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Minimizing the levelized cost of electricity production from low-temperature geothermal heat sources with ORCs: Water or air cooled?

Daniël Walraven [a,c], Ben Laenen [b,c], William D'haeseleer [a,c,*]

[a] University of Leuven (KU Leuven) Energy Institute – TME Branch (Applied Mechanics and Energy Conversion), Celestijnenlaan 300A Box 2421, B-3001 Leuven, Belgium
[b] Flemish Institute for Technological Research (VITO), Boeretang 200, B-2400 Mol, Belgium
[c] EnergyVille (Joint Venture of VITO and KU Leuven), Dennenstraat 7, B-3600 Genk, Belgium

HIGHLIGHTS

- System optimization of organic Rankine cycles powered by low-temperature geothermal heat.
- Models of heat exchangers, dry and wet cooling and axial turbines.
- Minimization of the levelized cost of electricity.
- Combined optimization of the configuration of the cycle and of the components.

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ABSTRACT

A system optimization of ORCs cooled by air-cooled condensers or wet cooling towers and powered by low-temperature geothermal heat sources is performed in this paper. The configuration of the ORC is optimized together with the geometry of all the components. The objective is to minimize the levelized cost of electricity (LCOE) and the performance of ORCs with different types of cooling systems are compared to each other. The results show that it is economically more interesting to use mechanical-draft wet cooling towers instead of air-cooled condensers. The difference in performance is especially large for a low brine-inlet temperature. The investment cost of wet cooling towers is much lower than the one of air-cooled condensers, so the discount rate has less influence on the former type of cooling. The effect of the water price and the climate conditions on the economics of ORCs is also investigated. Both the brine-inlet temperature and the dry-bulb temperature of the surroundings have a strong influence and values of the optimized LCOE between about 55 and 185 €/MW h are obtained.

1. Introduction

It is expected that low-temperature geothermal heat sources will be used more often in the future for electricity production [1,2]. One issue with these sources is that the conversion efficiency to electricity is low due to the low temperature of the source. Many researchers have tried to maximize this efficiency by optimizing the performance of organic Rankine cycles (ORCs), but the absolute efficiency remains low due to the Carnot limit. Most of the research on ORCs focuses on the optimization of the thermodynamic cycle. Simple cycles, recuperated cycles and cycles with turbine bleeding are proposed, they can be subcritical or transcritical and have one or more pressure levels [3–11]. In most cases, the components in these cycles are assumed to be ideal or they are modeled very simplistically. Some researchers have already taken the influence of the sizing of the components into account. Madhawa Hettiarachchi et al. [12] have minimized the ratio of the total heat exchanger surface and the net power produced by the cycle. Franco and Villani [13] have optimized the cycle and the heat exchangers separately, but used an iteration to make the connection between the system level and the component level. Walraven et al. [14] have shown that it is possible to optimize the configuration of shell-and-tube heat exchangers together with the configuration of the cycle, which was extended in Walraven et al. [15], in which an air-cooled condenser was included.

A consequence of the low conversion efficiency of heat into electricity is that most of the heat, which is added to the cycle,

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* Corresponding author at: University of Leuven (KU Leuven) Energy Institute – TME Branch (Applied Mechanics and Energy Conversion), Celestijnenlaan 300A Box 2421, B-3001 Leuven, Belgium. Tel.: +32 16 32 25 11; fax: +32 16 32 29 85.

E-mail addresses: Daniel.Walraven@mech.kuleuven.be (D. Walraven), Ben.Laenen@vito.be (B. Laenen), William.Dhaeseleer@mech.kuleuven.be (W. D'haeseleer).

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Nomenclature

Greek

η	efficiency (–)
θ	tube bundle angle (°)

Roman

A	surface area (m^2)
C	cost (€)
d_o	tube outside diameter (m)
D_s	shell diameter (m)
f	correction factor (–)
H	fin height (m)
H_x	height of x (m)
i	discount rate (%)
I	income (€)
l_c	baffle cut length (m)
L_b	baffle spacing (m)
LCOE	levelized cost of electricity (€/MW h)
L_t	length of the tubes (ACC) (m)
$\dot{m}$	mass flow (kg/s)
MINLP	mixed integer non-linear problem
N	number of full load hours (–)
n_{tubes}	number of tubes (–)
ORC	organic Rankine cycle
p	price (€)
p_t	tube pitch (m)
S	fin pitch (m)
T	temperature (°C)
t	time (year)
V_{Amin}	velocity at minimum flow area (m/s)
$\dot{W}$	mechanical power (kW)
W_s	tube small width (m)
W_t	tower width (m)
W_l	tube large width (m)

Sub-and superscripts

air	air
brine	brine
drilling	drilling
E	equipment
el	electrical
EPC	engineering, procurement and construction
fan	fan
I	installation
in	inlet
LT	lifetime
M	material
net	nett
OM	operation and maintenance
ORC	ORC
P	pressure
pump	pump
T	temperature
turbine	turbine

has to be dumped into the environment. The cooling system is therefore very important in power plants powered by low-temperature heat sources. Power plants can be cooled in three ways: air cooling, water cooling with a cooling tower and direct cooling with water, of which the two first options are most often used. The auxiliary power consumption of air-cooled condensers (ACC) is about twice as high as that one for mechanical-draft wet cooling towers (WCT) used for low-temperature geothermal power plants [16]. When low condensing temperatures are used in these plants, the investment cost of a binary plant with an ACC can be 50% higher than that of a plant with a wet cooling tower for the same conversion efficiency [16]. The disadvantage of using a wet cooling tower is of course that water is consumed, which is a big drawback when water is scarce. The type of the cooling method is therefore very important in the design of a geothermal binary power plant.

The comparison between air cooling and wet cooling has already been performed in the literature. Barigozzi et al. [17] developed a model of a cogeneration power plant powered by burning waste, while the cooling system consists of both an ACC and a WCT. They found that when the environmental temperature is below 15 °C, it is best to use the ACC. When the environmental temperature is higher than 15 °C, both the ACC and the WCT are used. First, the ACC is used to cool down the steam and afterwards the WCT is used to cool it further down. These results are valid for high-temperature heat sources (turbine-inlet-temperature of 450 °C). Mendrinos et al. [16] compared cooling methods for geothermal binary plants. They concluded that wet cooling towers are the best choice, except when water is a very scarce product or when the climatic conditions are extreme.

The above mentioned works often use simplified models of the cooling system. Other researchers have optimized the configuration of the cooling system itself. Rubio-Castro et al. [18] used the work of Kloppers and Kröger [19] to simulate and optimize the performance of a mechanical-draft wet cooling tower and compared the Merkel to the Poppe method. They repeated the optimization for different fill types. Serna-Gonzaález et al. [20] performed a similar research, but defined the problem as a MINLP (Mixed Integer Non-Linear Problem) in which the type of packing and the type of draft were the integer optimization variables. They used the Merkel method to calculate the heat and mass transfer in the cooling tower.

In this work we combine the three above mentioned research areas: optimization of ORCs, comparison between cooling systems and optimization of cooling systems; all at once simultaneously. In our previous work [15], we maximized the net present value of an air-cooled ORC, in which the parameters of the ORC, the configuration of the heat exchangers and the configuration of an ACC are optimized together. In this paper we add a model for a wet cooling tower based on the work of Kloppers [21] and minimize the levelized cost of electricity production (LCOE)[1] for both water-cooled and air-cooled ORCs. The results of both types of cooling are compared to each other and the influence of the brine-inlet temperature, brine-outlet temperature, discount rate and water price on the performance of the power plant are investigated.

2. Physical model

2.1. Organic Rankine cycle

Organic Rankine cycles (ORCs) can have different configurations of which a few are modeled in this paper. The cycles can be simple or recuperated, subcritical or transcritical and can have one or two

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[1] This is the constant electricity price needed during the lifetime of the power plant to reach brake-even at the end of the lifetime of the power plant.