Energy 112 (2016) 17–27

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Optimization of a recompression supercritical carbon dioxide cycle for an innovative central receiver solar power plant

M.A. Reyes-Belmonte, A. Sebastián, M. Romero*, J. González-Aguilar

IMDEA Energy Institute, Avda. Ramón de la Sagra, 3, 28935, Móstoles, Spain

ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form
11 May 2016
Accepted 3 June 2016

Keywords:
Supercritical carbon dioxide
Thermodynamics optimization
Concentrated Solar Power
Central receiver systems

ABSTRACT

Peculiar thermodynamic properties of carbon dioxide (CO_2) when it is held at or above its critical condition (stated as supercritical CO_2 or sCO_2) have attracted the attention of many researchers. Its excellent thermophysical properties at medium-to-moderate temperature range have made it to be considered as the alternative working fluid for next power plant generation. Among those applications, future nuclear reactors, solar concentrated thermal energy or waste energy recovery have been shown as the most promising ones. In this paper, a recompression sCO_2 cycle for a solar central particles receiver application has been optimized, observing net cycle efficiency close to 50%. However, small changes on cycle parameters such as working temperatures, recuperators efficiencies or mass flow distribution between low and high temperature recuperators were found to drastically modify system overall efficiency. In order to mitigate these uncertainties, an optimization analysis based on recuperators effectiveness definition was performed observing that cycle efficiency could lie among 40%–50% for medium-to-moderate temperature range of the studied application (630 °C–680 °C). Due to the lack of maturity of current sCO_2 technologies and no power production scale demonstrators, cycle boundary conditions based on the solar application and a detailed literature review were chosen.

1. Introduction

Over the last few decades, electricity power production systems have experienced a fast development with the introduction of new technologies allowing high conversion efficiencies. These technologies have been mainly focused towards power plant heat recuperation as for example the introduction of combined cycles, regenerative strategies or low temperature cycles based on organic substances [1]. Technologies allowing better energy conversion utilization such as multistage reheated expansion or multistage cooling compression are the common practice for modern power stations. Current developments on new high-performance materials able to withstand higher operative pressures and temperatures are also increasing power block efficiency. Nowadays power plant schemes using the aforementioned technologies are approaching to their technological limit and new cycle concepts and/or new operation fluids are needed seeking for higher conversion efficiency.

Power plant efficiency improvement is key for cost reduction achievement, meeting tight legislation standards and fighting against global warming and climate change. In that scenario, increasing the contribution of renewable energy sources to the energy production market is seen as one of the most promising ways to accomplish with emission standards. In that frame, concentrating solar power (CSP) is almost unique amongst renewable energy sources since large amounts of energy can be stored at high temperature at competitive cost [2]. These facts can mitigate operation disruption or the transient performance of the power plant but also allowing dispatch electricity production flexibility and a detailed design of power plant components working under steady state operation.

Another interesting feature of CSP is the possibility of increasing operating temperatures what is seen as key to achieving cost reduction. Higher temperatures allow the use of higher efficiency power conversion cycles, reducing the size of the solar collector field required to drive the power plant. But for this, new heat transfer media (nor steam neither current molten salts) are needed, which can both reach higher temperature and easily be stored. In this paper, a CSP plant using a dense gas-particle suspension (DPS) as the heat transfer fluid (HTF) in the receiver has been chosen [3]. This

---

* Corresponding author.
E-mail address: manuel.romero@imdea.org (M. Romero).

http://dx.doi.org/10.1016/j.energy.2016.06.013
0360-5442/© 2016 Published by Elsevier Ltd.

decision has been taken due to particles can be used at extremely high temperatures (above 1000 °C), limited only by the thermo-physical properties of the absorber tubes [4]. Furthermore, due to the high particle density, and the ease of separating the particles from the entraining gas flow, thermal energy storage can be easily implemented through simple bulk storage of hot particles. DPS CSP plant flexibility also facilitates the implementation of new thermodynamic cycles and/or novel heat transfer fluids in the power block, as for example Helium or supercritical carbon dioxide (sCO_2) [5]. In this paper, a power cycle using sCO_2 for CSP application has been considered due to its attractive thermodynamic properties allowing very high efficiency and high compactness for moderate turbine inlet temperature [6,7]. These properties, coupled to the free-water (and/or wet cooling) cycle configuration has attracted the attention of many researcher from solar field [7–10].

Among the interesting characteristics of sCO_2, it can be pointed out that it is not expensive and abundant, non-flammable nor toxic. It has a critical temperature near the ambient temperature, critical pressure leading to acceptable operative conditions, very high power density leading to a turbine size 10 times smaller than its equivalent steam and “tunable” properties than can be changed with slight modifications on pressure and/or temperature as shown on Fig. 1 [11]. Another interesting feature that favours sCO_2 as a working fluid is that its specific heat capacity is a factor of 4–5 times greater at ambient temperature than at high temperature. In addition, density changes of 8–10 times for cycle temperature, with steep changes near the critical point are observed in Fig. 1. Air series cannot be distinguished on the left picture due to scale effect (collapsed with the x-axis), meanwhile on the right picture air series are appearing flat due to the not significant change on specific heat with temperature. This high sCO_2 density allows getting more compact turbomachinery designs compared with the equivalent steam or air conventional power cycles.

Interesting properties of sCO_2 are observed on specific enthalpy as well. As it can be observed from Fig. 2, enthalpy ratio for sCO_2 (defined as the rate between turbine enthalpy drop and compressor enthalpy rise) is around 3.5 to 4 times bigger than compressor enthalpy change at low temperatures and it can reach a ratio of 7 for higher temperatures. Therefore, turbine can produce 7 times more energy than the consumed by the compressor [10]. However, enthalpy ratios below 2.5 are the common practice for air Brayton cycles. In other words, compressor from air Brayton cycles consumes one third of the energy produced by its turbine what leads to a poor cycle efficiency. However for a supercritical carbon dioxide cycle, compressor will be using less than one-seventh the energy produced by the turbine, what will lead to higher cycle efficiency. All these non-ideal variation on CO_2 properties close above the critical point are leading to high cycle efficiencies.

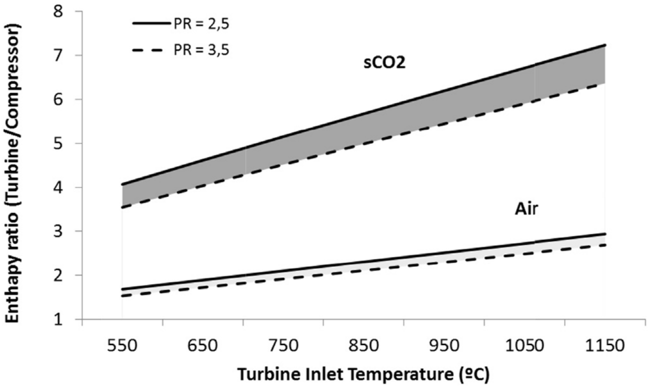

Fig. 2. Enthalpy ratio between turbine and compressor for sCO_2 (solid lines and dark grey shaded area) and air (slashed line and light grey shaded area). For two pressure ratio cases (PR).

Despite the fact that several research works have been already focused into the use of closed loop Brayton cycles working with sCO_2 [5,12,13] and its optimization have been already addressed [14], this paper is proposing an optimization methodology for the split fraction and recuperators efficiency of sCO_2 power block coupled to a solar central receiver application. In addition, difficulties on sCO_2 Brayton cycle components design, originated from very strong non-ideal fluid characteristics, will be addressed along this paper paying special attention to recuperators design. This work has been structured into the following sections;

- First, CSP plant layout will be described (location, design criteria, etc.). Design point will more or less fix some of the working operative conditions of the power cycle. For example, turbine inlet temperature will be determined by the temperature achieved at the receiver since no back-up burner has been considered. While power cycle inlet temperature will be dominated by solar plant heat rejection system; mainly dependant on plant location.
- After solar plant description, sCO_2 power cycle layout will be presented. Recompression cycle was chosen amongst several existing schemes [15].
- Selection of boundary conditions that were not established by the plant layout and design point will be reviewed on the fourth section. Working operative pressures and components efficiency (turbomachinery and recuperators) will be chosen according to current state of the art.
- Recompression fraction (the amount of sCO_2 that is diverted through each recuperator) will be optimized in the next section

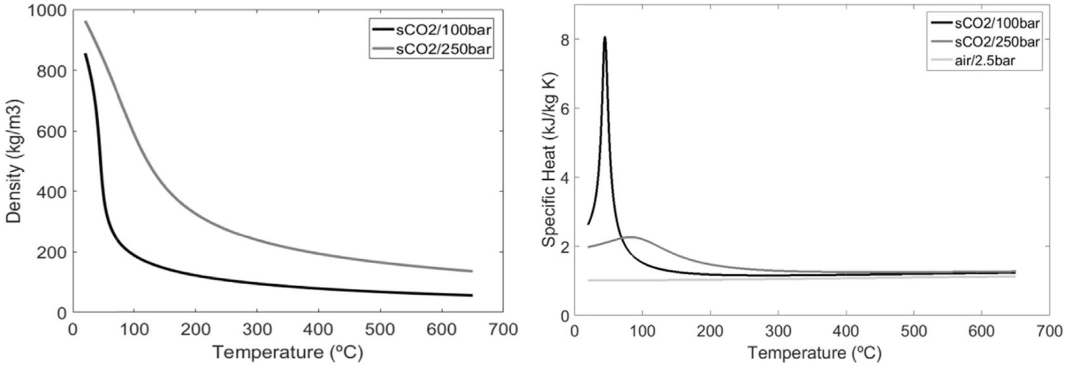

Fig. 1. Density and specific heat dependency of sCO_2 with temperature.