Guidance page for practical work 5: OTEC closed and open cycle

1) Objectives of the practical work

The project objective is to study OTEC cycles Ocean Thermal Energy Conversion designed to generate electricity in warm tropical waters using the temperature difference between water at the surface (26–28 °C) and in depth (4–6 °C), from 1 000 m (figure 3.1) and to show how they can be realistically modeled with Thermoptim.

Two main types of cycles are used: closed cycles and open cycles, invented by two French, respectively Jacques d'Arsonval in 1881 and Georges Claude in 1940, who proceeded to a first experiment.

Although technically valid, OTEC cycles are not yet economically viable. Prototypes of various capacities have been realized or are being considered, including in Hawaii and Tahiti.

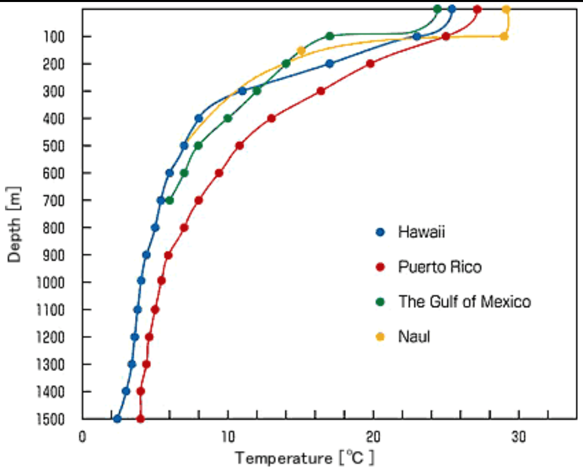

Figure 3.1: Ocean thermal gradient

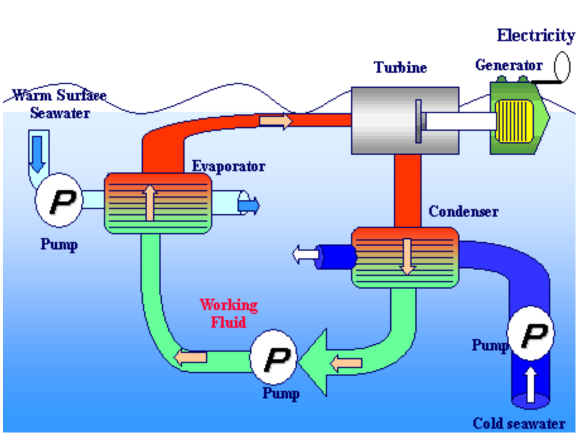

Figure 3.2: OTEC closed cycle

In all cases, the need to convey very high water flow rates and pump cold water at great depth induces significant auxiliary consumption. Optimization of an OTEC cycle is imperative to take into account those values.

Closed cycles (figure 3.2) use hot water at about 27 °C to evaporate a liquid that boils at a very low temperature, such as ammonia or an organic fluid. The vapor produced drives a turbine, then is condensed by heat exchange with cold water at about 4 °C from deeper layers of the ocean.

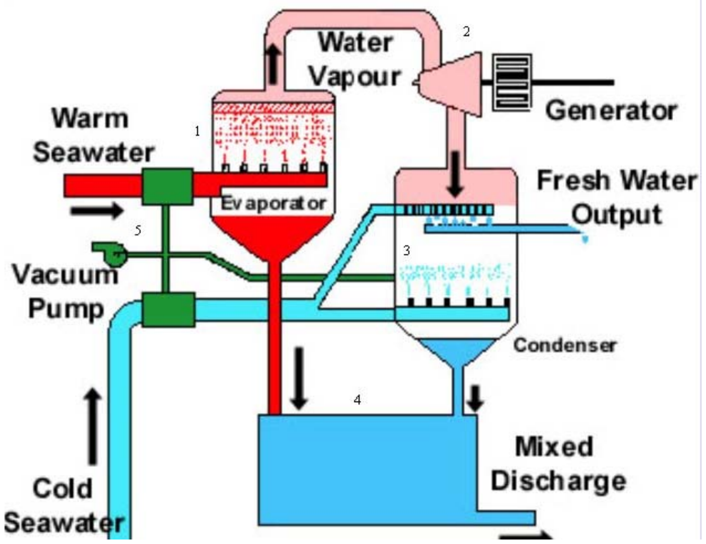

Figure 3.3: OTEC single flash open cycle

In open cycles (figure 3.3), warm water at about 26 °C is expanded in a low-pressure chamber (called flash), which allows to evaporate a small fraction (around 5%). The steam produced drives a turbine and is condensed in a low pressure chamber by heat exchange with cold water at about 4 °C from deeper layers of the ocean. The condensate is virtually pure water, which can be used for food.

The open cycle thus has the advantage of producing both electricity and fresh water, but the very low expansion ratio involves using very large turbines.

Figure 3.3 shows the cycle operation. It involves five elements: a flash evaporator (1), a turbine (2), a condenser (3), a basin for collecting used sea water, and a vacuum pump (5).

Hot water is pumped at the surface and brought to a certain height (1), then it is injected into the evaporator in which there is a slight depression determined by the height of the water column between the evaporator and the collection basin. Because of the pressure difference, water undergoes an isenthalpic throttling (fl ash) and a small fraction is vaporized (2), then headed to the turbine (2-3).

In the condenser pressure is lower than in the evaporator, thanks to the vacuum pump and the height of the water column between the condenser and the collection tank. The turbine expands the steam produced in the evaporator, producing mechanical power. The steam is then condensed (3-4) by exchange with cold water, producing fresh water. The hot and cold water mixed in the collection basin (8) are fed back into the sea at a depth of sixty meters.

The TD has two parts:
- The first, relatively simple, deals with the closed OTEC cycle and is designed for students who have studied steam plants. If this is not the case, they should do it first
- The second, a little more complex, dealing with the open OTEC cycle. It allows students to deepen the concept of flash.

2) References

We recommend the site of Luis A. Vega in Hawaii: http://www.hawaii.gov/dbedt/ert/otec/ which has many useful information, provided by one of the few experts to have worked on these cycles. A paper by L. Vega is attached to this guidance page.

3) Main practical work

3.1 OTEC closed cycle

The thermodynamic cycle: it is aHirn or Rankine cycle, whose modeling in Thermoptim poses no particular problem.

The objective of the work is to model such a cycle and to calculate its efficiency, then to build its exergy balance. Among the available thermodynamic fluids availble in Thermoptim (ammonia, butane, propane and R134a), the one which leads to the best performance should be sought.

The sizing of heat exchangers is obviously critical given the low temperature difference between hot and cold sources. The values of pinches should be as low as possible while remaining realistic. Obviously, when attempting to compare the performance of cycles using different fluids, the values of pinches should be about the same.

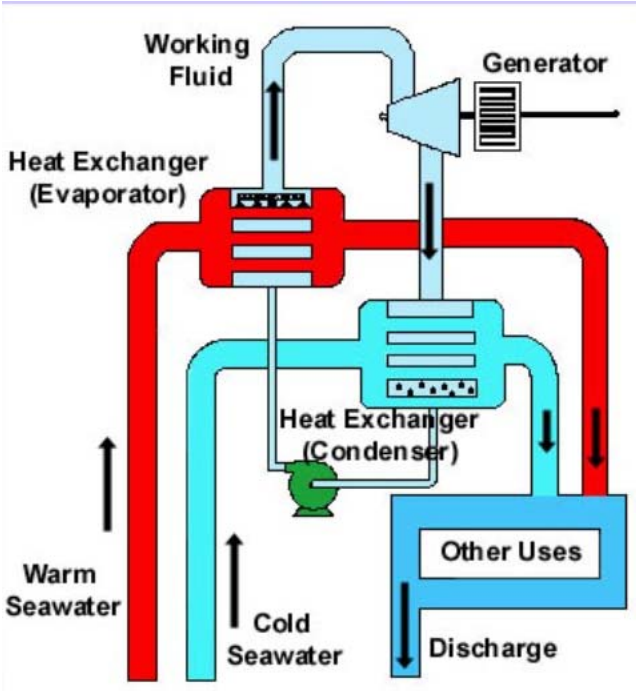

Figure 3.1 : schéma d'une centrale OTEC à cycle fermé

It will be seen that although the energy performance of closed cycle OTEC is very low (<3%), the exergy efficiency may be correct.

The flow of hot water is 27 000 kg/s, its temperature is 26 °C, and the temperature of the cold water is equal to 4 °C.

All other values must be determined, justifying the assumptions made. Estimations of system size magnitudes (exchange surfaces, free flow areas...) should be done, not forgetting to take into account the pumping power, a priori not negligible. The last seven stages of the Diapason session ENR01[1] (in French) is a brief introduction to OTEC cycles, that students can usefully consult.

Modeling in Thermoptim of closed-cycle OTEC plant leads to a diagram like the one in Figure 3.2. The efficiency is very low (2.5%) due to the small temperature difference between the two sources.

For students who have modeled a simple steam cycle (if it is not the case, they must begin by working on the sessions S25En and S26En), the only difficulty is the construction and configuration of the three part heat exchanger.

How to solve this problem is explained in detail at the end of session S18En on the thermodynamics of heat exchangers in an exercise where are set exchangers representing a steam cycle boiler.

3.2 Open OTEC cycle

A diagram of a single flash open cycle OTEC is given in figure 3.3, and data on the state of certain points are provided below:

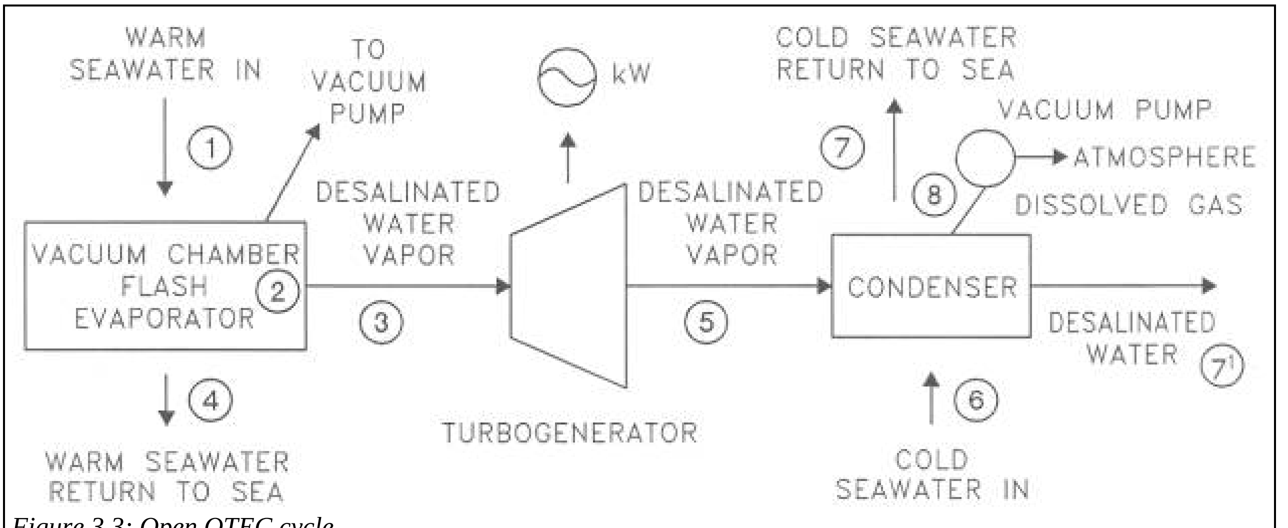

Figure 3.3: Open OTEC cycle

All other values must be determined, justifying the assumptions made (the thermodynamic properties of salt water will be assimilated to that of pure water).

point	T (°C)	P (bar)	x
1	26	1	0
2	23.39	0.0288	?
3	23.39	0.0288	1
4	23.39	0.0288	0
5	?	0.0129	?
6	4	1	0
7	?	1	0
7'	9.5	0.0129	0

	Flow rate (kg/s)
Hot water	6156
Cold water	2702
Pure water	?

[1] Session ENR01: http://www.thermoptim.org/SE/seances/ENR01/seance.html

A Thermoptim model of this cycle is given figure 3.4.

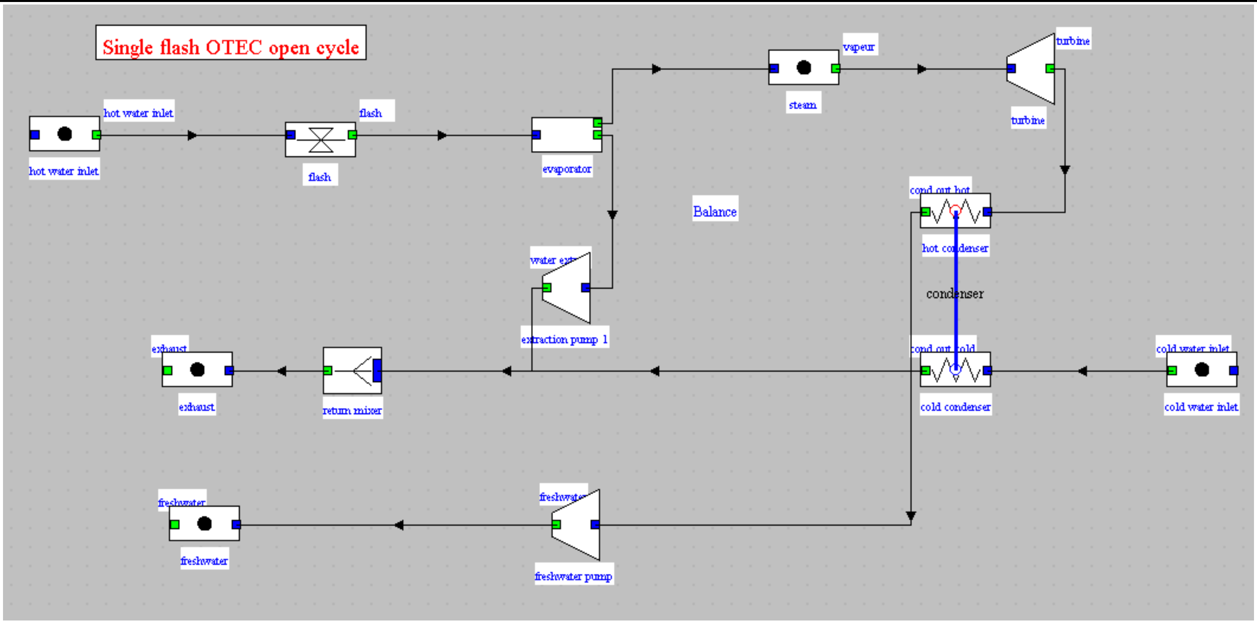

Figure 3.4: Synoptic view of a single flash OTEC open cycle

As in the first part, the objective of the work is to model such a cycle and to calculate its efficiency, then to build its exergy balance. Estimations of system size magnitudes (exchange surfaces, free flow areas...) should be done, not forgetting to take into account the pumping power, a priori not negligible.

While not very complex, understanding of this cycle by students is not usually immediate. Even if they have studied the isenthalpic expansion of a refrigerant in a refrigerating machine, they often fail to realize that the expansion of sea water will spray a small part.

To achieve the partial vacuum necessary firstly to flash, and secondly at the turbine exhaust, we use the change in hydrostatic pressure due to the difference in altitude of water collectors. The warm seawater is pumped a few meters above sea level, while the collector output of the flash is a little lower, and that at the turbine outlet even lower.

Reference is made to L. Vega document for more details.

To calculate the purchased power in a simple way, we selected here the energy supplied to the condenser, which is not entirely accurate. In addition, the pure water produced is not taken into account in this balance, which distorts the results a bit.

3.3 Representation in thermodynamic charts

Once the cycle points determined, it is easy to plot them in a diagram such as the thermodynamic entropy chart using the features offered by Thermoptim. It may be particularly interesting to display the flash on such a diagram so that students understand what is happening in this unit.

4) Variants

As this practical work has already two variants, we only propose here two others, but many alternatives can be imagined, depending on the time available, the level of students, their number, and educational objectives pursued.

4.1 Study of a two-stage flash open cycle

The attached document by L. Vega shows a double-stage open-cycle flash, a diagram of which is given in Figure 4.1 given next page. The study of this more complex cycle, with the data shown in the diagram and those provided in the document is a variant quite interesting, though somewhat more complex.

4.2 Cycle exergy balance

It is now possible to ask students to build up the cycle exergy balance, if they have enough time. The great interest of this work is to show that cycles with very low efficiency (due to the low thermal gradient available) may still have a pretty good exergy efficiency.

Diapason session S06En will provide necessary explanations on how to proceed, the S28En session being devoted to the simple steam exergy balance.

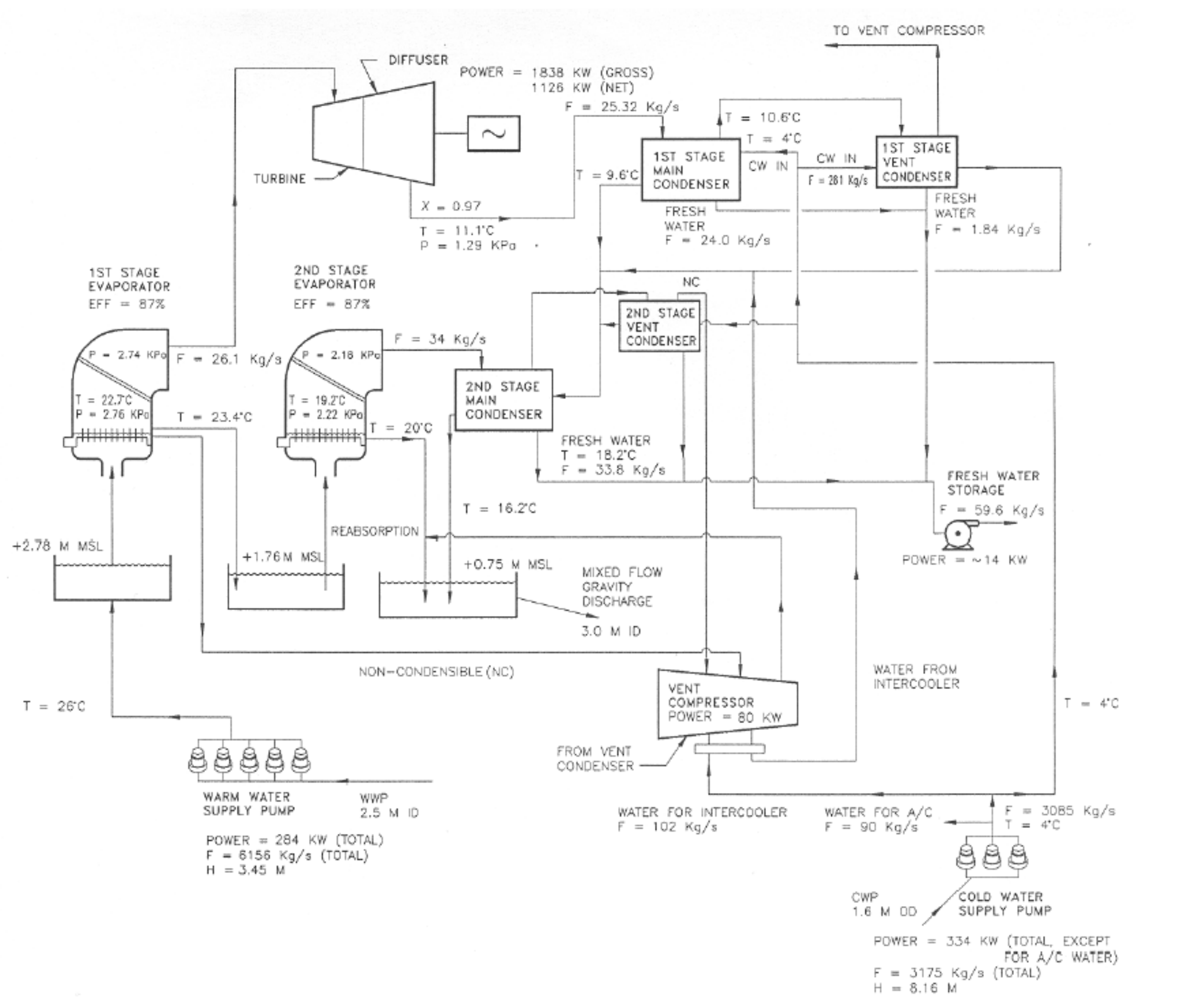

Figure 4.1: *Synoptic view of a double flash OTEC open cycle*

5) Work files

The following work file is attached:

- Document Ocean Thermal Energy Conversion (OTEC) by L. A. Vega, Ph.D., Hawaii, USA (OTECbyVega_with_photos.pdf)