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Parametric study of a direct-fired supercritical carbon dioxide power cycle coupled to coal gasification process

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ABSTRACT

The direct-fired supercritical carbon dioxide power cycle not only has the potential of reaching high efficiency, but also achieves near 100% carbon capture in a more inherent and natural manner. A conceptual flow sheet of the direct-fired supercritical carbon dioxide power cycle that is coupled to the coal gasification process is built in this study. A detailed turbine cooling model is added to better assess the performance of the power plant. To investigate the effect of key cycle variables on the cycle performance and determine potential chances for efficiency improvement, a parametric study is conducted in this paper. The result shows that the turbine inlet temperature and turbine outlet pressure have significant effect on the cycle efficiency while the effect of the turbine inlet pressure is minor. The cycle efficiency is susceptible to the inlet condition of the carbon dioxide pump, which is the weakness of the supercritical carbon dioxide power cycle. The flow sheet and some of the cycle parameters are modified based on the conclusions drawn from the parametric study. The net efficiency of the power plant is calculated to be 38.87% (on lower heating value basis) at a turbine inlet temperature of 1200 °C, while capturing most of the carbon dioxide derived from combustion.

1. Introduction

Coal is one of the most important primary energy sources in the world. According to statistics by the International Energy Agency (IEA), 28.6% of the world's total primary energy is supplied by coal and 40.8% of the world's electricity is generated from coal in 2014 [1]. In China, coal plays a more vital role as 72.6% of the electricity is produced from coal in 2014. However, burning coal has caused serious environmental problems, such as the notorious fog and haze in north China in recent years [2]. Another problem is the global warming caused by the excessive CO_2 emissions from burning fossil fuels, especially from coal. CO_2 emission from the coal is the highest among the three main fossil fuels (coal, oil and natural gas), accounting for 45.9% of the total CO_2 emissions in the world in 2014 by statistics of IEA. Carbon capture and storage (CCS) is a possible solution to this problem, but significant efficiency penalty and increased price of the electricity have precluded its application in the near future [3]. An efficiency penalty of at least 10 percentage points is generally acknowledged when CCS is applied, no matter what kind of CCS technologies are considered: pre-combustion, oxy-combustion or post-combustion [4]. Therefore, novel methods that generate electricity from coal and reduce CO_2 emissions while keeping high efficiency is needed.

The direct-fired supercritical carbon dioxide (sCO_2) power cycle is one such promising candidate. By combustion of the fuel gas with stoichiometric oxygen and recycling CO_2 as the combustor temperature moderator, the working fluid of the power cycle is highly enriched in CO_2, with its molar concentration well above 90% [5]. The sCO_2 based power cycles are well known for their high efficiency potentials [6]. The high efficiency comes from the superior physical property of CO_2—the moderate critical point at 30.98 °C and 73.8 bar [7]. The much lower critical point of CO_2, compared with that of water, facilitates the utilization of the unique thermodynamic advantages brought by the supercritical fluid. On the one hand, as a consequence of the low critical temperature, the compression of the sCO_2 power cycle could occur near the critical point, an area where the physical property experiences abrupt variation, especially the density [8]. The working fluid in this area behaves more like liquid rather than gas. The compression work can thus be much reduced and the efficiency enhanced. On the other hand, owing to the low critical temperature again, the isothermal evaporation or condensation process of the working fluid is avoided in the cycle. Exergy destruction during the heat exchange process can be reduced to the minimum, which is beneficial for efficiency

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Nomenclature

Acronyms

AGR	acid gas removal
ASU	air separation unit
CCS	carbon capture and storage
CPU	CO_2 processing unit
HHV	higher heating value
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
LHV	lower heating value
NETL	National Energy Technology Laboratory

Latin symbols

C	turbine coolant
H	enthalpy, enthalpy difference
I	inlet
K_1	parameter to determine the turbine coolant mass flow rate
K_2	parameter to determine the pressure drop in the turbine cooling model
K_3	parameter to determine the pressure drop in the turbine cooling model
m_C	mass flow rate of the turbine coolant
N	expansion steps of the turbine cooling model
p	pressure
P_{high}	turbine inlet pressure
T	temperature
T_W	the allowable turbine blade temperature
V	volume flow rate of the turbine working fluid
W	the power generated by the turbine expansion step

Subscripts

EXP	turbine expansion step or turbine expander
H	inlet of the valve in the turbine cooling model
i	serial number of the turbine expansion step
O	outlet

enhancement. Because of the high efficiency potential of the sCO_2 power cycle, it is widely researched in various applications. Tian et al. conducted a multi-objective optimization, both thermodynamically and economically, of several sCO_2 power cycle configurations aimed at engine waste heat recovery [9]. Ortiz et al. explored possible integration schemes of the sCO_2 power cycle in a concentrated solar power plant and validated its efficiency superiority over the steam Rankine cycle [10]. Mehrpooya et al. performed exergoeconomic and sensitivity analyses on a tightly integrated system composed of air separation unit, oxy-combustion direct CO_2 power cycle and liquefied natural gas regasification process to facilitate the carbon capture [11]. The high efficiency advantage of the sCO_2 power cycle has been well proved by these studies.

When the direct-fired sCO_2 power cycle is applied in the fossil energy applications, not only the advantages stated above can be inherited, but the carbon capture process will also be significantly simplified since high pressure and high purity CO_2 can be directly separated from the power cycle, eliminating the associated auxiliary equipment and energy consumption. In this sense, the direct-fired sCO_2 power cycle provides a solution of inherent and more elegant carbon capture. Coal needs to be gasified into clean and ash-free syngas prior to feeding into the direct-fired sCO_2 power cycle. Research work concerning the coal-fueled direct-fired sCO_2 power cycle is still limited in the literature but has begun in recent years along with the booming development of the closed indirect-fired/heated sCO_2 power cycle. The Allam cycle proposed in 2013 is a direct-fired sCO_2 recuperative Brayton power cycle [12]. The impressive reported net efficiency of the coal version Allam cycle is 51.44% (LHV) with near 100% carbon capture at a turbine inlet temperature of 1150 °C. Key cycle design and integration considerations, optimization and reheat options of the Allam cycle were discussed in a successive paper [13]. Lu et al. made further introduction of the coal version Allam cycle, concerning the unique considerations, possible hurdles, and advantages of integrating a commercially available gasifier with the Allam cycle [14]. Performance of the coal version Allam cycle with different combinations of various gasifier types, coal types and heat recovery schemes were reported, ranging from 43.3% to 49.7% (HHV, or about 45% to about 51–52% on the LHV basis [15]). However, as part of the proprietary intellectual property, detailed flow sheet, component assumptions and boundary conditions achieving the above efficiencies have not been disclosed in the literature yet. Hume studied the effect of gasifier transport gas and oxygen purity on the performance of an sCO_2 coal gasification power plant [16]. The predicted net efficiency is 39.6% (HHV, which is 42.9% on the LHV basis) with a carbon capture rate of 99.2%. Weiland proposed a conceptual flow sheet of the direct-fired sCO_2 cycle based on coal gasification. A net efficiency of 37.7% (HHV, which is 39.1% on the LHV basis) was reported by Weiland's research [17]. The effect of key cycle parameters on the cycle performance was investigated by sensitivity analysis in Weiland's study. However, Weiland's study assumed a CO_2 turbine model without blade cooling, which may overestimate the cycle performance. In a recently published study by Weiland [18], the turbine cooling model is added and by improved process heat integration, the net efficiency has increased to 40.6% (HHV, which is 42.1% on the LHV basis).

Review of the previous research works shows that the development of the coal-fueled direct-fired sCO_2 power cycle is still in its early stage and its potential has not been well explored and proved. The effect of key cycle parameters on the net efficiency has not been investigated thoroughly when a cooled turbine is considered. Cycle parameters of the Allam cycle are simply continued to be used in other researchers' work. The reason why these cycle parameters are adopted, at least from the thermodynamic point of view, has not been discussed adequately in the literature. Motivated by the current status, a direct-fired sCO_2 power cycle that is coupled to the coal gasification process on the basis of Weiland's work [17], is investigated in this study. An improvement of Weiland's work is that a detailed turbine cooling model is considered in this study to obtain more realistic cycle performance. The novelty of this work lies in the determination of the effect of key cycle parameters on the cycle performance through a comprehensive parametric study in a broad parameter range, while considering practical thermodynamic models (i.e. cooled turbine model). The results of this study will provide meaningful guidance in selecting proper cycle parameters of the direct-fired sCO_2 power cycle and lay foundation for cycle layout improvement in the future.

The remaining of the paper is organized as follows. A brief introduction of the power plant is given in Section 2. Models and assumptions used for simulation are presented in Section 3. Detailed parametric study is conducted in Section 4. Modifications to the base case are made to further improve the performance of the power plant in Section 5. Conclusions and main findings of this study are summarized in the last section.

2. System description

The power plant studied in this paper comprises four main subsystems: the coal gasification island, the supercritical CO_2 power cycle,