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Thermodynamic cycles optimised for medium enthalpy units of concentrating solar power

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ABSTRACT

Concentrated solar power presents the drawback of decreasing radiation capture efficiency as the temperature of the receiver increases, because thermal losses increase as well. Low temperature at the receiver is an advantage for radiation concentrators, as they present high capture efficiency, but this fact changes into a drawback because of the low efficiency of the thermodynamic cycles working with a low temperature heat source.

An analysis is presented on the performance of real fluids working with such a type of heat sources that can be generated in simple solar thermal units. Both Joule–Brayton cycles and dry-turbine Rankine cycles are considered, using regenerative heat exchangers for heat recovering. The driving force of this research is to look for working fluids with actual thermodynamic characteristics which fit well with temperatures of the heat source and sink. Some unconventional substances, as refrigerant R-125 or SF_6, show good performance. They may be suitable at certain regimes of Rankine and Brayton cycles and could work in fast-reacting systems. Of course, differences in the performance of Brayton and Rankine cycles convey differences in the complexity and cost of the components, but they offer a wide field for coherently choosing the working fluid and thermal conditions.

1. Introduction and background

In the field of future electricity generation, STPPs (solar thermal power plants) will have to play an important role for energy sustainability. The major feature of concentrating solar power is its renewable nature, as STPPs use solar irradiation as the energy source. Very briefly, STPPs consist of two main components: the solar field & receiver and the power block. Of course they may include a thermal storage system and other auxiliary systems. This structure makes STPP form a thermal energy chain, whose links or components should be designed each one according to the others.

The key feature of the solar field & receiver is the radiation concentration factor achievable. Different concentrating technologies (Fresnel, parabolic trough collectors, solar central tower and parabolic dishes) achieve different concentration factors at different cost and power levels. All technologies may be optimised to collect the maximum incident irradiation to the receiver and, therefore, to attain maximum temperatures in the cooling fluid that, in turn, feeds the thermodynamic cycle. But all of them also share another essential characteristic: the higher the concentrating factor and working temperatures, the higher the thermal losses to the environment and cost. Thus, a trade-off between those conflicting aspects is required. In the short and medium term, this trade-off, together with the possible limitations of the cooling fluid in the case of using an intermediate heat transfer carrier, will lead to another feature of concentrating solar power plants: the low-to-moderate temperature that feeds the thermodynamic cycle or engine.

The low or moderate temperature of the thermal source prevents the primary heat from being efficiently converted to electrical power. As it is well known, the maximum conversion efficiency is limited by the Carnot efficiency, which depends on the ratio of the heat source and heat sink temperatures. Furthermore, the Carnot efficiency is not reachable because actual cycles are unable to fulfil Carnot cycle's conditions. Therefore, when the heat source temperature is low, an extra effort should be paid to improve the thermodynamic cycles, because a small increment in absolute terms represents a high increment in relative terms, which has an obvious positive effect in terms of economic viability.

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Nomenclature

Symbols

CN	Carnot factor or extreme temperature ratio (–)
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
F_h	mean heating temperature factor (–)
F_c	mean cooling temperature factor (–)
$F_{\Delta s}$	entropy generation factor (–)
h	specific enthalpy (J kg^{-1})
I	specific irreversibility (J kg^{-1})
$\dot{I}$	irreversibility (J s^{-1})
$\dot{m}$	mass flow (kg s^{-1})
ORC	organic Rankine cycle
p	pressure (Pa)
PP	pinch point (K)
Q	thermal energy from the heat source (J kg^{-1})
r	pressure ratio (–)
R	constant gas (J kg^{-1} K^{-1})
s	entropy (J kg^{-1} K^{-1})
STPP	solar thermal power plant
T	temperature (K)
$\tilde{T}$	mean temperature (K)
UA	UA factor, product of the overall heat-transfer coefficient and the heat exchange area (W K^{-1})
v	specific volume (m^3 kg)
W	specific work (J kg^{-1})
x	steam quality (–)
z	compressibility factor (–)

Greek letters

Δ	increment
ε	efficiency of the regenerator (–)
η	thermal efficiency (–)
η_s	isentropic efficiency of the compressor and turbine (–)
η_p	polytropic efficiency of the compressor (–)
ξ	percentage of pressure drop (–)
Ψ	compressor and turbine size parameter (–)

Subscripts

c	cooling; critical point
h	heating
i	element index
LM	logarithmic mean
R	reduced
Reg	regenerator
0	ambient conditions
1	compressor or pump inlet

Up to date, conventional steam Rankine cycle has been the most extended technology in STPP. Conventional steam Rankine cycle is a wet cycle, in the sense of having the turbine exhaust steam with some moisture. Used configurations include reheat to avoid excessive moisture, and turbine extraction lines to preheat the steam generator feed water. Experimental and commercial data of these power plants are well known and available from many sources.

In the technical literature there are many works that study thermodynamic cycles fed by low-moderate temperature or low grade heat sources. ORCs (organic Rankine cycles) have been considered as a good technology for this kind of applications (for example, Refs. [1,2]). Unlike in steam Rankine cycles, in an ORC, the turbine exhaust vapour is dry, and a regenerative heat exchanger may be included to preheat the fluid without any extraction line from the turbine. These features allow simpler facilities than those using conventional steam Rankine cycles, and enable unattended operation. Tchanche et al. [3] and Velez et al. [4] performed detailed review works on ORCs.

There are works aimed to find the most appropriate fluids. Some of them analyse the effect of properties (density, specific and latent heat, critical point and thermal conductivity) [5]. Others make a fluid selection regarding the maximum working temperatures [6,7]. Also, there are works aimed at designing the fluid rather than selecting it [8], once the maximum and minimum temperatures have been defined. Among the possible applications, solar-driven ORCs have been studied, just for electricity production [9,10] and also for desalination applications [11].

For moderate or low temperature sources, Joule–Brayton cycles have been barely studied. Although they might introduce additional advantages for unattended operation, like simplicity and robustness (since they are one-phase cycles, without boiling or condensing, and they may operate at low pressure ratios, which simplifies the compressor and turbine designs) and thus they may lead to cheap designs, the disadvantages seem to have a higher impact in the selection process of the cycle [12]. Brayton cycles have been proposed for pure solar power plants (for example, Refs. [13,14]) but considering moderate-to-high turbine inlet temperatures and, thereby, ideal gas behaviour of the working fluid. On the contrary, Angelino and Invernizzi [15] and Rovira et al. [12] studied the advantages of working at operating conditions close to the critical point. Angelino and Invernizzi [16] also made a proposal of a real gas Brayton cycle to make use of the cooling capability of liquid natural gas. Recently, some mixtures of carbon dioxide and hydrocarbons have been proposed [17].

Some other authors focus on several transcritical Rankine cycles [18,19]. These cycles operate with the heating isobar at supercritical pressure, avoiding the boiling process and reaching good performance with simple devices. Supercritical Brayton cycles using CO_2 (S-CO_2) have been also studied [18,20] and proposed for solar applications [21].

This paper analyses the close-to-critical point region as a thermodynamic region where the properties of the fluid may provide some advantages in order to design a simple and unattended facility, regardless of the cycle: Rankine- or Brayton-like; and the most convenient fluids for both cases, regardless the kind of fluid (alkanes, HFCs, FCs, siloxanes, etc.). These advantages are related to the strong variations of the isobaric specific heat and the compressibility factor around the critical point. Originality of this work is rooted in how to manage the variation of properties of the working fluid in the cited domain and to perform a coherent and standardised comparison of the cycles.

First of all, a theoretical review is done in order to establish the efficiency limits of the conventional Brayton and Rankine cycles and the causes that originate these limitations. Then, the advantages of working close to the critical point are introduced and studied taking into account some technical constrains and the type of fluid. Finally, some transcritical and supercritical cycles are presented and optimised using a genetic algorithm, accordingly to the results obtained from the previous study. The cycles work with unconventional and promising fluids, R125 and SF_6, different from CO_2, which has been treated with an exclusive character so far.