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A solar energy storage and power generation system based on supercritical carbon dioxide

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ABSTRACT

This paper proposes a new type of solar energy based power generation system using supercritical carbon dioxide and heat storage. The power generation cycle uses supercritical carbon dioxide as the working fluid and integrates the supercritical carbon dioxide cycle with an efficient high-temperature heat storage. The analysis shows that the new power generation system has significantly higher solar energy conversion efficiency in comparison to the conventional water-based (steam) system. At the same time, the heat storage not only overcomes the intermittent nature of solar energy but also improves the overall system efficiency. The study further reveals that the high temperatures and high pressures are favorable for solar energy storage and power generation. Moreover the expander and the heat storage/regenerator are found to be the key components that determine the overall system performance.

1. Introduction

The application of solar energy to generate electricity and heat has become increasingly important, and have received considerable attention [1–5] during the past few decades. Solar collector is the heart of solar thermal power technology–the most proven and lowest cost large-scale solar power technology available today [1]. Large number of researchers have been working on developing new and more efficient solar collectors [5–10] and currently the parabolic trough collectors are able to produce steam up to a temperature of ~850 K [9]. However, almost all the studies are based on water (steam) as the working fluid and aim to improve collector performances by changing solar collector structures, improving the absorptivity of the coating or reducing heat loss of the collector [5–10]. Little work is devoted to study the influence of the type of working fluid on the collector performances. This leads to an upper limit of solar heat to power ratio of about 40% [9] using steam, which urgently needs to be improved.

More recently, some work has been conducted on alternative working fluids for improving the solar thermal power cycles such as ammonia, ammonia/water mixture, air and silicon oil etc [10–13]. However, it was found that air thermodynamic cycle efficiency is low; ammonia is toxic and silicon oil is very viscous and difficult to handle [10–13]. Carbon dioxide (R-744) is a non-flammable and non-toxic fluid and friendly to environment. Its critical pressure and temperature are 73.8 bar and 31.1 °C, respectively, which are much lower and easier to put into a critical state than those of other alternative working fluids. This gives carbon dioxide a great potential for a higher heat to power ratio working fluid [11,14,15]. On top of this the thermodynamic and transport properties of CO_2 at supercritical conditions also seem very favorable in terms of heat transfer and pressure drop compared to other typical fluids [11]. Nevertheless only a small number of studies were dedicated to investigate the aspects of thermodynamic and transport properties [11], system design [11–13] using subcritical, transcritical and supercritical cycles, and measurements on components [13,16] in CO_2 based thermal power cycles. Hence there is a lack of a comprehensive thermodynamic analysis on the system, which otherwise could have been a good guidance for experimental investigations and system optimisation.

On the other hand, a major barrier for the extensive application of solar energy is its intermittency and non-controllability [16,17]. Integration of an energy storage technique could obviously provide an important (and even crucial) approach to deal with the intermittency of solar energy and the associated unpredictability of its output, letting the surplus to be stored during the periods when intermittent generation exceeds the demand and later be used to cover periods when the load is greater than the generation [17,18]. Solar thermal plants can store excess high temperature heat in molten-salt or thermal oil storage tanks, and packed beds which are generally used to store solar heat for domestic water and space heating have been investigated and appear to be more efficient and economical for heat storage in solar thermal power plant.

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This paper studies a novel solar energy storage and power generation system based on supercritical carbon dioxide. The system uses carbon dioxide rather than water (steam) as the working medium, and therefore possesses the following advantages: pushes the upper limit of the steam's heat to power conversion efficiency; the whole cycle runs in the supercritical condition rather than transcritical condition that further improves the thermal power performance; integrates a thermal storage system which can store and recycle the intermittent and non-controllable solar heat hence enhancing the stability of the system. The paper first conducts a detailed thermodynamic analysis in view of investigating the feasibility and typical performance of the system, and then does a parametric analysis to provide guidance to experimental studies and system optimisation.

2. System description

Fig. 1 shows the proposed solar energy storage and power generation system based on supercritical carbon dioxide. It consists of eight main components, a solar energy collector, a high temperature heat storage/exchange tank (HX2), a low temperature heat storage/regenerator (HX1), a heat exchanger (HX3), an expander, two pumps and relative valves and a control system. Parabolic trough, solar tower and solar disc collectors can be used in the experimental system to achieve the solar heat depending on the working temperature. Parabolic trough system is usually applied for medium temperature applications (<700 K), while the solar tower can achieve temperature as high as 1000 K [1,2,9], and therefore produces higher heat to power efficiency. Heat delivered by the solar collector system is strongly influenced by the season, weather and time of day, and heat storage unit can be used to smooth the solar heat fluctuation. The heat storage/exchange tank (HX2) and the heat storage/regenerator (HX1) used here are packed bed thermal storage tanks containing spherical granite. Other types of thermal storage systems such as molten salt, mineral oil and metal can also be used [19,20]. The heat exchanger (HX3) is a condenser where CO_2 is condensed back to liquid, either by water or by air, it can be shell and tube type or other suitable types. The working pressure of the heat exchanger (HX3) is 8 MPa, and the heat load is about 180 kW when the cooling air (or water) flow rate is 1 kg/s. These components are interconnected in a loop and the whole system is closed. As only a theoretical analysis is carried out in this paper, the structures of the components are not discussed in details.

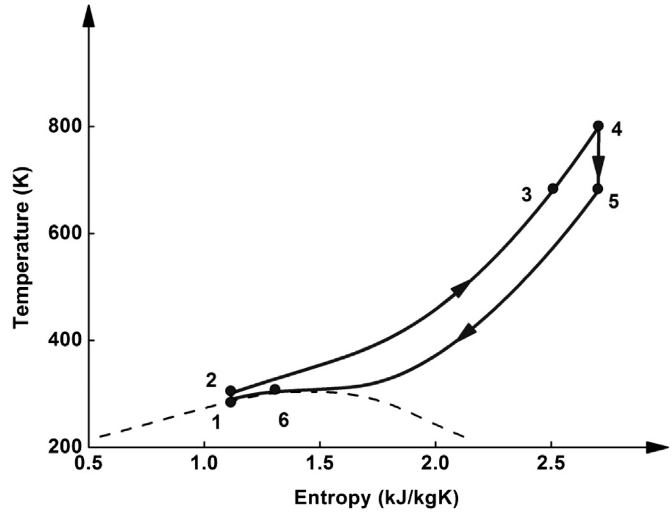

Fig. 2. Temperature–Entropy diagram of the ideal working process.

The principle of operation of the system is described as follows:

(1) Solar energy at a high temperature is collected and stored in HX2.
(2) The working fluid (CO_2) at room temperature and supercritical pressure (e.g. 80 bar) is pumped to a certain high pressure.
(3) The working fluid is heated by the regenerator HX1 and then further heated by the solar heat stored in HX2 to a certain high temperature.

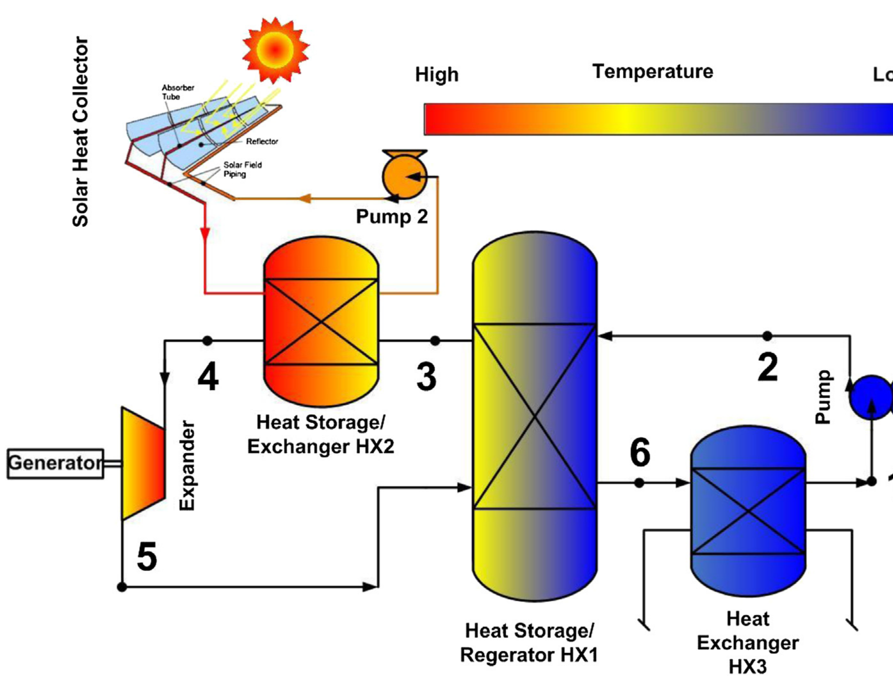

Fig. 1. Schematic diagram of the solar energy storage and power generation system based on CO_2.