A Review of Using Supercritical CO\textsubscript{2} Brayton Cycle in Renewable Energy Applications

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Abstract - Supercritical carbon dioxide (sCO\textsubscript{2}), which is an environmentally friendly working fluid, has very good thermal physical properties. Many researchers have studied the heat transfer mechanism and the enhanced heat transfer method of the supercritical CO\textsubscript{2} Brayton cycle (sCO\textsubscript{2}-BC). The sCO\textsubscript{2}-BC has many applications including the next generation of Fast Cooling Reactor (FCR), solar power system, extraction process and heat pump system. The sCO\textsubscript{2}-BC provides high efficiency and high compactness, which is important because system miniaturization is vital to these developing technologies. The present paper reviews the recent references on the research progress of the sCO\textsubscript{2}-BC system. Furthermore, it discusses the analysis of key components such as the compressor, turbine and heat exchanger, which differ from the devices used in the conventional steam Rankine cycle due to the special thermal properties of sCO\textsubscript{2}. Finally, the researchers propose some recommendations towards the development of sCO\textsubscript{2}-BC system for future work.

Keywords - Supercritical CO\textsubscript{2} Brayton cycle; Compressor; Turbine; Heat exchanger

I. INTRODUCTION

Carbon emissions are increasing rapidly due to the increasing rate of energy consumption by human beings. The utilizations of renewable energy conversion systems, like nuclear and solar energies, are imperative to slow or stop the environment pollution and destruction caused by carbon emissions. Carbon dioxide (CO\textsubscript{2}), which is an environmentally friendly working fluid, has excellent thermal properties when used in a supercritical state. Supercritical CO\textsubscript{2} (sCO\textsubscript{2}) is capable of performing expansion working with a lower pressure residence when compared with steam. For this reason, Feher \cite{1} proposed using sCO\textsubscript{2} as a working fluid in the Brayton cycle in 1967. The sCO\textsubscript{2} Brayton cycle (sCO\textsubscript{2}-BC) is an attractive working fluid for nuclear reactor systems \cite{2-4}, solar power systems \cite{5-7}, and other renewable systems \cite{8-11}, because of its high overall efficiency due to special thermal properties \cite{12}. The density of sCO\textsubscript{2} is of the same order of magnitude as water. However, the sCO\textsubscript{2} viscosity is similar to that of air. Fig. 1 illustrates the overall cycle efficiency of the sCO\textsubscript{2}-BC evaluated from the turbine inlet temperature in the reactor system compared with other thermal cycles \cite{3}. The sCO\textsubscript{2}-BC has a much higher efficiency, than other cycles, when the turbine inlet temperature is over 550\degree C. It is possible for the overall efficiency of the sCO\textsubscript{2}-BC to exceed 50\%. The cycle efficiency of the sCO\textsubscript{2}-BC with the turbine inlet temperature of 550\degree C is expected to be compared with the helium cycle at 750\degree C, which means that the cost of materials can significantly be decreased. Thus, the sCO\textsubscript{2}-BC has great potential for industrial applications \cite{2}.

Fig. 1. Comparison of power cycle options \cite{3}
the safety, stability and reliability of the operating components in the system should be considered and studied comprehensively [14,15].

In this paper, the performance evaluation, system optimization and economic analysis studies of sCO2-BC systems from the last five years are reviewed. Other studies of related key components, such as the compressor, turbine and heat exchanger, are introduced briefly. Then, some recommendations are proposed based on the latest studies.

II. STUDIES ON THE SCO2-BC SYSTEM

The original thermo-dynamic process of sCO2-BC is shown in Fig. 2, with only some basic components illustrated. In order to improve the overall efficiency of sCO2-BC, some more complex system compositions are developed. Wang et al. [16] summarize the six typical layouts of sCO2-BC. These include the simple recuperation cycle, recompression cycle, precompression cycle, intercooling cycle, partial-cooling cycle and split expansion cycle. The derivative relationships between these six typical layouts of sCO2-BC are shown in Fig. 3. It can be seen that the systems are gradually improved as the necessary components are added into the original cycle to overcome the deficiencies.

With the growing interest in renewable energy, the sCO2-BC applicability in the field of solar energy is investigated. The sCO2-BC configurations were explored and optimized for use in a concentrating solar power (CSP) application combined with a dry cooling process, which might achieve the efficiency with 50% or greater [5]. Ortega et al. [6] analyzed the sCO2-BC in a solar receiver with the power of 0.3-0.5 MW using MATLAB, which can predict the thermal performance of the receiving equipment coupling with the radiation mechanisms. Moreover, it was proposed that the transient nature of the solar resource is the biggest challenge in the CSP system. Nami et al. [14] proposed a standard for evaluating the compressor, turbine, recuperator and cooler considering the factors of energy, economic and environment. Iverson et al. [18] studied the behavior of sCO2-BC in response to a fluctuating thermal input. The investigation was similar to short-term transient environments and the results showed good agreement with experimental data. Padilla et al. [19] conducted a multi-objective optimization of the compressor, turbine and recuperator on the thermal performance of the sCO2-BC. It was determined that the more compact characteristics of designing a compressor and turbine operating with the supercritical fluid must be overcome in order to successfully bring the technology to the market. These challenges include the fact that all the components should be designed with a more compact structure because of the miniaturization characteristics of sCO2-BC. Recent studies focused on optimizing the design of the key components, like the compressor, turbine and heat exchanger, which is described next.
III. STUDIES OF SCO\(_2\)-BC COMPONENTS

1. Supercritical CO\(_2\) Compressor and Turbine

The compressor increases the working fluid pressure from a low to a very high pressure, which can be seen in the Temperature-Entropy (T-S) diagram shown in Fig. 2. Cardemil et al. [20] recognized that CO\(_2\) has better comprehensive performance when operated at supercritical conditions. The effect of the compressor on the overall efficiency of the sCO\(_2\)-BC was studied by Dyreby [21]. The results indicated that the overall efficiency could be improved by increasing the compressor inlet pressure. However, it was found that the increase of compressor outlet pressure never affects the thermal efficiency. Ibsaine [22] presented a new compressor design concept, which was especially suited for sCO\(_2\) heat pump applications. The compressor consists of an integrated thermal system that consists of a thermal compressor and a conventional vapor compression heat pump. The computational model was verified by comparison with experimental measurements from the thermal compressor prototype. In Ibsaine’s study, the impacts of the size of dead spaces and leaks between the displacer and the cylinder wall were studied parametrically. Pecnik [23] investigated a high-speed centrifugal compressor operating with sCO\(_2\) and compared the results with data from tests in the Sandia sCO\(_2\) compression loop facility. Then, Lettieri et al. [24] studied a multistage compressor operating with supercritical CO\(_2\) by CFD method. The thermal properties of supercritical CO\(_2\) was calculated with the National Institute of Standards and Technology real gas model [25]. In order to improve the stage efficiency, a vaned diffuser was analyzed instead of the standard vanless diffuser in order to decrease the meridional velocity and widen the gas path. Rinaldi et al. [26] calculated the compressor map for three different rotational speeds (45 krpm, 50 krpm and 55 krpm) and the methodology and results were validated against experimental data from the Sandia National Laboratory. The comprehensive assessment of sCO\(_2\) real gas effects is important for evaluating the performance of compressor considering the high variability of thermal properties of sCO\(_2\). Baltadjiyev [27] investigated the centrifugal compressors at different thermodynamic conditions relative to the pseudo-critical point of CO\(_2\). The results indicated that it has a reduction of 9% in the choke margin of the stage due to the thermal properties variations and the condensation was not a concern at the investigated operating conditions.

The turbine is the component used for power generation, and as such, it can directly indicate the system efficiency. The sCO\(_2\) turbine is far smaller than the steam turbine due to its low pressure-ratio. Furthermore, the sCO\(_2\) turbine is much simpler than the steam one because it does not need to allow for phase change and moisture separation. Kato et al. [28] found that the sCO\(_2\) gas turbine reactor system, with a partial pre-cooling cycle, attained the excellent cycle efficiency of 45.8% at the temperature of 650°C. Chen [29] proposed the centrifugal prototype turbine using the sCO\(_2\)-BC and analyzed the performance with experimental and numerical methods. The shape and size of the nozzle of the supercritical CO\(_2\) turbine was optimized and it was found that choked flow did not occur when the diameter of the nozzle was larger than 0.7 mm. Additionally; the turbine output torques and the electric power generation can be improved with the increase of the nozzle inner diameter. The achievable thermal cycle efficiencies of the steam turbine cycle, helium turbine cycle and sCO\(_2\) turbine cycle were studied and compared by Ishiyama [30]. These efficiencies were found to be 40%, 34% and 42%, respectively, when the heat source temperature is 480°C. Furthermore, the volume of a sCO\(_2\) turbine was estimated to be only half that of a steam turbine generating the same power.

![Fig.3. Schematic of derivative relationships of six typical sCO\(_2\)-BC](image-url)
2. Supercritical CO$_2$ Heat Exchanger

In the sCO$_2$-BC, the recuperator and cooler, which play important roles in maintaining safe operations, always have significant impacts on the efficiency of the whole system. The shell-and-tube heat exchanger (STHE), which has been used for nearly a hundred years and has a mature manufacturing process, is now in wide use in the high pressure and high temperature systems [31]. However, the application of the STHE is limited by its required large volume and high cost when systems require compactness and miniaturization. In recent decades, the HEATRIC Company has developed a new type of printed circuit heat exchanger (PCHE) [32]. This new PCHE meets compactness requirements and can reliably operate for long term in extreme temperature and pressure conditions. The PCHE has performed excellently when used in the sCO$_2$-BC system.

Mylavarapu et al. [33-36] at Ohio State University investigated the PCHE in the high temperature helium facility (HTHF) with experimental and numerical methods. The straight fins of Alloy 617 plates were fabricated by photochemical etching and assembled by diffusion bonding. The experimental test data could be used to determine the design operating conditions for the PCHE in the HTHF. Ma et al. [37] also analyzed the thermal and hydraulic performance of a PCHE with zigzag fins. It was found that the flow could not be fully-developed at the high temperature due to the significant variation of the thermal physical properties of sCO$_2$. Tsuzuki et al. [38-40] developed a new PCHE with S-shaped fins. They validated numerically that the PCHE with S-shape fins had the same heat transfer performance as the zigzag PCHE but with the benefit of one-fifth of the pressure drop. With continued focus on fin structures, the heat transfer performance of a PCHE with airfoil shaped fins was proposed and analyzed by Kim et al. [41]. It can be seen that the PCHE with airfoil shaped fin can obtain the same heat transfer performance as the zigzag channel PCHE with only 1/12 the pressure drop. This is due to the streamlined fin shape and the increase of heat transfer area. Furthermore, Xu et al. [42] analyzed the airfoil fin structure parametrically and proposed that it was necessary to reduce the flow resistance along the flow direction in order to improve the comprehensive thermal hydraulic performance of the PCHE.

IV. CONCLUSIONS

The sCO$_2$-BC is an efficient thermodynamic cycle due to the excellent thermal properties of the sCO$_2$, which have significantly improved the systems overall performance when compared with other conventional cycles. Researchers have studied the sCO$_2$-BC system extensively, including performance evaluation and component optimization.

- The sCO$_2$-BC has very high overall efficiency, possibly above 50%. The sCO$_2$-BC may be used in the next generation reactor systems and solar power systems, which can significantly reduce the system volume.
- It is a challenge to design the compressor and turbine with sCO$_2$ working fluid for stable system operation. The sCO$_2$ compressor and turbine are far smaller than conventional ones due to the low pressure ratio, which can definitely contribute to the system miniaturization.
- The PCHE is a compact heat exchanger with a volume of 85% that of a comparable STHE. Complex fin structures for the PCHE have been developed; ranging from continuous zigzag shape to discontinuous airfoil shape, which aim to improve the comprehensive performance.

According to the investigation review above, some recommendations for future work of the sCO$_2$-BC system are proposed. Firstly, the material problem is now becoming the focus, due to system operating temperatures and pressures exceeding 700°C and 20 MPa, respectively. Secondly, the behavior and the performance of the compressor and turbine operating close to the critical point, should be tested and evaluated due to the high variability of sCO$_2$ thermal properties. Finally, the dynamic analysis of the entire system should be studied with transient analysis in cases of great fluctuation, to ensure the system should operate near the stability point very well.

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