Applied Energy 217 (2018) 480–495

Contents lists available at ScienceDirect

Applied Energy

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

Thermodynamic analysis of a novel dual expansion coal-fueled direct-fired supercritical carbon dioxide power cycle

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HIGHLIGHTS

- A novel cycle layout is proposed for a direct-fired supercritical CO_2 power cycle.
- Tight heat integration is designed among different subsystems.
- Detailed heat exchange process analysis with $T-Q$ diagram.
- Net efficiency reaches 43.7% with ~100% carbon capture when using coal as fuel.

ARTICLE INFO

Keywords:
Supercritical carbon dioxide power cycle
Coal gasification
Heat integration
Zero emission

ABSTRACT

The direct-fired supercritical CO_2 power cycle not only has the potential of reaching high efficiency but also has inherent ability to capture almost all of the combustion derived CO_2. A novel direct-fired supercritical CO_2 power cycle layout is proposed in this paper, using the syngas produced by coal gasification as the fuel. The proposed cycle layout is specially designed to facilitate heat integration between the power cycle, the fuel conversion process and other auxiliary subsystems. Heat from the air compressor intercooler and the low temperature syngas is introduced to the regenerator to correct its imbalanced heat exchange, a typical problem of the supercritical CO_2 power cycle that is caused by the abrupt physical property variation. Design considerations of the proposed cycle layout are discussed in detail. The result shows that the net efficiency is 42.1%, with near-zero CO_2 emissions. The proposed cycle layout is then further modified by integrating more heat from the oxygen compressors and the syngas compressor, which reduces the hot end temperature difference of the regenerator to less than 10 °C and increases the net efficiency to 43.7%. Heat integration through novel cycle layout has been proved essential to guarantee the high efficiency of the supercritical CO_2 power cycle.

1. Introduction

Coal is still the most important and stable primary energy source for countries like China. In 2014, 72.6% of the electricity in China is generated from coal, reported by the International Energy Agency [1]. Burning coal has provided the necessary power for the rapid development of human society, but also resulted in serious environmental problems, such as air pollution and massive anthropogenic CO_2 emissions [2]. Among the three main fossil fuels (coal, oil and natural gas), coal is the most important contributor to the CO_2 emissions, which accounts for 45.9% of the total emissions in the world in 2014 [1]. In front of more and more stringent regulations on CO_2 emissions to alleviate the global climate change, efficient utilization of the coal and reduction of relevant CO_2 emissions are the pre-requisite of relying on coal as the main energy source in the future. Therefore, capturing the CO_2 from the coal-fueled power plants has become a hot research area in the literature [3–5]. Among various technologies that are under development to tackle this problem, the supercritical carbon dioxide (sCO_2) power cycle technology emerging in recent years is a very promising candidate, which has drawn extensive research in a variety of energy applications [6–10].

The most attractive advantage of the sCO_2 power cycle is its high efficiency at similar turbine inlet temperatures against other cycles [11]. The high efficiency of the sCO_2 power cycle originates in its

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https://doi.org/10.1016/j.apenergy.2018.02.088
Received 30 November 2017; Received in revised form 29 January 2018; Accepted 12 February 2018

combined advantages of the ideal Brayton cycle, which features single phase fluid, and the Rankine cycle, which features small back work ratio (ratio of work consumed by compression against work produced by expansion), by utilizing CO_2 in full or part of the supercritical region [12]. The single phase feature of the CO_2 working fluid reduces the exergy destruction occurring in the heat exchange process to the minimum due to the absence of isothermal phase change, which leads to considerable irreversibility and inefficiency that is quite common for steam based cycles [13]. The small back work ratio of the sCO_2 power cycle stems from operating the compression in a dense phase (such as liquid) or near the critical point where abrupt physical property variation happens [14]. The relatively high critical temperature (30.98 °C) of CO_2 compared with other gases such as N_2 and He, is the key reason that dense phase compression could be utilized to reduce the compression work at ambient conditions.

According to how the heat is added, the sCO_2 power cycle can be divided into two distinguishing groups: the indirect-heated and direct-heated or direct-fired. The direct-fired sCO_2 power cycle is more appropriate for fossil energy applications where carbon capture is desired. By combustion of the fuel with stoichiometric oxygen and moderating the combustor temperature with the recycled CO_2, the working fluid of the power cycle is a mixture highly enriched in CO_2 [15]. The combustion derived CO_2 can be captured in an elegant manner by bleeding the working fluid at proper location of the power cycle. Due to this fact, the direct-fired sCO_2 power cycle has inherent ability of carbon capture. This is why the sCO_2 power cycle is called “turbines can use CO_2 to cut CO_2” [16]. In addition to these advantages, the direct-fired sCO_2 power cycle offers the following benefits as well: (a) more concise and compact system of the power plant as a result of the heat transfer augmentation and low specific volume of the supercritical fluid and (b) water saving or even a net water producer [17].

Coal needs to be gasified into syngas before it can be used in the direct-fired sCO_2 power cycle. To make the most of the advantages of the sCO_2 power cycle, the cycle layout should be carefully adapted to integrate with the coal gasification process efficiently. Research work in this area has begun in recent years. The Allam cycle, named after its main developer Rodney Allam, is introduced in two papers [18,19] concerning cycle configuration, key design considerations, heat integration options, components design and cycle commercialization. The net efficiency of the coal version Allam cycle is reported as 51.44% (LHV), with a near 100% carbon capture rate [18]. Then the coal version Allam cycle is further discussed in more details in a subsequent paper [20] by Lu et al. with regard to the unique considerations, possible hurdles and advantages of integrating coal gasifier with the Allam cycle. Different technical options of the coal gasification process, such as coal type, gasifier type and heat recovery scheme, are investigated in six cases of the coal version Allam cycle. The reported net efficiencies of the six cases range from 43.3% to 49.7% (HHV, or about 45% to 51–52% on LHV basis [21]). Other relevant research works of the coal version sCO_2 power cycle are from Hume [22] and Weiland [23]. The effect of the coal gasifier transfer fluid and oxygen purity on the efficiency of the sCO_2 power cycle is studied by Hume. Hume concludes that CO_2 is preferred as the transfer fluid and oxygen of 99.5% purity should be used to minimize argon and nitrogen contaminants to improve the sCO_2 purity and, hence the cycle efficiency. The net efficiency calculated by Hume is 39.6% (HHV, or 42.9% on LHV basis) with a carbon capture rate of 99.2%. A parametric study of the direct coal-fired sCO_2 power cycle is conducted in Weiland's work in which key cycle variables, such as turbine outlet pressure, turbine inlet temperature, CO_2 compressor pressure and CO_2 cooler pressure, are studied to assess their effect on the efficiency. The net efficiency of the sCO_2 power plant reported by Weiland is 37.7% (HHV, or 39.1% on LHV basis) with a carbon capture rate of 98.1%, which is 6.5 percentage point higher than that of a reference IGCC plant with 90.1% carbon capture rate [23]. A similar parametric study is conducted by Zhao et al. [24] as well, through a refined model with the inclusion of turbine cooling. The cycle layout in [23] is modified in a recently published work by Weiland [25] through improving the heat integration between the regeneration process and the coal gasification. As a result of the improved heat integration, the net efficiency increases to 40.6% (HHV, or 42.1% on LHV basis). Zhao et al. [26] conducted a systematic heat integration and optimization on the direct-fired sCO_2 power cycle, using the black-box heat exchange model to eliminate the influence of concrete heat exchange structure on the cycle efficiency. The net efficiencies predicted by Zhao et al. range from 39.54% to 41.72% (LHV).

In spite of the aforementioned advantages in terms of efficiency and inherent capability of carbon capture that the sCO_2 power cycle possesses, it also has properties that present challenges to the cycle configuration in order to achieve high efficiency. CO_2 in its supercritical state exhibits strong real gas behavior, especially in the vicinity of the critical point [27]. The real gas effect manifests itself through the dependence of the specific heat c_p on not only the temperature but also the pressure. The abrupt increasing c_p of the supercritical pressure CO_2 in the low temperature region, such as below 250 °C, makes the heat that is available from the turbine exhaust insufficient to heat the cold recycled CO_2 to a reasonable high temperature. The consequence of the imbalanced c_p is the large temperature difference at the hot end of the regenerator, which penalizes the efficiency of the power cycle. Various methods have been devised to address this problem. One of the methods is to use the recompression cycle layout, or hot gas compression [28]. By compressing a portion of the CO_2 exiting the hot side of the regenerator without further cooling (this is why it is called hot gas compression), the recompressor works like a heat pump that adds additional heat to the cold side of the regenerator at the cost of consuming more electric energy. The remaining CO_2 that is recycled back then can be ideally heated by the turbine exhaust, without incurring large temperature difference in the regenerator. This method is more suitable for circumstances where there is only a single heat source and external heat is not available. Another method is to supply external heat at proper temperature levels to the cold, high pressure side of the regenerator. This method provides plenty of process integration opportunities, which is especially useful for complex systems. Examples of this method can be found in Kim's work [29] in which both low and high temperature heat sources are utilized to optimize the regeneration process of the sCO_2 power cycle. Given that there is considerable amount of heat at different temperature levels in the coal gasification process, it is more favorable to integrate these heat through a novel cycle layout to improve the regeneration process. Heat integration between the coal gasification process and the sCO_2 power cycle is essential for achieving the full benefits of the sCO_2 power cycle. On the one hand, the heat contained by the syngas between the gasifier and the combustor of the power cycle should be integrated with the downstream power cycle to enhance the overall efficiency, just as the case of IGCC power plant [30]. On the other hand, the sCO_2 power cycle needs external heat at low to medium temperature level to correct the heat balance in the regenerator, which can be conveniently drawn from the syngas cooling process. Although the reported efficiency of the coal version Allam cycle is very impressive, detailed cycle layout, boundary conditions and component models (for instance, the turbine cooling model) that achieve the claimed high efficiency have not been disclosed to the public yet, due to the proprietary nature of the Allam cycle technology. And as a preliminary investigation of the sCO_2 power cycle technology using coal as fuel, the research works by Hume [22] and Weiland [23] only consider minimal integration of the sCO_2 power cycle and the coal gasification process. Despite that the cycle layout has been improved by considering more heat integration options in Weiland's latest work [25], the heat integration is derived based on a pinch analysis in which how the cold and hot streams are matched with each other, in other words, how the heat is integrated explicitly between the auxiliary system and the sCO_2 power cycle, is not given. Simultaneous heat integration and optimization is considered in Zhao's work [26], but specific cycle layout is not proposed and the designed heat exchange