices that control must be achieved to prevent droplets to enter in the turbine if there is not a demister in front of the turbine.

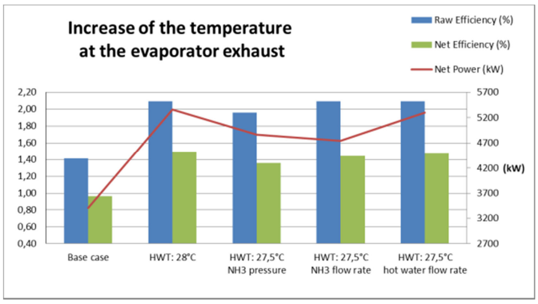

Figure 8 : Sensitivity of option 1 to the hot water temperature decrease

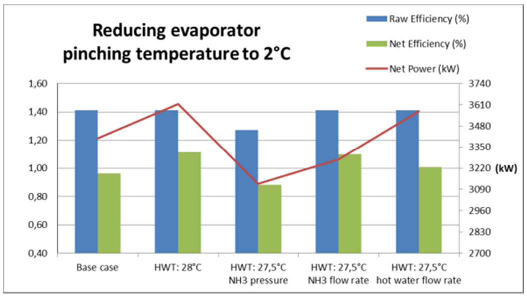

Figure 9 : Sensitivity of option 2 to the hot water temperature decrease

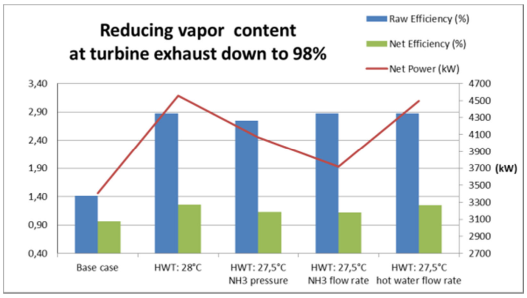

Figure 10 : Sensitivity of option 3 to the hot water temperature decrease

In all the case the most efficient control is the one on the hot sea water flow rate. However as shown in table 6 for a small variation of the hot sea water temperature (-1.8%) a large variation of the hot sea water flow rate must be applied.

Table 6 : Summary on variation of controlled parameters to respond to a hot water temperature decrease

	Control on		
	NH3 Pressure	NH3 Flow rate	Hot water flow rate
Temperature above dew point	-1,58%	-8,26%	9,39%
Pinching temperature at 2°C	-1,61%	-6,96%	7,49%
Liquid content = 2%	-1,64%	-8,19%	9,02%

3.5 Optimum case

Previously it has been shown that increasing the ammonia temperature at the evaporator exhaust, reducing the pinching temperature of the heat exchangers and increasing liquid content at the turbine exhaust enhance the process. An optimum case is now defined by the combination of these three enhancements. The effect of a fourth parameter has not been studied up to now: the ammonia pressure at the entrance of the evaporator. The figure 11 shows that an optimum in the net electrical power and the net efficiency is found with an ammonia pressure equal to 9.1 bar. This otpimum is reached when the hot and cold water flowrate are almost the same (figure 12).

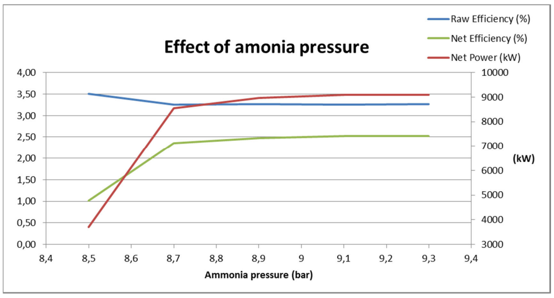

Figure 11 : Effect of ammonia pressure on Rankine process raw and net efficiency and on net Power

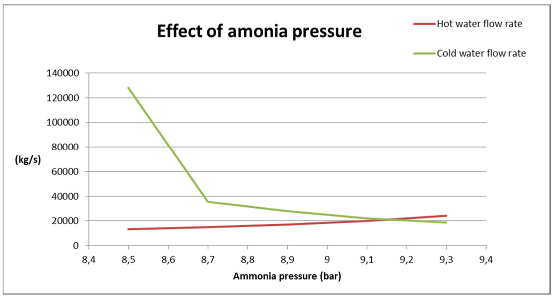

Figure 12: Effect of ammonia pressure on hot and cold water flow rate

At the optimum the net electrical power produced is equal to 9098 kW and the net efficiency equal to 2.52%. This is a gain of respectively of 167% and 162% compared to the base case. However the cold water flow rate must be increased from 12770 kg/s for the base case up to 22200 kg/s for the optimum one. Doubling the cold water flow rate means an increase of 25% of the diameter of this riser pipe to keep constant the pressure drop. It means also increasing the size of the heat exchangers. Only an accurate economic study can determine if the net electrical power optimum found here is an economic one.

The optimum case is also sensitive to the hot water temperature change. As before when it decreases, control must be achieved to keep the process performances stable (see figure 13 and table 7).

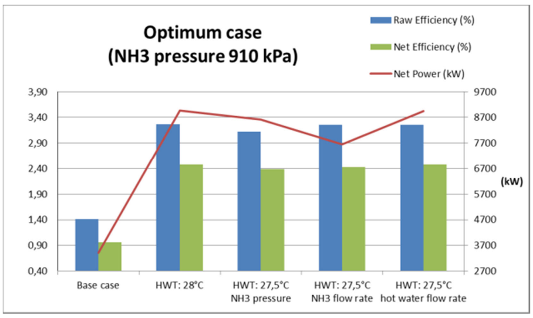

Figure 13: Effect of a decrease of the hot water temperature on the optimum case

Table 7 : Variation to achieve on controlled parameters for the optimum case

	Hot water temperature	NH3 Pressure	NH3 Flowrate	Hot water Flowrate
Variation (%)	-1,75%	-1,59%	-12,48%	14,19%

The control on the hot water flow rate allows to keep almost the same net power or efficiency but with a large variation of this flow rate compared to the small variation of the hot water temperature.

4 New proposed process

We have seen previously that the most effective way to enhance the Rankine process is to increase the ammonia temperature at the entrance of the turbine. It can be done by choosing an adequate heat exchanger technology as shown before but also by bringing some extra heat at the ammonia stream by adding a heater between the evaporator and the turbine. It must be said that adding a heater is compatible with the three options studied before.

Heat can be generated by many different sources but here we will study the case where the heat is generated by a heat pump using the hot sea water as the heat source.

The heat pump process is as follows: A working fluid is evaporated by exchanging heat with the hot sea water in the evaporator (figure 14). It is then compressed which increases its temperature. In the heat pump heat exchanger it brings heat to the ammonia stream of the Rankine process. The heat pump working fluid pressure is then reduced by passing through the valve before entering the evaporator. As before, ammonia is one of the best choice as working fluid.

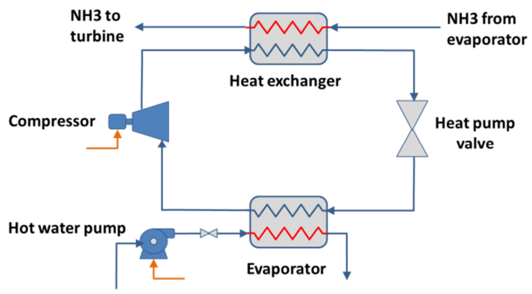

Figure 14: Scheme of an heat pump

As expected adding heat to the ammonia stream in front of the turbine has a large effect on the processes performances (see table 8). The net electrical power, which in that case takes into account the electrical power consumed by the heat pump compressor and heat pump hot water pump, is increased up to 5967 kW (75.3%) with only 3MW of heat brought by the heat pump. However if this gain has little effect on the hot water flow rate, it has a large effect on the cold water flow rate. It must be increased by 69.2% to generate the extra electrical power.

Table 8: Effect of the new proposed process on flow rates, efficiencies and net power

Heater power (MW)	0	1	2	3
Cold water flow rate (kg/s)	12770	16900	24050	41500
Hot water flow rate (kg/s)	13210	13210	13336	13398
Raw efficiency (%)	1,41	1,84	2,23	2,63
Net power (kW)	3405	4681	5650	5967
Net efficiency (%)	0,96	1,31	1,57	1,64

4.1 Comparison with previous options

As in floating OTEC, the value of the cold water flow rate is an important design parameter, it is interesting to compare from this point of view the different cases studied above. In figure 15 the power gain in percent is plotted against the percent of cold water flow rate increase. The round points are for the enhanced processes, the rectangular ones for the optimum processes and the diamond ones for the processes using a heater. We observe that for a heater power below 2 MW there is a slight advantage in using a heater: there are more power gains than increase in the cold water flow rate.

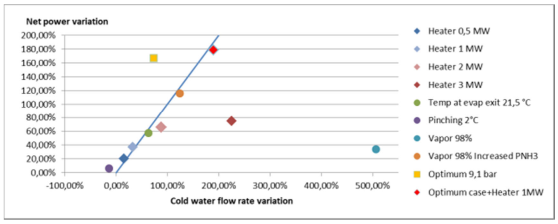

Figure 15: Comparison between the new proposed process and other ones

Using a heater is fully compatible with the options studied before. Therefore we simulate the optimum case with a 1 MW heater. It allows to produce almost 9500 kW with a net efficiency of 2.6%. However the cold water flow rate must be increased to 37000 kg/s.

4.2 Effect of hot water temperature decrease on this process

If the hot water temperature decreases from 28°C down to 27.5°C, the power brings by the heater is not sufficient to compensate the loss of heat and thus to prevent the presence of droplets at the turbine entrance. Thus a control on the process must be put in place if there is no demister in front of the turbine. Previously we have noticed that the control on the hot water flow rate is the one which allows to minimalize the loss of electrical power induced by the decrease of the hot sea water temperature.

To keep the evaporator and heat pump exchanger pinching temperature equal to 3°C, the hot water flow rate must be increase from 13210 kg/s up to 14447 kg/s or 9.4% and the reduction of the net electrical power is equal to -1.3 %. These values can be compared to the previous ones:

Table 9: Effect of the hot water temperature decrease on this new process

T = 27,5°C Control on hot water flow rate	Base case	Temperature above dew point	Pinching temperature at 2°C	Liquid content at 2%	Heater 1MW
Net power reduction (%)	-1,8%	-1,2%	-1,2%	-1,4%	-1,3%
Net efficiency diminution (%)	-1,8%	-1,2%	-1,2%	-1,4%	-1,3%
Hot water flow rate variation (%)	8,9%	9,0%	7,5%	9,0%	8,9%

It must be remembered that the processes with a temperature of ammonia above the dew point and the one with a pinching temperature below 2°C uses better heat exchanger technology than the three other ones.

If we compare the Rankine process plus a heat pump against the base case and the process with a higher liquid content at the turbine exhaust we can say that the addition of a heat pump allows a slightly less reduction of the electrical power generated. However when comparing this process with the ones with better heat exchanger technology, its performances are slightly under.

4.3 Conclusions

Ocean thermal Energy Conversion is often considered as a one of the renewable energy which will provide a constant energy all year round.

The Rankine process is one of the process to be used to convert the thermal energy to electric one. Enhancements of the Rankine process such as greater temperature of the working fluid at the evaporator exit, higher liquid content at the turbine exhaust or reduced pinching temperature in the heat exchangers allow to increase the raw and net efficiency and the net electrical power produced. Overheating the working fluid in front of the turbine through a heat pump allows also to get better efficiencies and higher electrical power.

However, as shown in this study all these processes are very sensitive to at least the hot water temperature variations. Its decreases could damage the turbine presence of droplets at its entry. This problem can be avoid by adding a demister but will not prevent the important loss of electrical power generated. One way to counteract the hot water temperature decrease is to add controls but they must be very reactive as a small change in this temperature will induce a large change of the controlled parameter.

1. [i] *"MODIS sst" by Giorgiogp2 - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons*
2. [ii] *Bruch, Vicki L. (April 1994). An Assessment of Research and Development Leadership in Ocean Energy Technologies (PDF). SAND93-3946. Sandia National Laboratories: Energy Policy and Planning Department*
3. [iii] *L. Meyer, D. Cooper, R. Varley. « Are We There Yet ? A Developer's Roadmap to OTEC Commercialization » Hawaii National Marine Renewable Energy Center. Retrieved 28 March 2013.*
4. [iv] *Avery, William H. and Chih Wu. Renewable Energy From the Ocean: A Guide to OTEC. New York: Oxford UniversityPress. 1994.*
5. [iv] *C.H. Twu, D. Bluck, J.R. Cunningham, J.E. Coon. A Cubic Equation of State with a New Alpha Function and a New Mixing Rule, Fluid Phase Equilibria, 1991, 69, p.33-50*
6. [v] *Rowley, R.L.; Wilding, W.V.; Oscarson, J.L.; Yang, Y.; Zundel, N.A., DIPPR Data Compilation of Pure*
7. *Chemical Properties, Design Institute for Physical Properties, (http//dippr.byu.edu), Brigham Young*
8. *University, Provo, Utah, 2006.*
9. [vi] *NIST. National Institute of Standard and Technologies*