Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 129 (2017) 479–486

Energy Procedia

www.elsevier.com/locate/procedia

IV International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

Application Of The Novel "Emeritus" Air Cooled Condenser In Geothermal ORC

M. Astolfi[b]*, L. Noto La Diega[a], M. C. Romano[b], U. Merlo[a], S. Filippini[a], E. Macchi[b]

[a] LU-VE Group, Via Caduti della Liberazione 53, 21040, Uboldo, Italy
[b]Politecnico di Milano, Dipartimento di Energia, Via Lambruschini 4, 20156 Milano, Italy

Abstract

The present work aims to investigate the potential advantages in using a novel wet and dry configuration for heat rejection units in ORC power plants. The reference case is a geothermal power plant that exploits a medium temperature brine and uses a closed loop of cooling water to release the condensation heat. In the calculations, the off-design operation of the whole plant is optimized by a techno-economic point of view with a realistic part-load behaviour for the ORC and the use of experimentally validated correlations for the heat rejection section. The performance attainable with the novel LU-VE Emeritus® unit equipped with a water spray system and adiabatic panels is compared with those achievable with the same unit in dry operation. Final results show a marked increase of revenues with Emeritus® units with respect to a dry unit.

Keywords: ORC, heat rejection, system optimization, condenser

1. Introduction

Geothermal ORC plants are usually designed to exploit medium-low temperature geothermal brines and they can inevitably achieve a limited efficiency. This fact, together with the large scale economies of this sector (that push average size to multimegawatt plants), lead to the necessity of rejecting to the environment a massive thermal power. The most convenient solution is to use cooling water from a river or a lake where is available, but in most of the

* Corresponding author. Tel.: +39 0223993903; fax: +0-000-000-0000 .
E-mail address: marco.astolfi@polimi.it

10.1016/j.egypro.2017.09.164

cases the remote location of geothermal resources and the scarcity of superficial water require the use of ambient air for the release of the heat of condensation [1]. In these cases (common for geothermal power plants but also relevant for many waste heat recovery applications) the heat rejection unit represents a critical component, affecting significantly the capital as well as the operating costs of the system because of the large electrical consumption of the fans. Direct air cooled condensers (ACC) can be used in some applications while indirect heat rejection through a closed cooling water loop may be preferable for the following reasons:

- It allows reducing the volume of condenser since a compact shell and tube unit can be used. Working fluid inventory is therefore reduced, leading to the possibility of using flammable fluids that are less expensive and often show higher performance with respect to refrigerant fluids.
- Minimum pressure of the cycle can be below atmospheric pressure, with fewer concerns about air in-leakage, leading to increased freedom in the selection of the working fluid.
- Pressure losses of working fluid at turbine discharge are reduced thanks to the compactness of the unit and the absence of long headers for fluid distribution.
- It is possible to use standard components developed in HVAC (Heating, Ventilation and Air Conditioning) field with a potential reduction of the investment cost.

Both with a direct air cooled condenser and with an indirect cooling water system, the use of a dry heat rejection system involves a marked reduction of annual plant energy production, especially in locations with significant yearly temperature variations. A possibility for limiting the drawbacks of dry cooling systems with much lower water consumptions than cooling tower[†]s is to adopt water spray systems, exploiting the latent heat of water sprayed and evaporated on the fins of the condenser. The LU-VE dry-spray system for ORC plants has been validated in a supercritical R134a ORC demonstration plant [2, 3], as well as in hundreds of applications in HVAC. To further boost this system, the novel LU-VE Emeritus® air cooler introduces adiabatic panels in addition to the spray system and a sophisticated control strategy. The combination of the adiabatic panels and the spray system allows reducing significantly the condensing temperature of the ORC in the hot season for a given cooler footprint. In addition, operation with the sole adiabatic panels active allows keeping low condensing temperature in intermediate seasons without the need of spraying water on the heat exchanger fins.

In this paper the optimal design and the optimal operation of the Emeritus heat rejection section for a geothermal ORC is discussed. Revenues attainable with the selection of the proper operation mode are maximized as function of the ambient temperature taking into account a realistic off-design behavior of both the ORC and the heat rejection unit.

Nomenclature and acronyms

η	efficiency
Δh_{is}	isentropic enthalpy drop in the turbine
s	specific entropy
T	temperature
UA	overall heat transfer coefficient (U) times heat transfer surface (A)
Vr_{is}	isentropic volume ratio at turbine outlet and inlet
HVAC	Heating, Ventilation and Air Conditioning
EC	Electrically Commutated motors

† The yearly water consumption of Emeritus is a small fraction of the one of wet cooling towers (generally between 10-15%, depending on ambient conditions).There are two main reasons for this reduction: (i) water is used only for limited period of time and (ii) a large fraction of heat Is rejected by heating air, rather than by evaporating water.

2. Methodology

The techno-economic performances of the geothermal ORC equipped with the Emeritus cooling system are assessed for different ambient temperatures. The models of the two units of the plant are described in the following sections.

2.1 ORC

Figure 1.a. depicts the plant layout of the ORC, which uses isopentane as working fluid and it is condensed by a closed loop of cooling water equipped with the air cooled heat rejection unit. Geothermal brine maximum temperature is 160°C and a minimum reinjection temperature limit of 70°C has been considered in order to limit the deposit of silica compounds and consequent fouling of the heat exchangers. The geothermal brine flow rate is defined to obtain a maximum available heat of 30 MW. As a common practice in geothermal plants, the ORC is designed as a subcritical saturated cycle with a recuperator that allows increasing the plant efficiency by reducing the irreversibility in both the heat introduction and the condensation processes. Evaporation takes place in a kettle reboiler provided by a demister on the top to remove the liquid droplets that can be dragged by the vapor stream. In the recuperator, the pressurized liquid flows in a bundle of finned tubes, while vapor flows on the shell side. The condenser is made by a shell and tube heat exchanger where vapor condenses on the cooling water tubes surface and is collected in the condenser hotwell as saturated liquid. The design of the ORC relies on the assumptions reported in Table 1.

Temperature differences in heat exchangers		Pressure drops in heat exchangers		Component efficiency	
$\Delta T_{pp,EVA}$	5 °C	$\Delta p_{REC(l)}$	0.5bar	eta turb	0.9
$\Delta T_{pp,REC}$	5 °C	$\Delta p_{REC(v)}$	2%	eta pump	0.75
ΔT_{sc}	5 °C	Δp_{ECO}	0.5 bar	etagenm-e	0.96
$\Delta T_{ap,COND}$	9 °C	ΔT_{EVA}	1°C	eta pumpm-e	0.95
		ΔT_{COND}	0.3°C	eta aux	0.98

Table 1. set of assumptions used in the ORC power system simulation

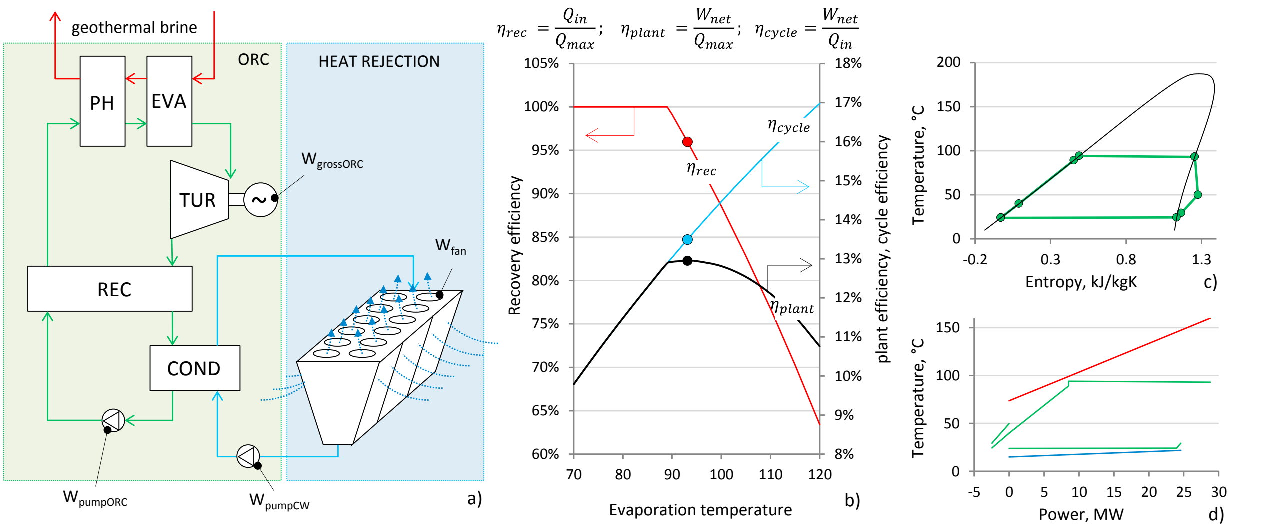


Figure1. Process configuration (a), heat recovery and cycle efficiencies (b) and Ts and TQ diagrams at the design point of the ORC plant assessed in this work.

Design point condensation temperature is set to 24 °C while the evaporation temperature is optimized with the aim of maximizing the ORC net electric power output. As reported in figure 1.b, the optimal evaporation temperature is found equal to 93.1°C as a result of the tradeoff between the cycle efficiency and the heat recovery efficiency of the heat source. Gross electric power output is 4.15 MW, while the net electrical power is equal to 3.885 MW, considering the consumption of both the ORC pump (102 kW) and the cooling water pump (88 kW, ΔT=7°C, Δp=1bar). Nominal efficiency is 13% with a second law efficiency of 51%. Figure 1.c and Figure 1.d show the Ts and the TQ diagram of the optimized configuration.

ORC off-design performance is then calculated for different condensation temperatures by varying the thermodynamic conditions of the cycle to keep the UA of the four heat exchangers and the reduced mass flow rate at turbine inlet equal to the design value. Both geothermal brine and cooling water mass flow rates are kept constant, while the organic fluid mass flow rate shows little variation within the investigated range of condensation temperature (from 14°C to 58°C). For this reason, we considered both pressure drops and global heat transfer coefficients of the heat exchangers unchanged with respect to the design values. Isentropic efficiency penalty of the turbine is accounted for in off-design operations as function of the ratios of Δh_{is} and Vr_{is} with the corresponding design values [4, 5].

Figure 2 depicts the variation of some key process parameters and performance indicators as function of the condensation temperature. By increasing the condensation temperature, both the evaporation and the brine reinjection temperatures increase, leading to a higher working fluid mass flow rate and to a lower exploitation of the available heat (Figure 2.a.). As a consequence, both ORC heat input and heat released to the cooling water decrease (Figure 2.b.) and the net power output of the cycle decreases (Figure 2.c.). When condensation temperature reduces below the design one, the ORC power output increases but with a lower slope, because the thermodynamic benefit of a lower condensation temperature are partly compensated by the reduction of the turbine efficiency (Figure 2.d.).

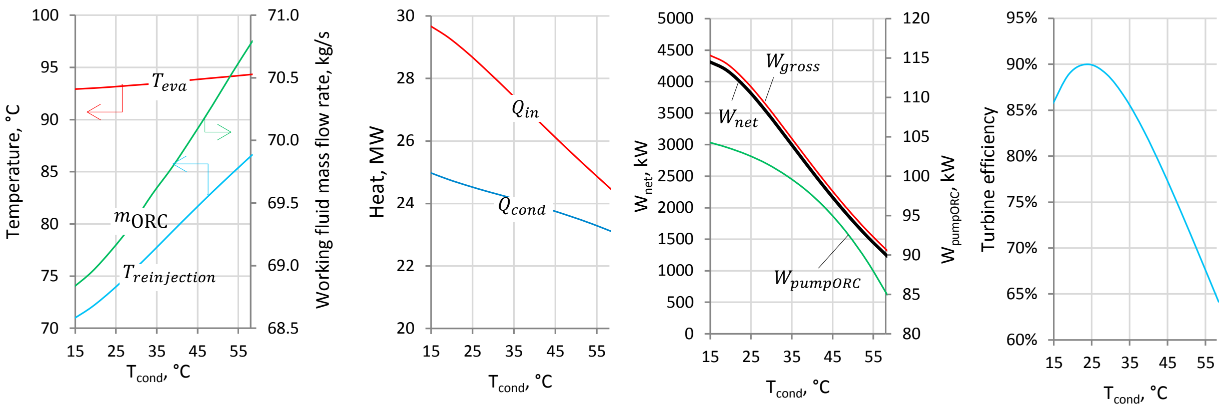


Figure 2: Key process parameters and performance indicators of the ORC in off-design operation as a function of the condensation temperature.

2.2 Heat rejection section

The conceptual configuration of the Emeritus® cooler is shown in Figure 3. In this heat rejection unit, water can be used to enhance the heat exchange in the following ways:

- By wetting adiabatic‡ cooling panels placed ahead the coil, which increases the air humidity and decreases the air temperature, thereby obtaining a greater temperature difference between the fluid to be cooled and the air. The adiabatic panels consist of a matrix of cellulose sheets, characterized by folds with different angles. A significant advantage of this solution is the possibility of using mains water, without any limits on the wet operating time.

‡ The panels are called “adiabatic” because the thermodynamic transformation undergone by air is obtained by the evaporation of injected water, without any heat transfer with the ambient

- By spraying water directly on the heat exchanger surfaces, which are suitably treated with the purpose of preventing deposition of salts and corrosion. In this case, water evaporation removes heat from the heat exchanger walls and therefore from the fluid to be cooled inside the tubes. Experience shows that, if demineralized water (e.g. from a reverse osmosis system) is used, no time duration limits exist. Conversely, when softened water is used, the annual spraying time should be limited to about 500 hours to avoid fin corrosion.

The innovative Emeritus® solution proposed by LU-VE [6] uses water on both the adiabatic panels and the heat exchange coil tubes. The control system operates so that at high ambient temperatures, treated water is sprayed onto the heat exchange coil. The softened or demineralized water which does not evaporate on the coil is collected at the bottom of the unit and recycled to the adiabatic panels. At intermediate (say, between 20-25°C) ambient temperatures, only the adiabatic panels are wet. The excess water from the adiabatic panels is not recovered. Finally, at low ambient temperatures (say, below 20°C), the unit operates in dry mode and the cooled water set point temperature is controlled by acting on the rotational speed of the Electronically Commutated (EC) fans. Figure 4 depicts the 22 fans Emeritus configuration with its main characteristics.

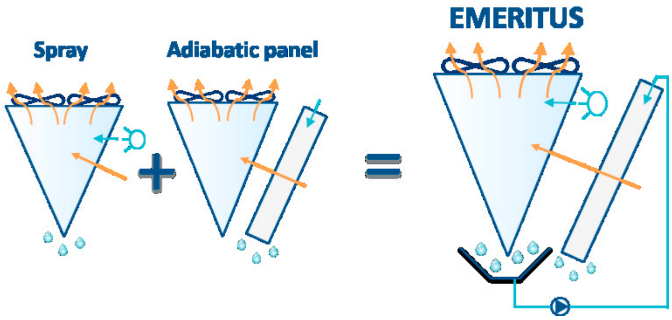
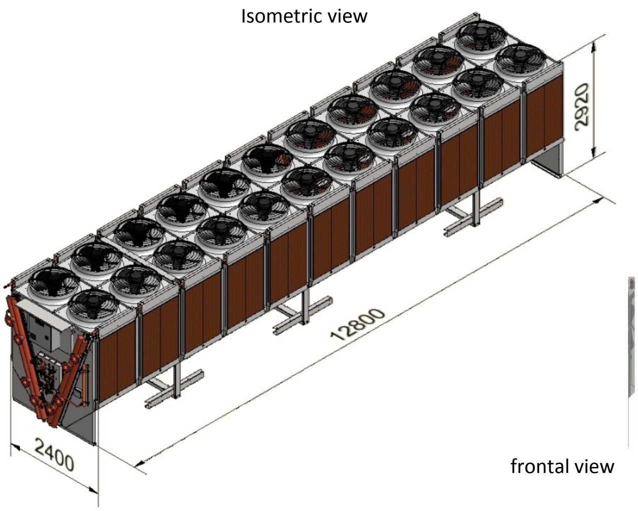


Figure3. Conceptual configuration of LU-VE EMERITUS technology, combining adiabatic panels and water spray system. Air is represented by orange streams while water by light blue streams



cooling water	Mass flow rate	32800	kg/s
	Temperature (in/out)	29.3/24.13	°C
Air	Volume flow rate	243196	m^3/h
	Temperature (in/out)	26.5/27.3	°C
	Wet bulb temperature (inlet)	20.62	°C
Fin pack	materials	Tubes	Cu
		Fins	Painted Al
		Headers	Cu
		Connections	Fe
	External surface	5103	m^2
	Int/ext surface	16.302	
	Tube int. diameter	9.52	mm
	Tube spacing	25	mm
	Fin spacing	2	mm
Spray system	Configuration: 44 nozzles on 3 rows for each side		
	water needed	3840	kg/h

Figure4. Isometric and frontal views of a 22 fans Emeritus heat exchanger and main characteristics

3. Results and discussion

In Figure 5.a, the cash flow of the ORC plant equipped with 25 Emeritus® coolers 22 fans each is reported for the three operating modes (dry, adiabatic panels only, spray + adiabatic panels), as a function of the ambient temperature. For each ambient temperature, the optimal fan rotational speed and flow rate of sprayed water are determined to maximize the total cash flow of the plant, accounting for the ORC electric power output and the consumption of electricity and water of the Emeritus® coolers. The reference cash flow (100%) has been set at the ambient temperature of 7.7°C, which is the condition at which the optimal operation of the Emeritus® cooler leads to the achievement of the design ORC condensing temperature of 24°C. In this analysis, the electricity selling price and the water price have been assumed 200 €/MWh (representative of a feed-in tariff) and 1 €/m^3 respectively. The relation between ambient temperature and relative humidity is obtained by averaging climatic data from central Italy, from [7].

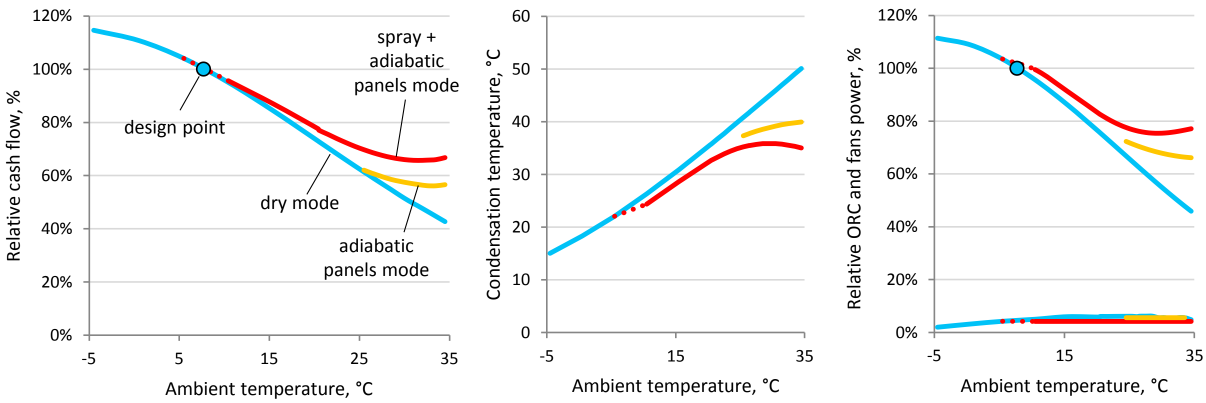


Figure 5. Relative cash flow as function of the ambient temperature for the reference case with 25 Emeritus® units in different operation modes, with optimized fans rotational speed and water flow rates.

In dry operation mode, the relative cash flow sharply decreases with the ambient temperature. At 30°C, the cash flow is 50% of the reference value, due to both the reduced ORC power output, caused by the increasing condensing temperature, and by the increased consumption of the fans, as shown in Figure 5.b and Figure 5.c. For ambient temperatures higher than 25°C, the use of the adiabatic panels is convenient from the economic standpoint. In this temperature range, the cost of the water consumed by the cooler is more than compensated by the economic benefit resulting from lower condensing temperature and lower fan consumption. With spray + adiabatic panels mode operation, better performance is obtained, mainly because water is used twice, first on the heat exchanger coil and then on the adiabatic panels, leading to increased water evaporation efficiency, further reduction of condensing temperature and a higher ORC power production. As a result, water spray + adiabatic panels mode is in principle convenient over the dry mode even at ambient temperatures as low as 10°C.

The largest advantages in the wet operations are achieved at the highest ambient temperatures. At 35°C, the cash flow in adiabatic panels mode is 27% higher than the dry operation mode (57% vs. 45% of the design point cash flow). At the same ambient temperature, the cash flow with the spray + adiabatic panels mode is about 70% higher than with dry operation. From Figure 5, it can also be observed that the cash flow is barely affected by the ambient temperature in case of wet operations. This is due to the reduction of the relative humidity when ambient temperature increases, which increases the water evaporation efficiency.

In Figure 6, the relative cash flow of the ORC plant for three sizes of the Emeritus® heat rejection system is reported. The largest differences in the cash flow of the three cases are observed at intermediate-low ambient temperatures (roughly between 5 and 23°C), where the largest heat rejection system composed of 30 Emeritus® units shows relative cash flows 5-10% higher than the smallest one composed by 20 units.

A step change of the cash flow is shown at 26.5°C of ambient temperature, corresponding to the spray switch temperature. Below this ambient temperature spray operations are not allowed by the control system, in order not to exceed the maximum annual spraying time of 500 hours. Such a switching temperature depends on the yearly ambient temperature distribution of the specific location considered. Therefore, below 26.5°C, the system is forced to operate in dry mode or adiabatic panels mode. In Figure 6, the ambient temperature at which the water injection to adiabatic panels is started is shown for the three cases. It can be noticed that when the number of units is decreased, it is convenient to activate the adiabatic panels wetting system at lower ambient temperature (23.5°C with 20 units vs. 25.5°C with 30 units). This result depends on the higher optimal rotational speed and electric consumption of the fans in dry mode when less Emeritus® coolers are used, which makes economically convenient an earlier switching on of the adiabatic panels system.

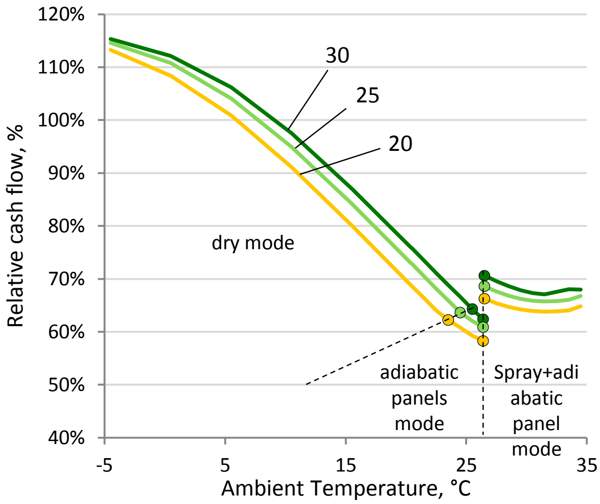


Figure 6. Relative cash flow as function of the ambient temperature for cases with 20, 25 and 30 Emeritus® units with optimized fans rotational speed and water flow rates.

In figure 7, the dimensionless water consumption and the water balance for the reference case with 25 Emeritus® units is shown. Between 25 and 26.5°C, the system operates in adiabatic panels mode and consumes about 75% of the maximum water consumption. The evaporation efficiency at these conditions is about 23%, meaning that 77% of the water used on the adiabatic panels is ultimately lost. When spray + adiabatic panels mode is activated, water evaporation efficiency increases significantly. Mainly due to the reduction of the relative humidity, water evaporation efficiency also increases with the ambient temperature, reaching a total efficiency higher than 60% for the maximum temperature assessed in this work.

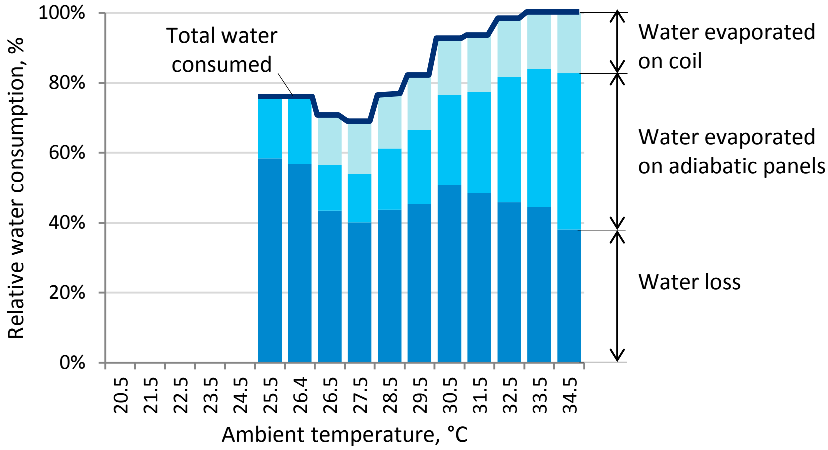


Figure 7. Water balance of the case with 25 Emeritus® units and optimized operating conditions.

4. Conclusions

In this work, the coupling of the novel Emeritus® cooling system and an ORC for a geothermal heat sources is assessed. The results obtained refer to a specific ORC but the trends presented for the different quantities can be extended to any other ORC exploiting a low-medium temperature heat source.

These results highlight the impact of ambient temperature on the plant efficiency and power production. At low ambient temperatures, the use of high efficiency fans, provided with variable speed electronically commutated motors, allows reducing the heat rejection unit consumption. However, at high ambient temperatures the increase of cycle condensing temperature strongly penalizes the power production. The Emeritus configuration gives a significant contribution to this problem thanks to the use of a novel water spray system, combining water spray on the coil surface and adiabatic panels for pre-humidification of the inlet air.

The convenience to adopt the Emeritus® configuration from both thermodynamic and economic perspective strongly depends on the daily and seasonal ambient temperature and humidity patterns. In the investigated case, characterized by a relatively mild climate, the use of water is limited to about 10% of the operating hours (almost equally divided into adiabatic panels and spray + adiabatic panels modes) and enables additional revenues of about 50 k€ per year, close to 1% of total annual revenues.

This figure compares favourably with the additional investment costs related to the addition of adiabatic panels and spray system to the dry version. Of course, Emeritus® cooling system would yield much higher revenues increments in warmer climates. It can be noticed that the condensation temperatures obtained with the proposed system are similar to the ones typical of wet cooling towers, but are achieved with a much lower water consumption, limited only to a relatively small fraction of the ORC operating hours.

References

[1] Birkinshaw K., Masri M., Therkelsen R. L., Comparison of Alternate Cooling Technologies for California Power Plants Economic, Environmental and Other Tradeoffs, Consultant report, California Energy Commission, 2002

[2] Rossi N., Testing of a new supercritical ORC technology for efficient power generation from geothermal low temperature resources, Asme ORC 2013 conference, Rotterdam

[3] Macchi E., Astolfi M., 2017, "Organic Rankine Cycle (ORC) Power Systems", Woodhead Publishing Series in Energy Number 107, Elsevier

[4] Capra, F. and Martelli, E. (2015). Numerical optimization of combined heat and power Organic Rankine Cycles – Part B: Simultaneous design & part-load optimization. *Energy*, 90, pp.329-343

[5] Ghasemi, H., Paci, M., Tizzanini, A. and Mitsos, A. (2013). Modeling and optimization of a binary geothermal power plant. *Energy*, 50, pp.412-428.

[6] Luve Petent, 2016 n.102016000099929

[7] http://www.nrel.gov/