Experimental Ocean Thermal Energy Conversion (OTEC) project on the Reunion Island

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Abstract

Ocean Thermal Energy Conversion (OTEC) is a process able to produce base electricity through the temperature differences existing between warm seawater at the surface and cold depth seawater.
Up to now, very few experiments have been conducted and oil prices fluctuations have often prevented results exploitation. Recently, two factors have re-launched researches: a need for the production of a renewable energy ensuring the stability of the electric grid and the increase in oil prices. The purpose of this experiment is to demonstrate the sustainability of an offshore 10 MW power plant. Some issues first need to be examined: heat exchanges, control strategies, cycle risks, working fluids, and thermodynamic cycles.

This paper presents an experimental prototype as a first steppingstone of an "Eliminating Risks Program" and as a preliminary installation to the setting up of the first full scale OTEC power plant. The prototype is a reproduction on a reduced scale of a demonstration plant producing an electric power of 10 MW. To reduce costs and hazards of offshore installations (waves, cyclones, maintenance, etc.), decision has been made to build an onshore plant (settled on the Réunion island), creating artificial heat sources with a heat pump.

In the first part of the paper, the principle of OTEC will be explained. Then, the prototype detailed: cycle, main components (the electricity production is directly related to the quality of the heat exchanges, so some different heat exchanger technologies are developed), working fluids, heat sources, and control strategies. Finally, results of an experimental parametric analysis will be presented, highlighting the major importance of heat exchanges, within the evaporator. Results show, for instance, that a vertical plate-type evaporator show better capacities than a shell and tube one.

1. INTRODUCTION

Nowadays, the expansion of renewable energies can be explained through international facts: indeed, between 1970 and 2004, greenhouse gas emission increased by 70%, and fossil energy prices increased by 50% [1]. Furthermore, the number of inhabitants on earth increased: in the beginning of 2012 to roughly 7 billion. Moreover, the standards of living improved with phone, car and computer advances, so did the need for electricity [2].

These assessments have lead governments to encourage projects for developing renewable energies. The purpose is to use resources available on earth in large quantities and have the capacity to replenish itself, to produce electricity in a "green" fashion: wind power, solar power, water power etc. This type of energy can be called infinite energy [3].

One of these projects is the GERRI program on the Reunion Island. It encourages the decrease of electricity consumption and greenhouse gas emission. The Reunion Island is no exception. Indeed, in the number of inhabitants increases too (1.55% increase per year) [4].

The objective of the politic based on renewable energies for the Reunion Island is to be energetically independent.
This island is located north of the tropic of Capricorn, so it becomes the best candidate to use the Ocean Thermal Energy Conversion.

Indeed, this process produces electricity from the temperature difference between warm water at the surface of the ocean, and cold depth seawater. One of the advantages of this energy is that it might provide base-load electricity. The thermal resources of the ocean ensure an all day availability of the power source and with only modest variations from summer to winter [5].

Before building an OTEC power plant on the Reunion Island some matters need clarification.
The first step is to study heat exchanges, cycle risks, working fluids, thermodynamic cycle etc. To that purpose, an onshore prototype has been built. It functions with artificial heat resources and without alternator. Therefore the prototype is not connected to the sea and to the grid.

The second step will be the construction of an offshore 10 MW OTEC power plant. It will cover the electricity consumption of roughly 30 000 homes. Control strategies, maintenance issues, water pipes and pumps etc. will be clarified.

This paper presents the onshore experimental set up and the experimentation to compare two evaporator technologies and performances. Indeed, as Sinama et al. [6] have established, the most important component in the OTEC cycle is the evaporator. The challenge here is to generate the highest heat exchange with the lowest quantities of working fluid (for security and cost reasons).

2. THE PRINCIPLE OF OTEC

The principle of the Ocean Thermal Energy Conversion is to convert into electricity the differences in temperature between surface seawater and the depth ocean seawater. Some cycles can be used to that purpose: Rankine, Uehara, Kalina.

The first one is the most common cycle used because of its simplicity and its proven results.

2.1. Rankine

The Rankine cycle is a thermal machine which produces electricity from a hot and a cold source. This cycle is illustrated on Figure 1 and the (P;h) diagram is drawn on Figure 2.

In number 1, the ammonia is in its liquid phase under a low pressure. The pump supplies the working fluid to the evaporator where it is heated and vaporized (2) by the warm seawater from the sea surface. The generated high pressure vapour flows into the turbine (3) and its enthalpy is converted into work and then in electricity with the alternator. The low pressure vapour exits the turbine and is led to the condenser where it is liquefied (4) by the depth seawater. The liquid in the condenser is pumped back to the upper heat exchanger and a new cycle begins [7].

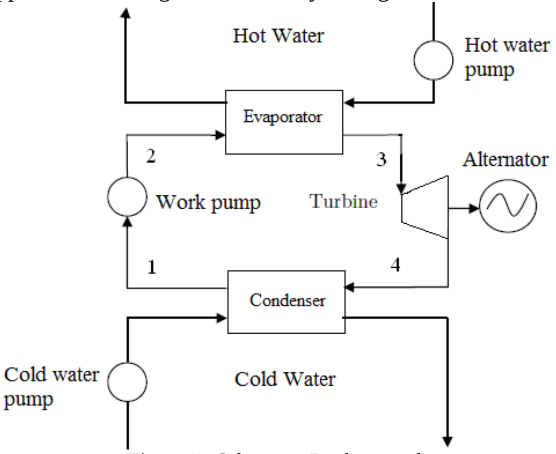

Figure 1: Schematic Rankine cycle

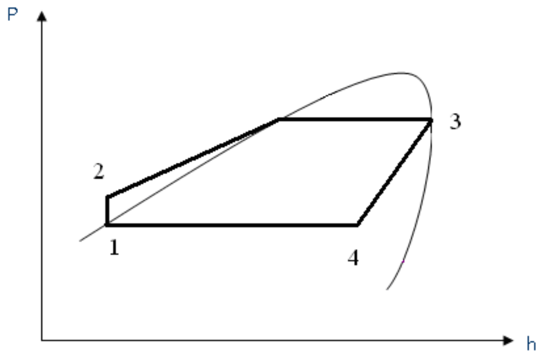

Figure 2: P;h diagram of the Rankine cycle with ammonia

2.2. Working fluid

The working fluid used here is ammonia. This choice has been made for different reasons: first of all, it is a fluid naturally present in the environment and its evaporating pressure is low in comparison to other refrigerating fluids [8], then its latent heat is the highest after water's (907.7 kJ/kg [9]), for one power ammonia has the highest performance [10], moreover its molar mass is one of the lowest [9] which leads to a decrease of the pipe diameter [10].

However, ammonia presents some risks. A vapour leak from 1700 ppm could lead to respiratory damages in the human body [11], and a liquid leak if there are eye or skin contact, could lead to cold burns [8].

The advantage is that all these risks are well known and a series of security measures have been taken: ammonia detectors, ventilation, ammonia training for staff, high tightness of the pipe's process division, individual equipment protection etc.

Furthermore, in terms of explosiveness, ammonia is safe enough: the interval of explosiveness is from 16 to 28% of the room volume and its self-flammability temperature is very high, 651°C [11].

Despite of theses risks are known and controlled, if the quantity of ammonia is reduced, risks and cost will be too.

2.3. Heat sources

The temperature differential must be of at least 20°C and stable enough. This is the reason why the tropical zone is considered as the best geographic location on earth to develop the OTEC plant. Indeed, all requirements are met: 4.9°C cold seawater can be found at 1000 m deep and a temperature over 25°C at the surface. This area represents 1/3 of the ocean's surface, and could produce 10 million MWe [12].

3. EXPERIMENTAL INSTALLATION

An experimental installation has been built by a French firm: DCNS. It has been decided to realise an onshore prototype to avoid sea related issues such as anchorage, floating platforms, 1000 m long flexible to pump cold water etc.

Concerning its power, it is a 1/200 scale prototype in comparison to the first 10MW OTEC plant. It is designed to produce the equivalent of 15 kW. But for scale and cost reason, no alternator has been installed.

Besides, for scale reasons, this onshore prototype doesn't produce electricity.

Cold and hot sources are simulated by a heat pump, so that the hot water temperature can be adjusted to simulate the hot seawater temperature round the year (from 23 to 28°C). Concerning the cold water temperature, it is stabilized to around 5°C.

To bring the prototype as close as possible to the 10MW OTEC plant, it is necessary that they have the same working pressure.

The prototype has been designed for having stable regime.

3.1. Ammonia loop and its main components

On Annex 1, the ammonia loop is drawn.

The ammonia loop has been designed to extrapolate results on this loop to the first OTEC power plant ammonia loop.

The components are going to be presented in the circulating flow way.

The PAF is the pump which makes liquid ammonia flow into the pipes.

Then ammonia is vaporized in the evaporator.

The pseudo-turbine replaces the turbine. It reproduces the same thermodynamic effect as a turbine (isentropic expansion).

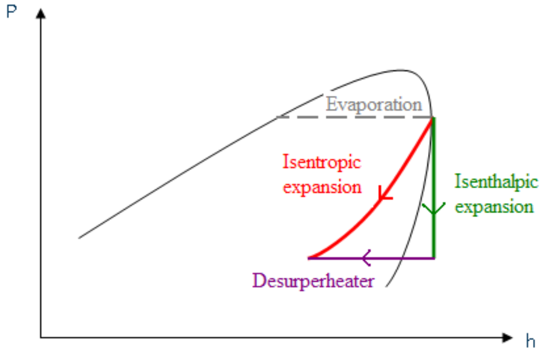

Figure 3: p-h diagram "as a guide"

Thereby, an expansion valve and a desuperheater have been installed. In Figure 5, this is explained. Before the turbine, the working fluid is in its vapour form (after the evaporator) at high pressure. The “isentropic expansion” line represents the path that follows the ammonia with a real turbine. So the working fluid is expanded as an isenthalpic process through the expansion valve. Then, the temperature of the vapour decreases when injecting cold liquid ammonia through the desuperheater.

Number of tubes	Passes number	Length (mm)	Tubes’ materials	Exchange surface (m²)	Ammo-nia volume (L)
280	4 tube passes	3050	Titanium bare tubes	39.6	17

Table 1: Condenser information

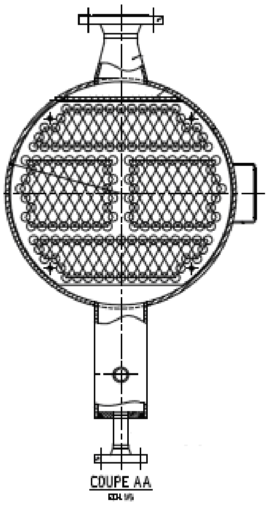

Figure 4: Shell-and-tube condenser

Ammonia vapours are condensated into the condenser. The condenser installed on the onshore prototype is a shell-and-tube exchanger. Water circulates through the tubes, and ammonia around in the grille. The working fluid in its vapour form arrives on top of the grille. At tubes’ touch, the vapour condensates and flows at the bottom in the grille. It is paramount for the performance of the condenser not to have the tubes flooded. In Figure 6, there is the representation of a condenser used on the onshore prototype. In Table 3 gives some information about the condenser.

Finally, ammonia is pumped again through the PAF pump.

3.2. Evaporators

After the turbine, the evaporator is the most important component in electricity production [6]. Indeed, the higher the output pressure, the higher is the electricity production. This is the reason why two different evaporators are tested on this onshore prototype: a flooded shell-and-tube evaporator and an aluminium plated evaporator.

- Flooded shell-and-tube evaporator is the most widely used type of heat exchanger for industrial evaporator applications [7]. Water flows through the tubes and the working fluid arrives on the bottom of the grille and floods the tubes. The nucleation appeared around the tubes surface and vapour is evacuated through the top of the grille. In Figure 3 there is a cross-section of the flooded shell-and-tube evaporator, and in Table 1, detailed information are presented.

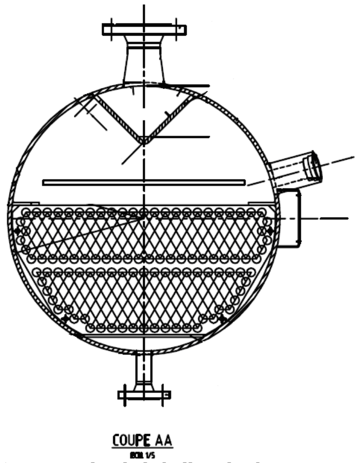

Figure 5: Flooded shell-and-tube evaporator

Number of tubes	Passes number	Length (mm)	Tubes’ materials	Exchange surface (m²)	Am-monia volume (L)
259	2 tube passes	4911	Titanium bare tubes	64.8	270

Table 2: Flooded evaporator specification

- Plate evaporator is a vertical aluminium brazed plate evaporator. Figure 4 illustrate of this evaporator. It is composed of a series of aluminium plates grazed together. Then between each plate, another aluminium wave is brazed. The working fluid flows through the small tubes and water through the large one. Please note that the aluminium wave is hollow in order to ease fluid flow and heat exchange. Finally, ammonia and hot water enter from the bottom of the evaporator and are injected at the same time between the aluminium plates. Please note that ammonia is evaporated vertically so it is hard to know exactly the liquid quantity. The Table 2 details information on the aluminium brazed plate evaporator.

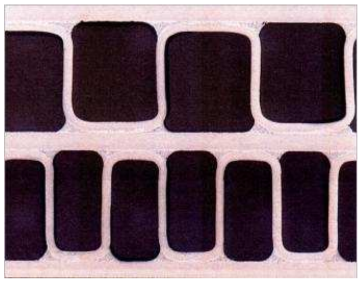

Figure 6: Aluminium brazed plate evaporator top view [13]

For the plate evaporator tests, a separator has been added (annexe 3) because the outlet quality of vapours is unsure.

High (mm)	Plates’ materials	Exchange surface (m²)	Ammonia volume (L)
2978	Alumi-nium	69	37

Table 3 : Plate evaporator information

3.3. Water loops

The two water loops of the prototype are very different from the OTEC plants. Indeed, a heat pump produces heat sources, the pipes' geometry, pumps etc. They have been designed to reproduce the ocean temperature only. The mass flow-rate is calculated following the similitude between the ammonia loop of the prototype and the ammonia loop of the OTEC plant. Therefore, none of the results from water loops will be significant for the Rankine cycle.

The components and principle of cold and hot water loops are similar. Annex 2 presents the supervision image of the hot water.

The temperature requirement is given in the box entitled "heating pump". Water circulates in the heating pump thanks to the pump "EPEC2", and thanks to the "EPEC 1" in the evaporator. The separating bottle delivers a constant water flow in the heat pump, while controlling the water flow in the evaporator.

4. TESTS AND RESULTS

4.1. Tests

A test is defined by the value of several parameters: hot water temperature, cold water temperature, hot water mass flow rate, cold water temperature and eventually ammonia mass flow rate.

For the study of the prototype using flooded evaporator, four points have been tested. Five points have been tested for the plate evaporator. The warm water temperature ranges from 23 to 28°C, cold temperature is at 4.9 °C. Flow rates are calculated to keep similitude between the prototype and the first OTEC power plant.

4.2. Results and discussion

All data used to calculate the thermal power have been averaged on a stable period of a minimum of 20 minutes.

The thermal power reflects the energetic performance of the evaporator. The two evaporators have not the same exchange surface. So, to compare their energetic performance, it is necessary to compare the thermal power divided by their exchange surface: the thermal surface power.

In an evaporator, the refrigerant begins to warm up, and when it reaches its saturation temperature, it is vaporized.

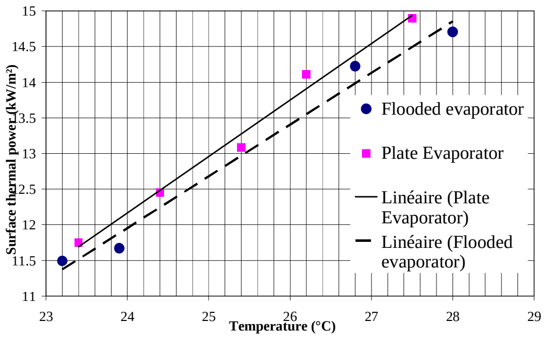

Figure 7: Evolution of the thermal surface power in function of the warm water temperature

So, the thermal power is the addition of the reheat power and the evaporation power. Here is the equation:

$$P_{th} = P_{reheat} + P_{evap} \quad (4.1)$$

$$P_{th} = \dot{m}_w Cp_w (T_{ew} - T_{sw}) + \dot{m}_{ft} (h_{sft} - h_{eft}) \quad (4.2)$$

Figure 7 shows the thermal surface power of the two types of evaporator in function of the hot water temperature.

The thermal surface power of the plate evaporator is upper than the flooded evaporator one. Indeed, at the warm water temperature of 28 °C, the thermal surface power of the plate evaporator is 4.1 % higher.

Even if the plate evaporator exchanges more thermal power than the flooded one, another important parameter to compare is the outlet evaporator pressure. Indeed, this value is the inlet data for the turbine. The more it is high, the more the alternator produces electricity.

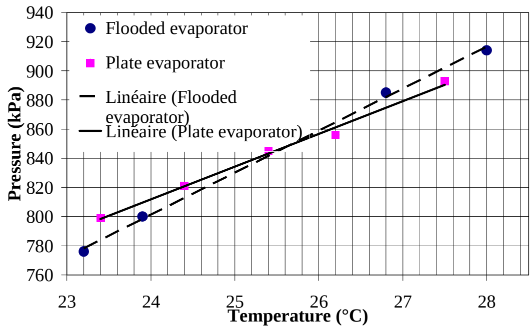

Figure 8: Evolution of the outlet ammonia pressure for both flooded and plate evaporators

Figure 8 details the outlet ammonia pressure of the two evaporators depending on the hot water.

The two evaporators have an evaporation pressure similar.

As shown above, the plate evaporator exchanges more thermal power but with the same outlet pressure. So, it would have been interesting to study the global electricity production (P_{brute}) minus the electricity consumption for the auxiliaries (ammonia pump, cold water and hot water pumps) : defined as the net electric power.

$$P_{net} = P_{brute} - P_{NH3\,pump} - P_{hotwaterpump} - P_{coldwaterpump} \quad (4.3)$$

As it is written above, a pseudo-turbine replace the turbine in the Rankine cycle. The thermal power in the pseudo-turbine is calculated from the enthalpy difference between the point 3 and 4 (Figure 1). But, to calculate an electrical power, these hypothesis must be taken: a 100% turbine and alternator efficiency.

First, the thermal power which is lost in the pseudo-turbine is calculated as follow (see Figure 1):

$$P_{turbine} = \dot{m}_{ft} (h_3 - h_4) \quad (4.4)$$

Secondly, the ammonia pump consumption is calculated from the constructor consumption curves.

As it is detailed in the paragraph 3.3, water loops have not been designed to extrapolate water results on the OTEC plant. So, water loops and ammonia loop (for the prototype) does not have the same scale. The two water pump consumption can be calculated, but including them in the 4.3 equation is meaningless.

P_{net}' is the electrical power produced minus the ammonia pump consumption: $P_{net}' = P_{brute} - P_{NH3\,pump}$ (4.5)

Figure 9 compares P_{net}'divided by the exchange surface for each evaporator (as in the study of Avery and Wu [6]).

According to Figure 9, the plate evaporator produces more electricity per m² than the flooded one. Indeed, for a hot water temperature of 28°C, the alternator in the plate evaporator version produces 26% more electricity than the flooded version.

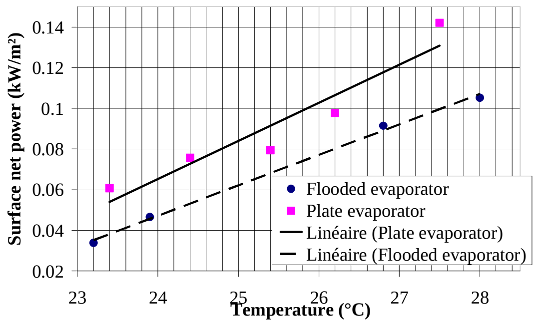

Figure 9: Evolution of the surface net power of the two evaporators depending on the hot water temperature

Concerning the water pumps consumption, it depends on few parameters: mass flow-rate, charge loss and pump technology (efficiency). The goal is to compare the electrical consumption of the pumps between the two evaporators. As the cold water loop does not change between the two tests, the cold water pumps consumption does not change either. Then, for the hot water loop, the evaporator changes only. Moreover, the mass flow-rates for each points are similar between the two evaporator. So, the comparison of the charge loss in the hot water loop between the two tests reflects the water pumps consumption between the two evaporators. And finally, between the two tests, the evaporator is the only thing which changes in the hot water loop. Therefore, the comparison of the charge loss in the evaporator reflects the comparison between the water pumps consumption.

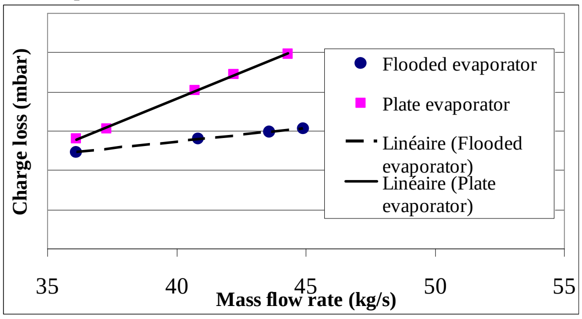

Figure 10 : Evolution of the water charge loss in the flooded evaporator and the plate one

Figure 5 show the charge loss for the two evaporators. But, the conclusion is: charge loss of the plate evaporator is higher than the charge loss for the flooded one. But, because of the scale effects (paragraph 3.3) the question of "how higher?" has no answer with the prototype.

5. CONCLUSION

This paper has presented the onshore OTEC prototype built by the firm DCNS. It has reminded the OTEC principle and exposed the specificities of this prototype: it does not produce electricity, and hot and cold water are produced by a heat pump.

Then, the different components have been shown, with a focus on the two evaporators tested (a flooded shell-and-tube evaporator and a brazed plate evaporator).

First, all tests permit to conclude that the plate evaporator exchange more heat per square meter than the flooded one with the same evaporation pressure. Then the comparison of the net electrical power (calculated on the ammonia loop) between the two evaporators has been made, leading to conclude that the plate one produces more electricity.

The most important difference between the two evaporators is the quantity of ammonia. As written above, the plate one need only 37L versus 270L for the flooded one and produces more net electricity power.

Nevertheless, the plate evaporator has some drawbacks: the intern technology lead to increasing charge loss (water pump consumption increase), fouling issue, and corrosion of the material (aluminium), addition of a separator (space lost and higher cost).

All those drawbacks lead to investigate on water pumps consumption (On the OTEC power plant, are the charge loss generated by the plate evaporator insignificant in front of the charge loss of the water pipes?) on other evaporator technology (a falling film one will be tested), other thermodynamic cycles etc.

In the future, the prototype can be used to validate the simulation model established by Sinama [6] with the Gibbs method.

6. REFERENCES

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7. NOMENCLATURE

P_{th}: Thermal power of the evaporator (kW)

P_{reheat}: Power generated by the reheat part of the evaporator (kW)

P_{evap}: Evaporation power of the evaporator (kW)

$P_{turbine}$: Thermal power lost by the working fluid in the turbine (kW)

$\dot{m}_w$: Hot water mass flow rate ($kg.s^{-1}$)

Cp_w: Thermal capacity at constant pressure of the water ($kJ.K^{-1}$)

T_{ew}: Inlet water temperature (°C)

T_{sw} : Outlet water temperature (°C)

$\dot{m}_{ft}$: Working fluid mass flow rate (kg/s)

h_{sft} : Outlet working fluid mass enthalpy (kJ.kg^{-1})

h_{eft} : Inlet working fluid mass enthalpy (kJ.kg^{-1})

h_{inlet}: Working fluid mass enthalpy which arrives in the turbine

h_{inlet}: Working fluid mass enthalpy which goes out of the turbine

Annex 1

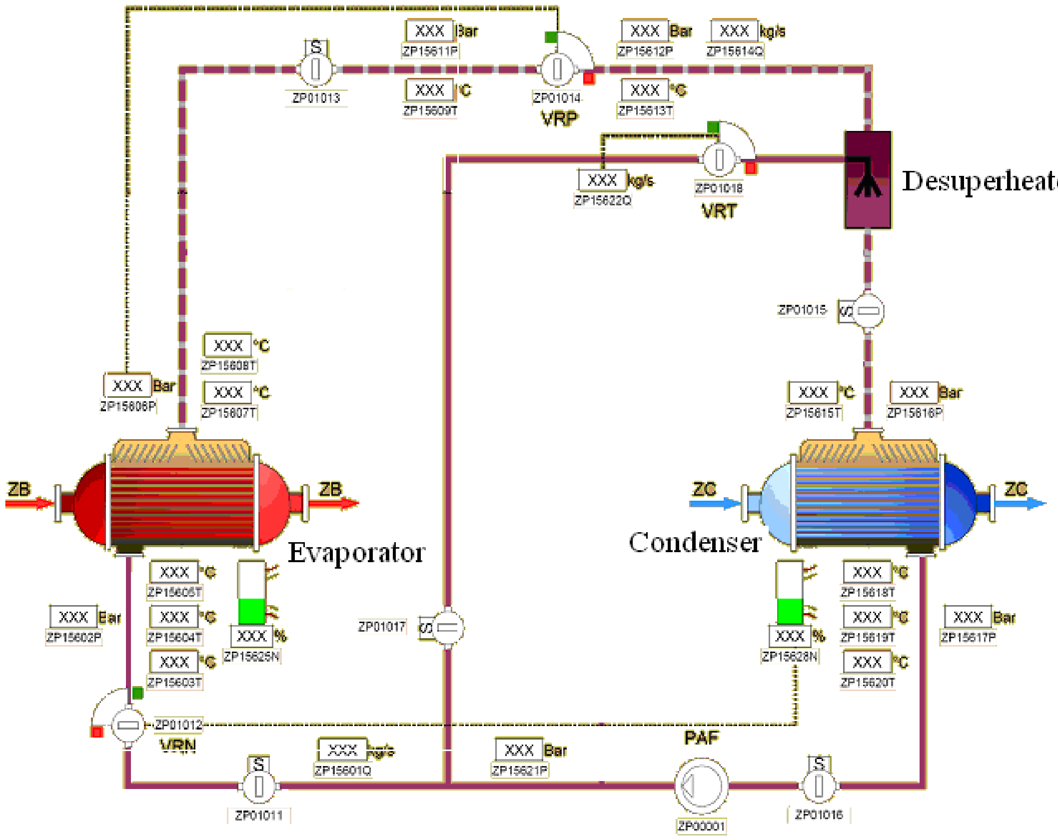

Figure 11: Ammonia cycle in the flooded evaporator version

Annex 2

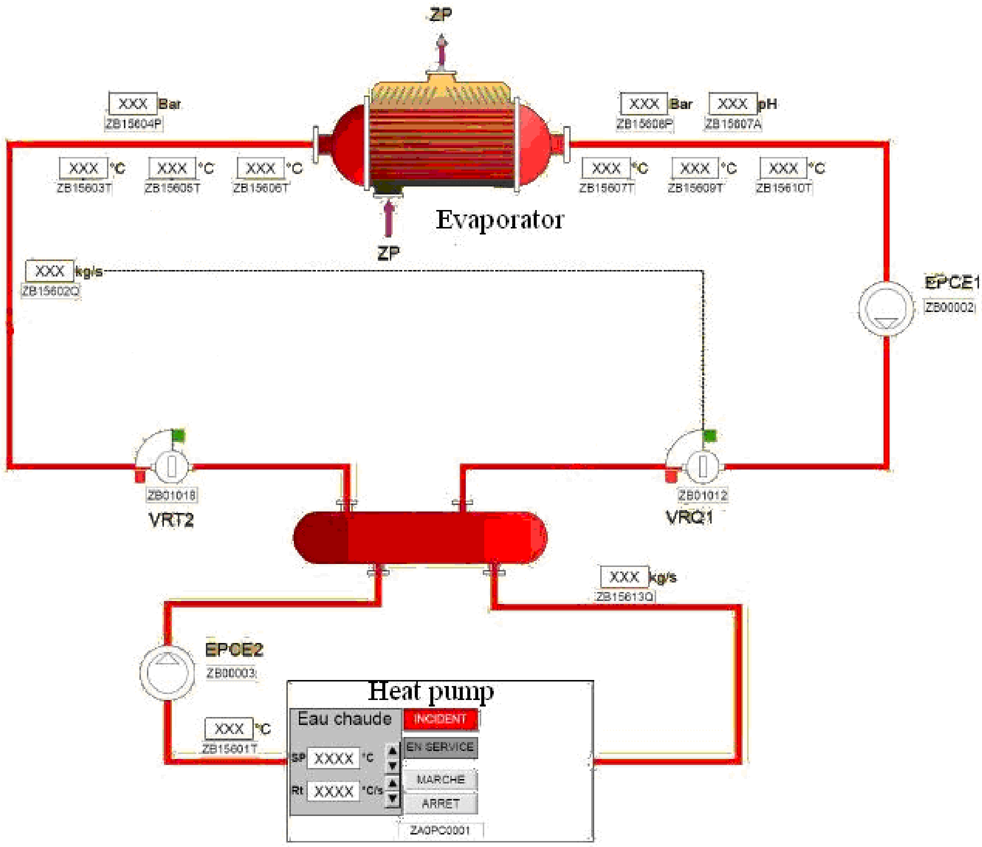

Figure 12: Warm water cycle

Annex 3

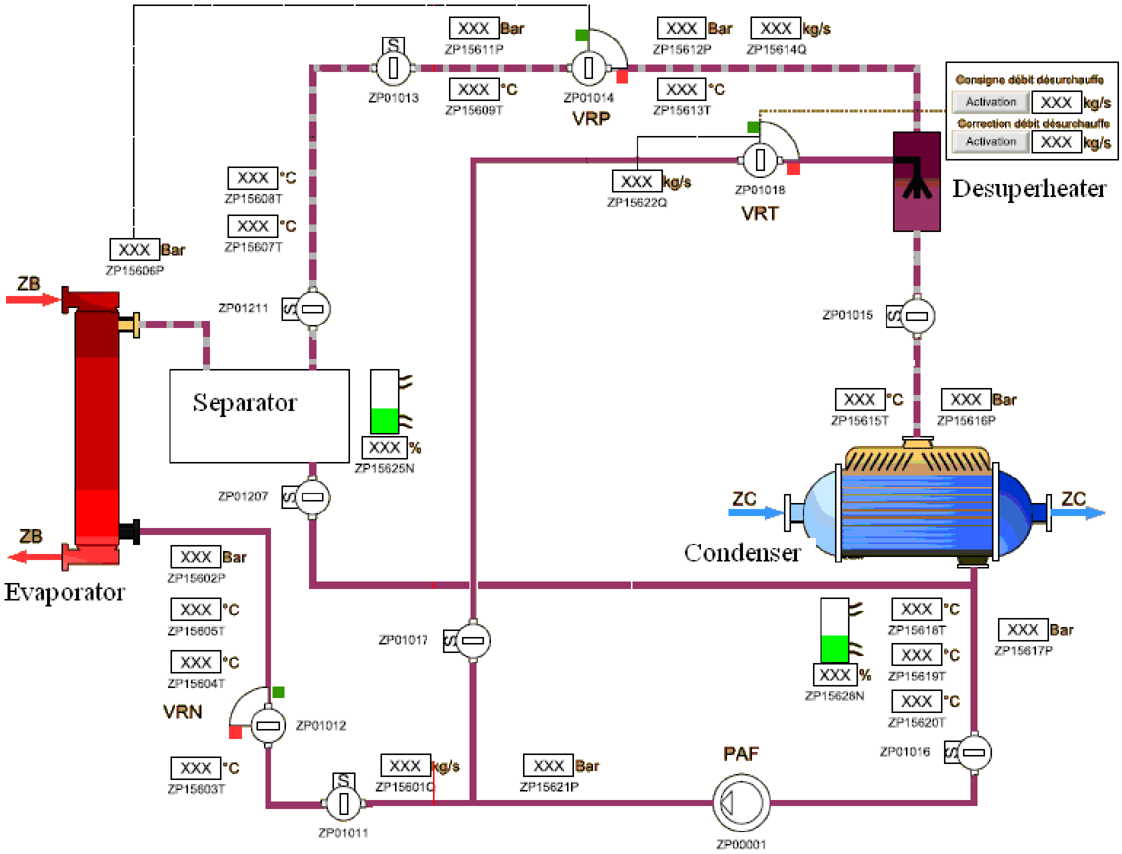

Figure 13: Ammonia cycle in the plate evaporator version