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Dynamic modelling and start-up operation of a solar-assisted recompression supercritical CO_2 Brayton power cycle

Minh Tri Luu [a], Dia Milani [a], Robbie McNaughton [b], Ali Abbas [a,*]

[a] School of Chemical and Biomolecular Engineering, The University of Sydney, NSW 2006, Australia
[b] CSIRO Energy Technology, PO Box 330, Newcastle, NSW 2300, Australia

HIGHLIGHTS

- Investigated the operation of sCO_2 Brayton cycle in transient conditions.
- Start-up to full-load scheme for a solar-assisted recompression cycle is developed.
- The scheme consists of four consecutive phases with distinct control events.
- Flexible heat sources (fossil fuel, solar energy) can be used during the start-up.
- Initial cooler by-passing is a vital event for sustaining supercritical condition.

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ABSTRACT

In this paper, we propose and analyse a start-up scheme that can be used to bring a solar-assisted recompression sCO_2 Brayton cycle from cold-start to full-load operation (i.e. design point). For this purpose, a comprehensive dynamic model for the entire solar integrated process is developed. It is found that the proposed scheme (consisting of four consecutive operational phases) can successfully bring the cycle to full-load operation in-line with the peak hours of solar energy harvesting. This scheme is featured with the flexibility of using fossil fuel and/or solar energy when appropriate process controls are in place. By utilising the CO_2 pressure-temperature-density diagram, an effective strategy is developed and integrated with the start-up scheme for guiding the cycle through the transient period and sustaining the supercritical phase. During full-load operation, there can be unexpected incidents, e.g. loss of charge (LOC). It is found that the LOC event decreases the CO_2 cumulative mass of the cycle and consequently reduces the overall solar energy utilization of the system. The sCO_2 recompression Brayton cycle intrinsically shows high tolerance to the loss of CO_2, thus the supercritical phase can mostly be sustained during a possible LOC event.

1. Introduction

The emergence of climate change as a grand challenge of this century has stimulated a considerable progress in sustainable practices and technologies, respectively. In this context, large-scale power production from concentrated solar power (CSP) is one of the most important areas for research and development in the 21st century [1]. Different power production technologies can be used (e.g. steam Rankine cycle, etc.) for the ultimate conversion of solar thermal energy into electricity. Among those, the closed-loop Brayton cycle using supercritical CO_2 (sCO_2) as a working fluid has gradually gained much attention in recent years due to its high compatibility with CSP [2–6]. This is mainly attributed to the compact design of turbomachines and less dependency on vast water demand compared to the conventional steam Rankine cycle [2]. In addition, for the same turbine inlet temperature (TIT), the sCO_2 Brayton cycle achieves the highest thermal efficiency when compared to other power cycles [6,7]. This desirable outcome originates from the significant reductions in the compression shaft-power demand when the CO_2 is compressed near its critical point (31.1 °C and 73.8 bar) [8]. As a result, the concept of solar-assisted

Abbreviations: AFB, auxiliary fossil fuel back up; CSP, concentrated solar power; CIT, compressor inlet temperature; FNP, fraction of nominal power; HTF, heat transfer fluid; HTR, high temperature recuperator; LOC, loss of charge; LOL, loss of load; LTR, low temperature recuperator; PDD, power demand driven; SAM, system advisor model; SSD, solar supply driven; TIT, turbine inlet temperature.

* Corresponding author.
E-mail address: ali.abbas@sydney.edu.au (A. Abbas).

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sCO_2 Brayton cycle has progressively come under the spotlight in the context of electricity generation from CSP technologies.

1.1. Dynamic studies for the solar-assisted Brayton cycle

Operating the sCO_2 Brayton cycle requires careful consideration in order to sustain the integrity of the working fluid (i.e. maintaining the CO_2 supercritical phase). This is important for achieving high thermal efficiency as well as preventing possible damage to turbomachinery components [9]. However, during the transient period, maintaining the supercritical phase is a challenging task as the CO_2 at the compressor inlet is often in the vicinity of the critical point [10]. Singh et al. [9] performed a dynamic analysis for a sCO_2 Brayton cycle integrated with solar energy. They found that during the start-up period, the CO_2 at the compressor inlet might go into the two-phase region (i.e. liquid and vapour CO_2 coexistence) and this could damage the compressor components. Carstens [11] studied the dynamic characteristics and controllability of a sCO_2 Brayton cycle integrated with a nuclear reactor for part-load operation. It was found that during the transient period, the CO_2 at the compressor inlet can lose the supercritical phase [11]. In addition, during the transition from full-load to part-load, Carstens pointed out that the cycle could have passed through the two-phase region [11]. This undesirable outcome was a result of simultaneous reduction in the CO_2 density and temperature at the compressor inlet.

Dynamic modelling and simulation is a useful tool in the development of operation strategies to sustain the CO_2 supercritical phase during the transient periods. By analysing the dynamic behaviour of the sCO_2 Brayton cycle, one can understand the underlying causes of undesirable CO_2 phase transitions. As a result, one can develop appropriate operation strategies to avoid those adverse phenomena. For example, in the study of Carstens [11], the author proposed the CO_2 compressor inlet temperature (CIT) should be increased above 32 °C in order to push the CO_2 away from the critical point and avoid the two-phase region [11]. To the best of our knowledge, most of the existing open literature regarding the dynamic features of the Brayton cycle is based on the heat sources from either fossil-fuel or nuclear energy [11–13]. However, there are few studies on the dynamics of solar-assisted sCO_2 Brayton cycle. Unlike other heat sources, the controllability of the solar-assisted cycle is further complicated by the fact that the power block (i.e. Brayton cycle) and the solar block can have different dynamic characteristics, respectively. As a result, it is a challenging task to balance between the thermal demand (for the power block) and supply (from the solar block) in order to achieve a stable operation. Most literature on the solar-assisted sCO_2 Brayton cycles is mainly parametric studies for steady-state analysis and optimization, but not for dynamic operation [4,14–17]. There are some studies that focus on the dynamic characteristics of the solar-assisted system [3,9,18–21]. However, those studies often associate with some draw-backs. In Singh et al.'s papers [9,18,19], the authors consider a regenerative layout which by all means shows a lower thermal efficiency and a modest operation/control compared to other advanced and highly-efficient layouts (e.g. recompression based) [6,22,23]. Other studies only consider the dynamic of the solar block by assuming the power block can instantly reach a steady-state thereafter [3,20,21]. This could be true for some processes if the time constant is very small. In the context of process control, time constant is defined as the period required for a process to respond to change(s) in the input(s) and reach a steady-state [24]. However, for a sCO_2 Brayton cycle, the time constant can be considerable because of the extreme sensitiveness of the CO_2 thermophysical properties vs temperature/pressure changes. Furthermore, no off-design consideration for the Brayton cycle during solar transient periods is found in those studies [3,20,21].

1.2. Operational modes for the solar-assisted Brayton cycle

There are two methods to transfer the harvested solar thermal energy to the working fluid (CO_2): direct and indirect heating, respectively [3]. In the direct-heating configuration, the solar radiation is concentrated in a focal area where a spiral of pipes carries the working fluid (sCO_2). The sCO_2 then directly captures the solar heat consequently raising its temperature. In contrast with the indirect-heating configuration, solar energy is transferred to the sCO_2 via an intermediate heat transfer fluid (HTF). There are associated pros and cons for each configuration. Milani et al. [3] presented a comparative study for a solar-assisted Brayton cycle using these two configurations. It was found that the indirect-heating requires less fossil fuel back-up but larger solar field compared to the direct-heating. This is mainly attributed to the presence of thermal energy storage (TES) which might not be highly feasible in the direct-heating configuration. In contrast, direct heating can achieve a higher thermal efficiency due to possible operation at a higher TIT (up to a maximum of 750 °C). However, this is not possible in the indirect heating due to the temperature cap of the HTF [25].

For the direct-heating, real-time operation of the solar-assisted Brayton cycle has two major transitions: 1/ start-up to full-load and 2/ full-load to shut-down. The 1st transition aims at bringing the cycle from an initial resting state (i.e. cold and no CO_2 circulation) to a designed full-load operation. On the other hand, the 2nd transition aims to take the cycle from the full-load mode into part-load and eventually shut-down, respectively. As a result, it can be said that the 1st transition involves ramping-up thermal supply while in the 2nd transition is ramping-down. These two transitions can happen at any time during a day depending on the operation philosophies, i.e. power demand driven (PDD) or solar supply driven (SSD) [26]. In PDD, the demand for electricity will initiate the suitable transitions. For example, if power demand is declining, the full-load to shut-down transition is initiated to bring the cycle into part-load mode. On the other hand, in SSD, when solar energy ramps-up, the start-up to full-load transition is commenced and vice versa for the other transition.

This paper focuses on the start-up to full-load operation of the SSD (Fig. 1). In this work, we propose a start-up procedure that can bring a solar-assisted sCO_2 recompression Brayton cycle from a resting state to full-load operation within a reasonable time frame without violating system constraints. Dynamic simulation for one typical day is carried-out to demonstrate and analyse the proposed scheme. Important findings (e.g. the role of pressure-temperature-density in maintaining the supercritical phase) are

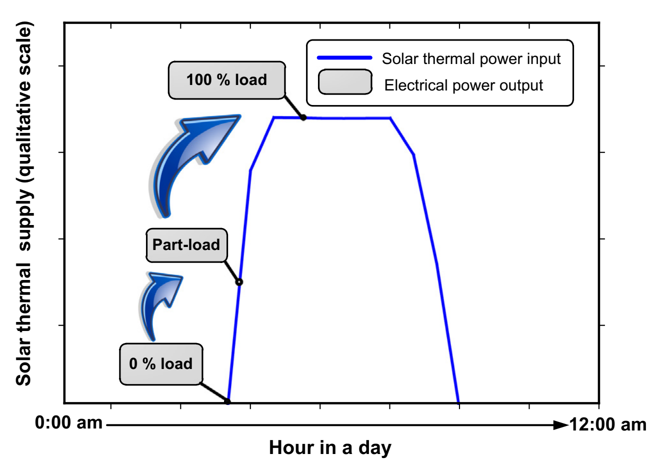

Fig. 1. Graphical illustration for the start-up to full-load transient operation studied in this work.