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Synthesis of efficient solar thermal power cycles for baseload power supply

Emre Gençer, Rakesh Agrawal *

School of Chemical Engineering, Purdue University, West Lafayette, IN 47907, USA

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ABSTRACT

Limited fossil fuel reserves and increasing greenhouse gas emissions from fossil fuels make it essential to develop alternative renewable energy conversion processes to meet energy needs. Advancements in renewable power production are especially important since electric power is the largest consumer of primary energy resources with the highest growth rate among alternate energy use sectors, and is currently responsible for greater than 40% of the global CO_2 emissions. Among the renewable energy sources, solar energy is prominent due to its abundance. Here, we introduce an efficient solar thermal power cycle, solar water power (SWP) cycle, with water as the working fluid, which undergoes reheats between expansions. SWP cycle is developed to maximize exergy efficiency, allow flexible operation and process intensification. Simulation and optimization of the SWP cycles are performed in an integrated Aspen Plus/MATLAB modeling environment. Modeling results predict that SWP cycle with 1 solar reheating stage has a potential to generate electricity with sun-to-electricity efficiencies greater than 30% at solar heat collection temperature as low as 750 K. The cycle also promises sun-to-electricity efficiencies in the unprecedented range of 40–46% for the corresponding temperatures above 1400 K. Further efficiency increase is estimated by the addition of more reheating stages.

1. Introduction

Decaying fossil fuel reserves [1] and increasing greenhouse gas (GHG) emissions from fossil fuels [2] increase ever-growing interest in developing alternative energy conversion techniques using renewable energy sources to meet energy needs such as solar thermal power generation [3], synergistic biofuel production [4,5], large scale energy storage for uninterrupted renewable power supply [6,7], solar thermal hydrogen production [8]. Renewable electric power production is especially important since electric power is the largest consumer of primary energy resources, has the highest growth rate among alternate energy use sectors, and is currently responsible for >40% of the global CO_2 emissions [9]. Among the renewable energy sources, solar energy is prominent due to its abundance [10]. We envision that producing building blocks foundational to meet all basic human needs of daily existence can create a sustainable economy. Our vision targets the maximization of inherent complementary aspects of energy conversion by creating, synthesizing, and integrating sustainable process solutions to design Solar Electricity Water Food and Chemicals (SEWFAC) processes. The recently proposed Hydricity concept where solar energy is used to efficiently coproduce electricity and hydrogen is an example SEWFAC process to enable a solar centric sustainable future [11]. Here, we present a detailed analysis of an efficient solar thermal power generation process, solar water power (SWP) cycle, which is developed to maximize exergy efficiency, allow flexible operation and optimum process intensification.

Solar power generation methods are generally classified as thermal and photolytic processes. Photovoltaic (PV) cells generate electricity directly from solar light [3,12]. They are capable of absorbing only a portion of the solar spectrum and thus generating electricity from a fraction of the incoming solar rays by a finite number of band gaps [13]. Yet, PV systems are suitable for both diffuse and direct sunlight applications, which allows them to be installed at a variety of scale and in diverse geographical locations [14]. PV cells are the most widely implemented solar power generation technique. The total global installed capacity at the end of 2014 was 177 GW, 40 GW of which was installed in 2014 [15]. To date, for lab-scale solar cells, the maximum reported STE efficiencies for silicon-crystalline is 27.6%, single-junction gallium arsenide is 29.1%, and concentrator four-junction is 44.7% [16].

Solar thermal power cycles utilize the heat collected from solar energy and thus are able to use a greater fraction of the solar spectrum. This main difference presents an advantage for solar thermal power generation processes to achieve high conversion efficiencies.

* Corresponding author.
E-mail address: agrawalr@purdue.edu (R. Agrawal).

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From solar ponds to current solar thermal reactors, use of solar thermal energy has always been a part of humanity's life. However, to truly benefit from solar thermal energy, heat must be collected and utilized at high temperatures, which requires the use of solar concentrators to focus the solar rays and increase the solar heat collection temperature. Concentrated solar power technologies are extensively studied in the literature for various concentrators, *i.e.* parabolic dish [17], linear Fresnel reflectors [18,19], central tower [20,21] and parabolic trough [22,23], for various power generation cycles, *i.e.* pressurized air cycles [24], molten salt cycles [25] and direct steam cycles [26,27], and for various operating regimes [28]. The total global installed capacity of CSP at the end of 2014 was 4.3 GW, 0.93 GW of which was installed in 2014 [15]. High solar energy collection and conversion efficiencies are essential to drive down the cost of solar power and to minimize the land area requirements [4,10,29]. Here, we present detailed analysis of recently proposed efficient solar thermal power generation process, solar water power (SWP) cycles. The novelties of SWP cycles, comparison of SWP cycles compared to current power cycle schemes, the effect of solar heat collection temperature, effect of reheating stages along with the modeling approach using an integrated MATLAB and Aspen Plus environment are discussed in subsequent sections.

2. Process performance metrics

Solar power production processes are evaluated based on two metrics: the process *heat-to-electricity* (QTE) *efficiency* and *sun-to-electricity* (STE) *efficiency*. While the former metric measures the thermal energy conversion performance of power cycles, the latter evaluates the performance of power cycles from solar energy conversion standpoint.

2.1. Heat-to-electricity (QTE) efficiency

QTE efficiency refers to the fraction of heat (thermal energy) recovered as the electricity output. In Eq. (1), W_{net} is the net electricity output, Q_{in} is the heat input to the process.

$$\text{QTE efficiency} = \frac{W_{net}}{Q_{in}} \times 100 \tag{1}$$

2.2. Sun-to-electricity (STE) efficiency and its theoretical limit

STE efficiency refers to the fraction of incident solar energy recovered as the electricity output. In Eq. (2), W_{net} is the net electricity output, Q_{in} is the heat requirement of the process, Ω_{opt} is the optical efficiency that accounts for optical losses associated with solar concentration system and is defined as the fraction of total incident solar radiation received by the blackbody absorber, σ is the Stefan-Boltzmann constant, T is the solar heat collection temperature, I is the solar intensity and C is the solar concentration ratio. The expression in the denominator of Eq. (2) refers to the solar heat required for the process. We assume an instantaneous solar intensity of 1000 W/m^2 (AM1.5 solar intensity). Note that Eq. (2) doesn't account for the intermittency and variability associated with solar energy. As a reference, the theoretical STE efficiency for a given solar concentration and solar intensity is given by Eq. (3) where T_a is the ambient temperature [30].

$$\text{STE efficiency} = \frac{W_{net}}{Q_{in}/\Omega_{opt}\left(1 - \frac{\sigma T^4}{I \cdot C}\right)} \times 100 \tag{2}$$

$$\text{Theoretical STE efficiency} = \left(1 - \frac{\sigma T^4}{I \cdot C}\right)\left(1 - \frac{T_a}{T}\right) \times 100 \tag{3}$$

3. Solar thermal power generation

Solar thermal systems use concentrators to absorb photons of all wavelengths in the incident spectrum as heat at temperatures that are higher than ambient [31,32]. Due to the use of optical concentrators, solar thermal power systems can only be operated under direct sunlight, which imposes geographical limitations [29]. Further, these systems are anticipated to be cost-effective only as large-scale baseload power plants (100's of MW), owing to the capital costs involved in installing solar concentrators [29,33]. Yet, the highest STE efficiency reported for a solar thermal power plant with molten salt heat transfer fluid is ~22% [3] and using the pilot Stirling engine system is ~31.2% [34].

To benchmark the estimated performance of the proposed power cycles, we simulated a direct solar thermal power (DSTP) cycle as the base case with the maximum and minimum operating pressures of 200 bar and 0.04 bar, respectively. The DSTP cycle, shown in Fig. 1, consists of solar concentrators, solar receiver, high pressure turbine (HPT), medium pressure turbine (MPT), condensing turbine (CT) and a generator. DSTP cycle is a Rankine type [35] power cycle for which solar energy is the heat source and water is the working fluid. The pumped water is both vaporized and superheated to the solar heat collection temperature, T_{shc}, by direct heat from the solar receivers. Superheated steam is consecutively expanded in HPT, MPT and CT to sub-ambient pressures. For a solar concentration of 8000 and T_{shc} in the range of 650–2300 K, the calculated STE efficiencies are in the range of 20.1–38.5% with the maximum value at 1800 K.

4. Solar water power (SWP) cycle

We have conceptualized a solar thermal power production cycle, Solar Water Power (SWP) cycle shown in Fig. 2. The SWP cycle is a Rankine type power cycle with high pressure water as the heat transfer and working fluid. The cycle is developed based on two fundamental considerations; (i) to maximize utilization of high temperature thermal energy for power generation and (ii) to reject heat at the minimal attainable exergetic state. Water is an ideal working fluid because it allows heat rejection close to ambient temperature and it is in liquid state at ambient temperature, the energetic cost of pressurizing is significantly decreased.

Pressurized water (200 bar for the base case) is preheated against a process stream and superheated by solar thermal energy. The superheated steam is then expanded in single or multiple expansion stages with solar reheating in between expansions. The number of reheating stages, *n*, is indicated in the name of the cycle SWP-n. The discharge of the last medium pressure turbine is cooled down against the pressurized water before being sent to the condensing turbine. The partially condensed low-pressure two phase water stream is fully condensed in a condenser and pumped to the operating pressure of the cycle. The SWP-1 cycle with one reheat between high pressure expansion turbines shown as dotted lines is presented in Fig. 2. In the base SWP cycle, the exhaust of the high pressure turbine (HPT) is directly fed via line A to the medium pressure (MPT) turbine.

The proposed SWP cycle consists of a central tower and direct steam cycle type CSP plant. An attractive feature of the SWP cycle is the introduction of intermediate heat exchange between the discharge of final medium pressure turbine stage and the pressurized cold water stream. The proposed new heat exchange scheme allows to preserve high temperature heat in the system and to reject heat from the system only at ambient temperature after expansion in the condensing turbine with a minimum exergy loss. This allows the cycle to operate efficiently at various solar heat collection temperatures. Moreover, the introduced intermediate heat