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Review Article

Recent trends of supercritical CO_2 Brayton cycle: Bibliometric analysis and research review

Aofang Yu [a], Wen Su [a, *], Xinxing Lin [b], Naijun Zhou [a]

[a] *School of Energy Science and Engineering, Central South University, Changsha, 410083, Hunan, China*
[b] *Institute of Science and Technology, China Three Gorges Corporation, Haidian District, Beijing, 100038, China*

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ABSTRACT

Supercritical CO_2 (S–CO_2) Brayton cycle has been applied to various heat sources in recent decades, owing to the characteristics of compact structure and high efficiency. Understanding the research development in this emerging research field is crucial for future study. Thus, a bibliometric approach is employed to analyze the scientific publications of S–CO_2 cycle field from 2000 to 2019. In Scopus database, there were totally 724 publications from 1378 authors and 543 institutes, which were distributed over 55 countries. Based on the software-BibExcel, these publications were analyzed from various aspects, such as major research areas, affiliations and keyword occurrence frequency. Furthermore, parameters such as citations, hot articles were also employed to evaluate the research output of productive countries, institutes and authors. The analysis showed that each paper has been cited 13.39 times averagely. United States was identified as the leading country in S–CO_2 research followed by China and South Korea. Based on the contents of publications, existing researches on S–CO_2 are briefly reviewed from the five aspects, namely application, cycle configurations and modeling, CO_2-based mixtures, system components, and experiments. Future development is suggested to accelerate the commercialization of S–CO_2 power system.

1. Introduction

In the past twenty years, with the increase of population and economic activity, the global electricity demand rises continuously, which has caused serious environmental impact. Thus, how to efficiently deal with these challenges is a durable hot topic. In general, there are two solutions to balance the electricity growth and the environmental problem. One is to utilize renewable energy sources or exhaust heat to generate electricity. It is thought as a crucial step toward energy conservation and emission reduction in the future. Another solution is to improve the efficiency of energy conversion. Therefore, aiming at different energy grades, various power cycles such as supercritical water-steam Rankine cycle [1], organic Rankine cycle (ORC) [2,3] and supercritical Brayton cycle [4] have been developed to produce electricity with higher efficiency while consuming less conventional energy fuels. For the supercritical water-steam cycle, it has been widely used to generate electricity under the driven of coal, natural gas, nuclear and solar. Although the technologies required for supercritical water-steam cycle are very mature and thousands of water-steam cycle power stations have been built around the world [5], the water-steam Rankine cycle still has some limitations. For instance, when the steam temperature is around 700 °C, metallic corrosion is serious. This phenomenon indicates that with the increase of turbine inlet temperature, the improvement of cycle efficiency is limited by metallic materials [6]. Besides, in Rankine cycle systems, some facilities are operated at high pressure but others run at vacuum pressure. This large pressure difference results into a multistage steam turbine and large size of component. As for the ORC, organic working fluids are used instead of water. In general, ORC is preferred to be employed in medium and low temperature grade energy such as renewable energy and waste heat, due to the low boiling temperature of working fluids [7]. Since the temperature of heat source is relatively low, cycle efficiency of ORC is always low, just around 10% [8]. Meanwhile, considering the efficiencies of different working fluids and the environmental properties, much effort has been paid to the selection of working fluids [9]. However, due to the fact that organics are easily to be decomposed at a relatively high temperature, the efficiency increase is very limited

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* Corresponding author.
E-mail address: suwenzn@csu.edu.cn (W. Su).

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Nomenclature

Symbols	
AE	Applied Energy
ATE	Applied Thermal Engineering
CCPP	The capital cost per net power
CSP	Concentrated solar power
CPP	Citation per paper
D	A collaboration degree
DS	Direct search
ECM	Energy Conversion and Management
GA	Genetic algorithm
Gen IV	Generation IV Reactor
GFR	Gas-cooled Fast Reactor
GSS	Golden-selection search
IFPP	Impact factor per paper
LCOE	Levelized cost of energy
LFR	Lead-cooled Fast Reactor
MCFC	Molten-carbonate fuel cell
NSGA-II	Non-dominated sorting genetic algorithm II
n	The total number of publications
ORC	Organic Rankine Cycle
PCHE	Printed circuit heat exchanger
PEMFC	Proton-exchange membrane fuel cell
S–CO_2	Supercritical carbon dioxide
SFR	Sodium-cooled Fast Reactor
SNIP	Source normalized impact per paper
SOFC	Solid-oxide fuel cell
S_c	The total score
S_{ic}	The standard research score
3D	Three-dimensional
x_i	The number of the authors, institutions, and countries for each paper
y_{ic}	The original score
$\overline{y_{ic}}$	The average score
Subscripts	
c	Country
i	Indicator

[10]. In order to address the above issues existed in Rankine cycles, the supercritical Brayton cycles was proposed and numerous researches have yet been conducted by scholars. The used fluids in Brayton cycles usually include air [11], Helium [12] and supercritical carbon dioxide (S–CO_2) [4]. Due to the fact that S–CO_2 has a higher efficiency than air and Helium in the utilization of conventional and renewable energy, S–CO_2 Brayton cycle has been thought as one of the most promising power cycles [4]. In the past twenty years, governments and institutes around the world have paid much effort to developing this technology. Thus, the focus of this paper is on the S–CO_2 power cycle.

As an efficient energy conversion technology, the unique feature of S–CO_2 cycle lies on the properties of CO_2. First of all, CO_2 is non-toxic, non-corrosive, non-flammable and non-explosive. It has abundant stock and reasonable price. The cost of CO_2 is only one-tenth of helium and one-seventieth of R134a. On the other hand, CO_2 has critical temperature 30.98 °C, which is close to the ambient temperature, so that CO_2 can be easily in a supercritical state. Near the critical point, the required power for compressing S–CO_2 can be greatly reduced. This phenomenon makes S–CO_2 cycle have a higher efficiency than other cycles [13]. Furthermore, S–CO_2 exhibits a density which is close to liquid, and a viscosity and diffusion close to gas. Thus, during the expansion process, S–CO_2 has gas properties with liquid density. Meanwhile, CO_2 has critical pressure 7.38 MPa. The corresponding pressure ratio in S–CO_2 cycle is much lower than those of Rankine cycles, so that the number of stages in the S–CO_2 turbine can be greatly reduced. The above characteristics indicate that the turbo-machinery of S–CO_2 is much smaller than those of steam or organic vapor. The small size of the turbomachinery in S–CO_2 power has great advantages in system compactness and saving space [14]. Besides, CO_2 has good stability and inertness, which makes the cycle temperature up to more than 1000 °C theoretically [15]. In general, when the turbine inlet temperature is higher than 550 °C, the thermal efficiency of a S–CO_2 cycle is higher than that of a water-steam Rankine cycle [16].

Due to the outstanding properties of CO_2, S–CO_2 cycle was firstly proposed by Sulzer as early as 1950 [17]. It consisted of four principal components, namely heater, turbine, gas cooler and compressor. The corresponding ideal processes are isobaric heating, adiabatic expansion, isobaric heat release and adiabatic compression. Thereafter, in the 1960s, Feher [18] developed a single regenerative S–CO_2 cycle by equipping a regenerator. However, due to the difficulty caused by high pressure and temperature in engineering, S–CO_2 cycle was not accepted at that time. Along with the development of material and craft, in 2004, the department of energy of United States financed Massachusetts Institute of Technology to conduct a detailed system design and analysis of S–CO_2 cycle, thus evaluating the feasibility of applying S–CO_2 to nuclear reactor [19]. Since then, intensive researches have been conducted by more and more institutes. Nowadays, the excellent properties of CO_2 have made S–CO_2 cycle be more attractive in the field of energy conversion. S–CO_2 power cycle has been widely applied to the nuclear reactor, solar energy, fossil fuel, waste heat recovery, fuel cell and geothermal energy [20].

In order to accelerate the commercialization of S–CO_2 power cycle in different potential applications, much effort has been paid to investigate the various aspects of S–CO_2 cycle. For instance, aiming at the characteristics of heat source, different configurations of S–CO_2 cycle have been proposed to get higher cycle efficiency, better economic performance and stronger feasibility [4,20]. In general, according to different methods of heat exchange between S–CO_2 and heat source, S–CO_2 cycles can be classified into direct and indirect cycles. The direct S–CO_2 cycle uses CO_2 as the coolant to recover the heat source energy, but the indirect S–CO_2 cycle extracts the heat source energy via an intermediate heat exchanger. For concentrated solar power (CSP) applications, the direct S–CO_2 cycle has a higher global efficiency [21], while the indirect S–CO_2 cycle has lower efficiency due to various heat losses. As for the S–CO_2 cycle driven by fossil energy, the Allam cycle was proposed as a direct combustion system [15]. Natural gas is burned with the mixture of O_2 and CO_2 in a combustor to drive the turbine. The heat of exhaust gas is recovered in recuperators. The thermal efficiencies of Allam cycle can be up to 59% for natural gas and 52% for coal [15]. However, since the combustion of Allam cycle occurs at high pressure up to 30 MPa, cycle operation is still a great challenge. One the other hand, S–CO_2 cycle can recover the waste heat of a gas turbine in the range of 500 °C–600 °C [22]. However, being different with the system efficiency goal in the utilization of solar energy, fossil fuel and nuclear reactor, the target of waste heat recovery is to utilize the heat as much as possible for power generation. For various configurations of S–CO_2 power cycle, the recompression cycle is the most representative, because of its relative simplicity and higher efficiency [23]. However, due to the great amount of regenerative heat, the inlet temperature of S–CO_2 at the heater is much higher. If the recompression cycle is directly applied to the waste heat recovery, this characteristic will result in a high outlet temperature of exhaust gas. Therefore, on the basis of commonly used S–CO_2 cycle configurations, more advanced cycle layouts have been proposed for the waste heat recovery [24–26].

From the above discussion, it can be seen that there does not exist a fixed S–CO_2 cycle that can be suitable for all the heat sources. Although the recompression cycle is suitable for nuclear or solar energy, it is not good for waste heat. Besides, for the commercialization of S–CO_2 power cycle, system components have to be deeply investigated. Technic barriers of heat exchangers and turbomachinery such as fabrication, seal, leakage and rotodynamics stability need to be conquered.

In recent years, with the increasing researches on S–CO_2 cycle, a number of review articles, which cover different aspects of the researches, have yet been published. For instance, aiming at the S–CO_2 Brayton technology applied in fossil fuels, Zhu [27] reviewed the recent developments of S–CO_2, and discussed the technical challenges including the construction of turbomachinery, the design of low-cost and compact recuperators, and the development of oxy-combustor. Ahmadi et al. [28] reviewed various thermodynamic cycles, which work with solar-assisted gas turbines. Cycle structures of S–CO_2 were summarized, and pros and cons of different S–CO_2 cycles were compared. Kumar and Srinivasan [29] explored the potential and limitations of Brayton cycle for pure CO_2 and CO_2-based mixtures, and identified the challenges of developing S–CO_2 cycle specifically for solar power generation. Thereafter, focusing on nuclear reactors and solar energy industry, Li et al. [30] provided detail comprehensive study of S–CO_2 technology development and summarized the theoretical and experimental analyses. Meanwhile, the comparison with working fluids, component design and challenges were also discussed. Common technical barriers of the S–CO_2 power cycle applications were identified. As for other energy sources including waste heat and fuel cells, Ahn et al. [20] introduced the development progress of S–CO_2 technology and presented a comparison of various system layouts in terms of cycle performance. Liu et al. [4] summarized the different configurations of existing S–CO_2 cycles, and reviewed the applications of S–CO_2 to different heat sources including concentrated solar power, fuel cell, nuclear reactor and exhaust heat. On this basis, Liu et al. [4] found that so far, aiming at the variation of a heat source or a heat sink, few researches have been conducted for the control strategy of S–CO_2 system. Thus, further work is required to investigate the dynamic operation of system under different changing conditions. Besides, from the system design, energy transfer mechanisms and key components development, the research status of S–CO_2 cycles were analyzed by Xu et al. [31]. Based on the analysis, barriers for further promotion of S–CO_2 cycles were summarized, including the lack of system design and analysis methodology, not well understood mechanisms of energy transfer, and technic barriers such as seal, leakage and rotodynamics stability of key components. To overcome these issues, Xu et al. [31] have proposed corresponding perspectives and solutions.

From the published literatures on S–CO_2 cycle, it can be found that the existing review articles have presented comprehensive discussion and summarization on the system application, cycle layout, theoretical analysis, experimental study and component development. Few works have focused on the analysis of S–CO_2 publications quantitatively. However, with the progress of S–CO_2 Brayton cycle technology, the related publications have grown markedly. It's necessary to assess these publications, so that core researches, contribution of authors and institutes can be identified for the S–CO_2 field. Therefore, in this work, scientific papers of S–CO_2 cycle, which were published in the period from 2000 to 2019, are quantitatively evaluated. The employed method is called a bibliometric approach. By this method, the development patterns of a research field can be clearly presented, so that the future research scope can be determined. Nowadays, this approach has been widely used to analyze the corpus of scientific articles and quantitatively evaluate the research activities on a given research topic [32–36]. For the bibliometric analysis on S–CO_2 publications, various aspects such as published journals, hot articles and citations are investigated. Eight performance parameters are selected to evaluate the research output for authors, institutions, and countries. Thereafter, based on the statistical data of S–CO_2 publications, research status and future development of S–CO_2 power cycle are presented. The paper is structured as follows: the used methodology is briefly introduced in Section 2. In Section 3, the results are presented and discussed. Section 4 gives a brief review on the status of S–CO_2 cycle and highlights the future development. Concluding remarks of this work are provided in Section 5.

2. Bibliometric methodology

In order to analyze the research trends of S–CO_2 Brayton cycle, a number of publications have been obtained from Scopus database. By searching the words "Carbon dioxide" and "Brayton cycle", which are employed in the title, abstract, and keywords of publications, the raw data were collected on 25th February 2020. There were 810 papers. Considering that only seven papers were published before 2000, the obtained data were refined from 2000 to 2019. Then, the document type "article, conference paper and review" and language "English" were applied to further filter these data. Finally, 724 papers were obtained for S–CO_2 power cycle. Similarly, 1005 patents were found, based on the same searching method with the publications. In this bibliometric study, the above data were analyzed with the help of an advanced software tool, namely Bibexcel [37].

2.1. Research indicators

In the bibliometric analysis, the influences of the journals, authors, institutions and countries were evaluated by two parameters, namely impact factor and h-index. For the impact factor, it is generally calculated as the average citations for each paper published in a journal during the two preceding years. As for the h-index, it is equal to h if h publications have at least h citations each. It can be calculated from the total publications and the number of citations for each paper. In this work, for a given journal, the impact factor was determined, according to the Journal Citation Reports of 2019.

In order to evaluate the research output for different institutions and countries, research indicators including i-5 index, hot articles, productive authors and institutions have been used. The number of publications, which are cited by more than five times, is denoted as i-5 index. If an article is cited more than 30 times, it's classified as a hot article. As for the productive authors and institutions, they have published more than five papers, respectively. Furthermore, the citation per paper (CPP) and impact factor per paper (IFPP) are also employed to assess the research quality comparatively.

2.2. Collaboration degree

As is known, with the development of technology, there is usually more than one author for each paper. Multiple institutions and countries may have participated in the corresponding researches. In order to represent the research collaboration among authors, institutes and countries, a collaboration degree is defined as follows [36]:

$$\mathrm{D} = \sum_{i=1}^{n} x_i \Big/ n \tag{1}$$

where x_i can be the number of the authors, institutions, and countries for each paper, and n denotes the total number of publications.

2.3. Research score

Due to the fact that there are different research indicators to measure various aspects of publication quality for countries, a comprehensive approach is adopted to compare the research output quantitatively. By this way, a standard research score is calculated from various research indicators. In this work, the chosen eight indicators are the number of articles, number of citations, number of productive authors, number of productive institutions, h-index, total impact factor, number of hot articles and corresponding total citations, respectively. Based on these eight indicators of a country, a standard research score is defined as follows [36]:

$$S_{ic} = \frac{y_{ic} - \overline{y_{ic}}}{\overline{y_{ic}}} + 1 \tag{2}$$

where y_{ic} is the original score of indicator i for country c, $\overline{y_{ic}}$ is the average score of indicator i, and S_{ic} is the standard research score of indicator i for country c. Thereafter, the total score of a country (S_c) can be obtained by [36].

$$S_c = \sum_{i=1}^{8} S_{ic} \tag{3}$$

3. Bibliometric analysis

3.1. General statistics

Based on the methodology in Section 2, 724 publications and 1005 patents linked to S–CO$_2$ Brayton cycle from 2000 to 2019 were found in the Scopus. The frequency of publication and patents is presented in Fig. 1 as a function of year. The results indicate that publication number has overall increasing trends during 2000–2019. It's because that since United States completed the system design and analysis of S–CO$_2$ cycle in 2004 [19], governments all over the world have begun to vigorously develop the S–CO$_2$ cycle technology. As for the patents, they are mainly from United States Patent & Trademark Office, European Patent Office, World Intellectual Property Organization, United Kingdom Intellectual Property Office. Because of the constraints of English language, a large number of patents in Chinese are excluded. From Fig. 1, it can be observed that the patent number increases overall during the period of 2000–2017. However, after that, the number of patents decreases continuously. Maybe, this is because that most of technical bottlenecks of S–CO$_2$ power system have been gradually solved. For the commercialization of S–CO$_2$ cycle, only a few tricky issues need to be addressed in the future.

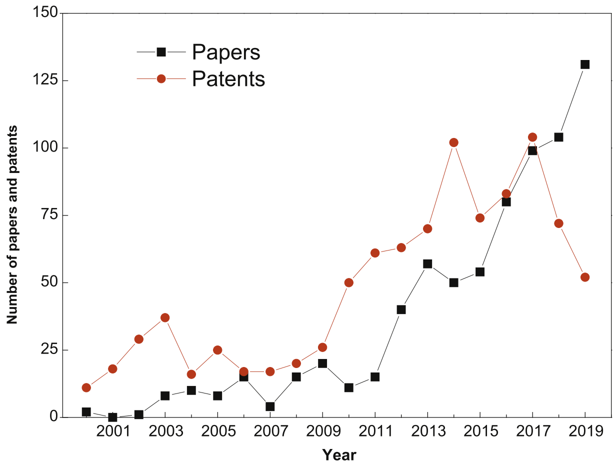

Fig. 1. Trends of publications and patents during 2000–2019.

Fig. 2 presents the type of publications. It's observed that the "Original articles" and the "Conference papers" account for 48.2% and 48.07% of the published papers, respectively. The share of review papers is 3.73%. This type distribution means that almost half papers of S–CO$_2$ cycle are published by holding the conferences such as Proceedings of the ASME Turbo Expo and International Conference on Nuclear Engineering Proceedings. Compared with the articles published in journals, the academic discussions on conferences are more beneficial to the development of S–CO$_2$ technology.

3.2. Country distribution

According to the statistics of Bibexcel, publications related with S–CO$_2$ Brayton cycles were from 55 countries. However, among these countries, there were up to 24 countries having only one article each. Most publications originated from only a few countries, such as United States, China and South Korea, as presented in Fig. 3 for the national distribution of publications on S–CO$_2$ cycle. In terms of the number of publications, the top 10 countries are provided in Table 1. If a publication was completed by authors from different countries, the publication was counted for these countries in the analysis. After statistics, about 85.77% of the publications are from these 10 countries. As a leading country, United States has published 242 articles during 2000–2019, accounting for 33.43% of the total papers. Besides the number of articles, United States also ranks the first place for other six research indicators including citations, productive authors and institutes, number of hot articles and corresponding citations, and h-index. As for the total IF, the leading country is China, followed by United States, as shown in Table 1. This phenomenon is explained that compared with China, United States published more conference papers, which had no IF for the corresponding conference journals. Furthermore, Table 1 indicates that the articles originating from the top three countries, namely United States, China and South Korea, account for 64.5% of the total papers.

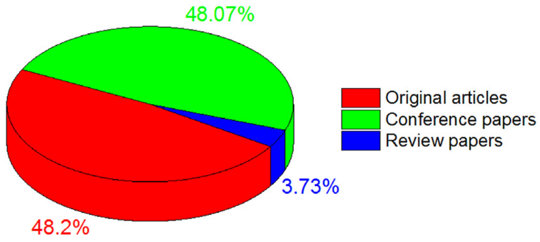

Fig. 2. Types of publications within the S–CO$_2$ Brayton cycle technology filed from 2000 to 2019.

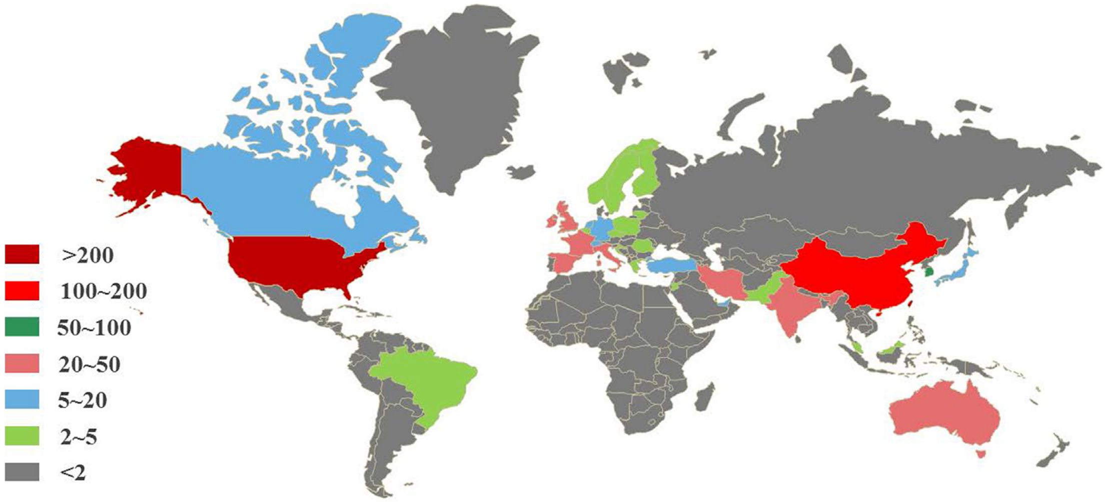

Fig. 3. National distribution of S–CO_2 publications.

Table 1
Top 10 countries of S–CO_2 Brayton cycle publications from 2000 to 2019.

Country	Total		Number of productive		Hot articles		Quality	
	Articles	Citations	Authors	Institutions	NO	Citations	Total IF.	h-index
United States	242	3622	26	17	29	2437	237.054	29
China	159	1812	21	13	17	980	476.309	23
South Korea	85	1368	20	6	12	908	152.601	19
Australia	41	669	7	5	9	453	130.412	14
India	35	504	4	2	3	263	62.309	11
Spain	31	502	6	3	4	227	93.349	13
United Kingdom	29	328	1	2	3	142	65.94	10
Italy	24	323	0	1	5	187	48.527	11
France	20	386	0	3	3	269	22.14	10
Germany	17	115	2	2	1	41	21.934	6

In order to compare the comprehensive research level for different countries, research scores are calculated using Eq. (2) and Eq. (3), based on the statistical data of publications in Table 1. The calculated results are illustrated in Fig. 4. It can be observed that the top countries are still United States, China and South Korea from the viewpoint of the total scores. Their corresponding values are much higher than those of other countries. In general, more publications come with an increase of other research indicators. However, when the number of articles is close to each other, the article number alone does not indicate the research quality. For instance, India has more four articles than Spain, while the total research score is a bit lower than that of Spain. This is because that Spain possesses more productive authors and institutes, more hot articles, higher IF and h-index, as illustrated in Table 1.

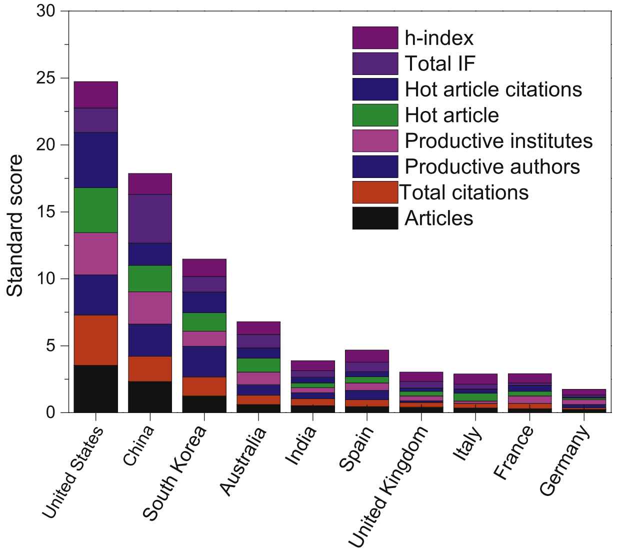

Fig. 4. Research scores of the top 10 countries.

3.3. Institute analysis

The searched publications on S–CO_2 Brayton cycle are from 543 institutes. For the productive institutes, the number is 55, and the corresponding published articles make up 71.27% of the total publications. On the basis of article numbers, the top 15 institutes are summarized in Table 2. After statistics, 44.75% of the total publications have been published by these research institutes from 2000 to 2019. From Table 2, it can be seen that Xi'an Jiaotong University from China ranks the first place. Meanwhile, the corresponding impact factor and h-index are also the highest. As for the total citation, the highest value is obtained by Sandia National Laboratories from United States. The second top institute is Korea Advanced Institute of Science and Technology from South Korea. Although IF is much lower than that of Xi'an Jiaotong University, total citation is still higher than that of the first institute. It should be noted that since most of papers were published on the conference journals including Proceedings of the ASME Turbo Expo and

Table 2
Top 15 institutes in the S–CO_2 Brayton cycle technology field from 2000 to 2019.

Institute	Papers	IF	h-index	TC
Xi'an Jiaotong University	57	227.47	17	880
Korea Advanced Institute of Science and Technology	53	80.76	16	913
Argonne National Laboratory	39	4.62	9	336
Sandia National Laboratories	35	53.08	12	1056
Ministry of Education China	33	113.04	13	534
University of Wisconsin-Madison	30	39.48	8	251
Korea Atomic Energy Research Institute	27	38.68	10	615
Indian Institute of Science, Bengaluru	26	43.20	9	332
Chinese Academy of Sciences	22	58.02	11	364
Institute of Engineering Thermophysics Chinese Academy of Sciences	20	46.25	11	362
Massachusetts Institute of Technology	19	15.69	10	545
University of Queensland	19	60.14	7	225
North China Electric Power University	13	60.41	7	190
Tsinghua University	13	15.14	3	55
University of Central Florida	12	0	5	45

International Conference on Nuclear Engineering Proceedings, Argonne National Laboratory and University of Central Florida have much lower IF than other institutes. Furthermore, for these 15 institutes, there are six from China, five from United State, two from South Korea, and one research institute each from India and Australia.

3.4. Authorship pattern

The analyses on the publication data show that there are 1378 authors from 55 countries to undertake the research of S–CO_2 technology. The number of productive authors with five or more papers sums up to 92. Although these authors only make up 6.58% of the total authors, the share of their published papers is up to 48.76%. Furthermore, based on the number of authors per publication every year, Fig. 5 illustrates the authorship pattern. It can be observed that publications are mostly completed by three or four authors, accounting for 23.76%, 20.86% of the total S–CO_2 publications respectively. For the publications with two and five authors, the proportions are respectively 18.37% and 15.61%. The least share (4.56%) is for the publications with one author. Meanwhile, papers published by seven or more authors only account for 6.49% of the total publications.

According to the descending order of S–CO_2 publication numbers, Table 3 summarizes the 10 most productive authors. The table shows that the most productive author is Lee J.I from South Korea. The author has published 44 papers, which are much higher than the rest authors. Up to now, these papers have been cited 801 times. Furthermore, h-index of Lee J.I is 13. The author has 6 hot articles, which have had 547 citations. Special care should be given for the authors Sienicki J.J, Moisseytsev A and Hejzlar P from United States. Their impact factors are much lower than those of other authors. This is because that most papers of these three authors were published on the conference journals, which have no IF. Even so, the three authors have quite good citations, especially for the author Hejzlar P. Although Hejzlar P has published only 13 articles, the corresponding citation is up to 502 and there are four hot articles. Furthermore, for these ten authors, the highest CPP 39.5 is obtained by Cha J.E from South Korea, while Bai S.J has the highest IFPP 2.53, as presented in Table 3. From the provided institutes, it can be observed that there are four authors from United States, five from South Korea, and one from India.

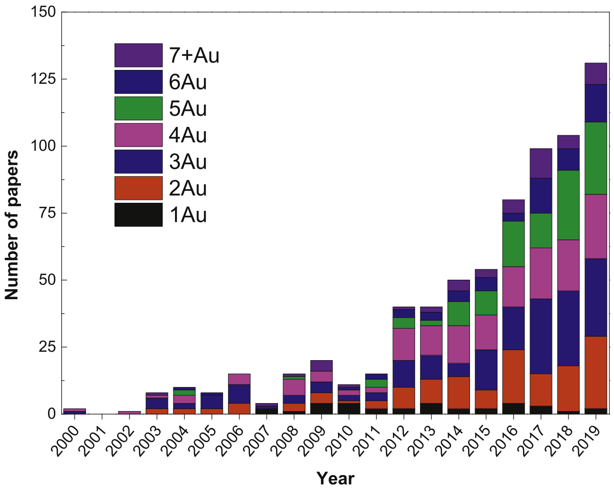

Fig. 5. Authorship pattern of publications in the S–CO_2 Brayton cycle field during 2000–2019.

3.5. Academic collaboration

Based on the definition of Eq. (1), the collaboration degrees are obtained for authors, institutes and countries, as shown in Fig. 6. From the figure, it can be observed that there are no obvious laws for the variations of the authorial, the institutional and the national collaboration degrees. Overall, the degrees in 2019 are all a little higher than those in 2000. This may be attributed to more convenient transportation and information exchange. Furthermore, it's deserved that the highest collaboration degree is obtained by authors, followed by institutes and countries.

For the total publications, the collaboration degrees of authors, institutes and countries are 3.8, 1.7 and 1.2 respectively. It means that on average, 3.8 authors, 1.7 institutes, and 1.2 countries have contributed to each paper. These values indicate that the research of S–CO_2 technology is mainly conducted by only a few countries and institutes.

3.6. Journal statistics

The findings show that the S–CO_2 publications are from 94 journals during the considered period. Based on the article number, the top 10 productive journals were identified, as listed in Table 4. Besides the article numbers, citations, h-index, the latest impact factor (2019) and source normalized impact per paper (SNIP) are also provided. For these top 10 journals, the corresponding publications make up 50.42% of the total publications.

Table 4 indicates that the conference journal "Proceedings of the ASME Turbo Expo" has published the largest share of articles and

Table 3
10 most productive authors in the S–CO$_2$ Brayton cycle technology field during 2000–2019.

Author	Institute	TP	CT	IF	CPP	IFPP	h-index	HA	HACT
Lee J.I	Korea Advanced Institute of Science & Technology, South Korea	44	801	75.18	18.20	1.71	13	6	547
Sienicki J.J	Argonne National Laboratory, United States	32	328	4.62	10.25	0.14	9	2	144
Moisseytsev A	Argonne National Laboratory, United States	26	264	4.62	10.15	0.18	8	2	144
Anderson M	University of Wisconsin-Madison, United States	20	118	20.93	5.90	1.05	4	1	33
Ahn Y	Korea Atomic Energy Research Institute, South Korea	19	651	26.36	34.26	1.39	10	5	502
Lee J	Korea Advanced Institute of Science & Technology, South Korea	18	308	30.05	17.11	1.67	8	4	175
Kumar P	Indian Institute of Science, India	15	216	19.04	14.40	1.27	8	1	104
Cha J.E	Korea Atomic Energy Research Institute, South Korea	14	553	22.82	39.50	1.63	8	5	487
Bae S.J	Korea Atomic Energy Research Institute, South Korea	13	457	32.91	35.15	2.53	6	3	392
Hejzlar P	Massachusetts Institute of Technology, United States	13	502	5.35	38.62	0.41	9	4	426

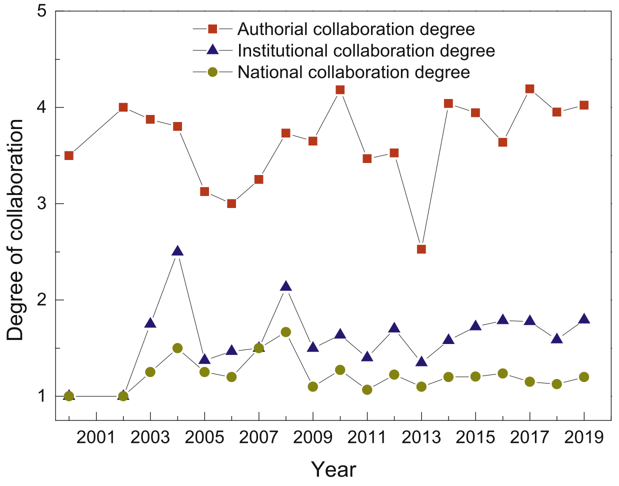

Fig. 6. Collaboration degrees of authors, institutes and countries.

makes up 15.61% of the total articles during 2000–2019. Although this journal has no IF, the corresponding h-index is 15. It means that the publication quality of this conference is recognized by researchers. As for the regular journals, papers are always published in Energy, followed by Applied Thermal Engineering (ATE), Energy Conversion and Management (ECM). These three journals have 18.23% of the total publications. For the citations, the numbers are 1593, 748, and 644, respectively. The citations of the three journals accounts for 30.78% of the total citations. In 2019, impact factors of Energy, ATE, and ECM are 5.537, 4.026 and 7.181, respectively. The corresponding h-indexes are respectively 20, 16 and 17, which rank in the top three. The above indicators show that the three journals are the leading journals to publish the original articles on S–CO$_2$ cycle. Energy and ECM are respectively established by United States and Netherlands. ATE is from the UK. Furthermore, it should be noted that for Applied Energy (AE) with the highest impact factor (8.426), although the number of publications is only 21, the corresponding citations are only less than those of energy, and h-index of AE is up to 12.

3.7. *Article citation*

For every year during 2000–2019, the total publications, citations, the number of hot articles and corresponding citations, i-5 and h-index are presented in Table 5. It should be noted that in 2001, there is no publications about the S–CO$_2$ Brayton cycle. Thus, the year of 2001 is not listed here. Table 5 indicates that the publication number has an increasing trend with the year. Due to the fact that the number of citations is not only related with the article quality, but also closely depends on the time interval between the published and statistical dates, citations for the paper published in 2019 are lower. The largest number of citations is obtained for the year of 2014. Furthermore, for the hot articles, i-5, and h-index, the highest values are all obtained in the year of 2016.

According to the number of citations, Table 6 provides the authors, the countries, the published years, total citations, and journals for the 15 most cited articles. The corresponding citations of these articles make up 25.37% of the total citations. Furthermore, out of the 15 most cited articles, there are four papers from United States, two from South Korea and Czech Republic. Every rest country such as China, India has only one paper. For these 15 highly cited articles, the latest articles were published in 2015. As illustrated in Table 6, these papers were frequently published on the leading journals. Six papers were published in Energy. Each of the three journals including Renewable and Sustainable Energy Reviews, AE, and Nuclear Technology has two papers.

3.8. *Keyword analysis*

In general, researchers employ the author-defined keywords and titles of publications to express the core values of publications,

Table 4
Top 10 productive journals for publications on S–CO$_2$ Brayton cycle during 2000–2019.

Journal	Total		Relative (%)		Journal quality		
	Papers	Citations	Papers	Citations	h-index	IF	SNIP
Proceedings of the ASME Turbo Expo	113	605	15.61	6.24	14	–	NA
Energy	52	1593	7.18	16.43	20	5.537	1.822
Applied Thermal Engineering	42	748	5.80	7.71	16	4.026	1.731
Energy Conversion and Management	38	644	5.25	6.64	17	7.181	2.151
International Conference on Nuclear Engineering Proceedings	27	90	3.73	0.93	4	–	NA
Energy Procedia	23	388	3.18	4.00	10	–	0.582
Journal of Engineering for Gas Turbines and Power	22	454	3.04	4.68	12	1.653	1.214
Applied Energy	21	802	2.90	8.27	12	8.426	2.616
Nuclear Engineering and Design	17	488	2.35	5.03	12	1.541	1.61
Nuclear Technology	10	22	1.38	0.23	3	0.953	1.152

Table 5
Publication statistics of S—CO_2 Brayton cycle publications from 2000 to 2019.

Year	Publications		Hot articles		Quality	
	Papers	Citations	NO	Citation	i-5	h-index
2019	131	218	1	31	17	6
2018	104	669	4	166	39	15
2017	99	1257	14	640	57	21
2016	80	1176	12	562	50	20
2015	54	985	8	706	26	14
2014	50	1305	11	972	36	18
2013	57	1224	10	976	29	15
2012	40	829	10	599	24	16
2011	15	300	3	132	11	11
2010	11	110	1	50	4	4
2009	20	425	4	335	11	8
2008	15	203	2	72	13	9
2007	4	33	0	0	3	3
2006	15	604	3	486	10	8
2005	8	193	2	146	5	5
2004	10	72	1	32	4	4
2003	8	50	0	0	5	5
2002	1	52	1	52	1	1
2000	2	5	0	0	0	1

such that development in a particular research field can be monitored [51]. In this work, author-defined keywords are extracted from the publication data using Bibexcel [37]. The reason for the use of author-defined keywords is that compared with the keywords of Scopus index, they are much more comprehensive to represent the content of the literature. The statistic results indicate that there are totally 1058 different keywords. Considering that the difference of keywords may originate from the expression format, the obtained keywords are further filtered according to core meanings. Based on the frequency of keywords, Table 7 lists the top 20 keywords. It's indicated that “Supercritical carbon dioxide” is the most used keyword, followed by “Brayton cycle” and “Supercritical CO_2 Brayton cycle”. The rest keywords involve the applications of S—CO_2 cycle (nuclear reactor, concentrated solar power, waste heat recovery), key system components (heat exchanger, turbine, compressor, recuperator), cycle layouts (recompression Brayton cycle, ORC, combined cycle), theoretical investigations (optimization, exergy analysis, thermodynamic analysis, numerical simulation) and CO_2-based mixture. In total, the main contents of existing researches on S—CO_2 Brayton cycle are focused on thermodynamic analysis and optimization. For the researches on experimental data or experimental verification of S—CO_2 cycle, publications only account for 6.35% of the total publications. It means that more experiments on S—CO_2 cycle should be conducted in the future.

3.9. *Subject distribution*

Based on the work of existing researches on S—CO_2 Brayton cycle, publications can be broadly divided into four major areas, namely applications of S—CO_2 cycle technology, cycle structure of S—CO_2, S—CO_2 system design and optimization, CO_2-based mixtures, as illustrated in Fig. 7. In fact, these research categories are similar with those of ORC [36]. However, being different from the core research areas of ORC, few researches have been published on the dynamics and control of S—CO_2 cycles, just as stated by Liu et al. [4]. From Fig. 7, it can be concluded that the application of S—CO_2 technology has the largest share of publications, namely 48.71%. Specifically, S—CO_2 cycle can be employed in the fields of solar power, nuclear reactor, fossil fuel, waste heat recovery, fuel cell and geothermal energy. The relative distribution of these specific application fields is illustrated in Fig. 8 (a). As for the S—CO_2 cycle structure, the number of related publications accounts for 29.34%. Generally speaking, by adding thermodynamic processes including recuperating, splitting and reheating, various configurations of S—CO_2 cycle can be generated from simple Brayton cycle. Meanwhile, in order to raise the energy conversion efficiency further, S—CO_2 cycle is usually combined with other thermodynamic cycles, such as ORC and vapor compression cycle. The related publications deal with the thermodynamic analysis of these cycle configurations and performance comparison. Sub-research areas of cycle structure are presented in Fig. 8 (b).

Considering the characteristics of heat source and the S—CO_2 employed cycle structures, system design and optimization are conducted. The corresponding publications account for 13.23%. Fig. 8 (c) provides the shares for cycle design and cycle optimization, namely 71.49% and 28.51% respectively. As for the last core research area, although CO_2-based mixtures have the ability to change the critical properties of cycle fluid, thus improving the cycle performance potentially, the topic of mixtures has a least share of publications, about 8.72%. For the cycle analysis on the CO_2-based mixtures, accurate properties of fluids are prerequisite. This results into the research of property modeling on the CO_2 and mixtures. The distribution of mixture performance and properties is provided in Fig. 8 (d).

4. Research status and future development of S—CO_2 cycle

Although the statistical data of S—CO_2 publications are comprehensively analyzed by considering various research indicators, the development status of S—CO_2 cycle technology has not been fully presented and discussed in the above bibliometric analysis. Thus, in this section, the existing researches on S—CO_2

Table 6
15 most cited articles in the S—CO_2 Brayton cycle technology field from 2000 to 2019.

Author	Country	Year	Total citations	Relative citations(%)	Journal
Ho and Iverson [38]	United States	2014	311	3.21	Renewable and Sustainable Energy Reviews
Ahn et al. [20]	South Korea	2015	304	3.14	Nuclear Engineering and Technology
Iverson et al. [39]	United States	2013	243	2.51	Applied Energy
Turchi et al. [40]	United States	2013	203	2.09	Journal of Solar Energy Engineering, Transactions of the ASME
Dostal et al. [16]	Czech Republic	2006	180	1.86	Nuclear Technology
Dostal et al. [41]	Czech Republic	2006	162	1.67	Nuclear Technology
Zhang and Lior [42]	China	2006	144	1.49	Energy
Le Moullec [43]	France	2013	130	1.34	Energy
Kim et al. [44]	South Korea	2012	126	1.30	Energy
Moisseytsev and Sienicki [45]	United States	2009	114	1.18	Nuclear Engineering and Design
Padilla et al. [46]	Australia	2015	111	1.15	Applied Energy
Sarkar [47]	India	2009	110	1.13	Energy
Alsulaiman and Atif [48]	Saudi Arabia	2015	107	1.10	Energy
Akbari and Mahmoudi [49]	Iran	2014	107	1.10	Energy
Romero et al. [50]	Spain	2014	107	1.10	Renewable and Sustainable Energy Reviews

Table 7
20 most frequent author-keywords in the S–CO_2 Brayton cycle publications from 2000 to 2019.

Keywords	Frequency	Keywords	Frequency
Supercritical carbon dioxide	178	Organic Rankine cycle	23
Brayton cycle	93	Compressor	22
Supercritical CO_2 Brayton cycle	86	Combined cycle	20
Nuclear reactor	50	Heat transfer	15
Heat exchanger	47	Thermodynamic analysis	15
Optimization	45	Carbon capture	15
Concentrated solar power	43	Waste heat recovery	14
Recompression Brayton cycle	41	Recuperator	12
Turbine	37	Numerical simulation	11
Exergy analysis	24	CO_2-based mixture	10

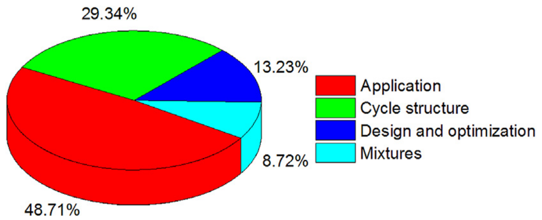

Fig. 7. Core research areas of S–CO_2 technology.

power cycle are further reviewed from the five aspects, namely applications of S–CO_2 cycle, cycle configurations and modeling, CO_2-based mixtures, system components and experiments. The corresponding issues are pointed out and future development is suggested.

4.1. Applications of S–CO_2 cycle

As presented in Fig. 8 (a), S–CO_2 power cycle can be applied to convert the energy from solar power, nuclear reactor, fossil fuel, waste heat, fuel cell and geotherm. The driven force for these applications is the characteristics of S–CO_2 power cycle, namely high efficiency, compact size and dry cooling. The corresponding power range, highest cycle temperature and pressure of each application are summarized in Table 8.

For the application of S–CO_2 in solar power, the typical power capacity is in the range of 10–100 MW。 Due to the requirement of high cycle temperature, S–CO_2 cycle has to be integrated into the CSP technology, such as parabolic trough collector and tower collector. Nowadays, researches on solar driven S–CO_2 power cycle mainly focus on the system design and optimization. For example, Wang and He [54] presented a molten salt solar power tower system integrated with a S–CO_2 Brayton cycle. The integrated system consists of the heliostat field, the molten salt solar receiver, the molten salt thermal storage, and the S–CO_2 recompression Brayton cycle with reheating. In order to investigate the effects of some key thermodynamic parameters, the authors developed an integrated model. Meanwhile, a genetic algorithm (GA) was employed to optimize the parameters to obtain the highest overall exergy efficiency. Furthermore, Dunham and Iverson [55] analyzed thermodynamic performances of different cycles with Helium, CO_2 and water for CSP systems. It was found that when the temperature was above 600 °C, the highest thermal efficiency was obtained by S–CO_2 recompression cycle. On the other hand, according to the SunShot Program of United States, the cost of electricity is up to 10.3 Cents per KWh in 2017. However, when S–CO_2 cycle is applied to the CSP with more than 12 h of thermal storage, the electricity price is expected to drop to 5 Cents per KWh in 2030 [56].

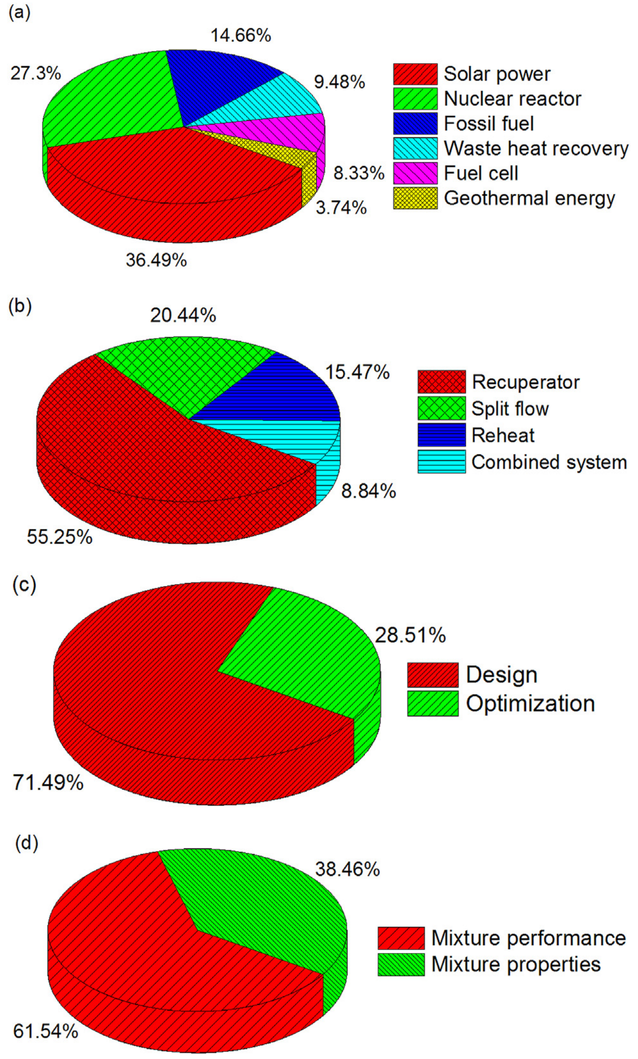

Fig. 8. Classification of the S–CO_2 core research areas and their relative distribution. (a) application of S–CO_2 cycle technology, (b) cycle structure of S–CO_2, (c) S–CO_2 system design and optimization, (d) CO_2-based mixtures and properties.

For the nuclear reactor, the Generation IV (Gen IV) reactor candidates such as Sodium-cooled Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR) and Gas-cooled Fast Reactor (GFR) are being developed. Compared with conventional water-cooled reactors, which operate around 300 °C, the operating temperatures of Gen IV reactors can reach up to 500 °C–900 °C [57]. At this high temperature range, S–CO_2 power cycle is widely considered to improve the next generation nuclear power plant performance and safety. So far, the related researches mainly focus on the theoretical

Table 8
Potential applications of S–CO_2 power cycle [52,53].

Application	Motivation	Power range (MW)	Highest cycle temperature (°C)	Highest pressure (MPa)
Solar power	Efficiency, size, dry cooling	10–100	500–1000	35
Nuclear reactor	Efficiency, size, water reduction	10–300	350–700	20–35
Fossil fuel	Efficiency, water reduction, CO_2 capture	300–600	550–1500	15–35
Waste heat recovery	Efficiency, size, simple structures	1–10	230–650	15–35
Fuel cell	Efficiency, size	–	600–1000	15–25
Geothermal energy	Efficiency	1–50	100–300	15

analysis. Liang et al. [58] compared the performance of S–CO_2 Brayton cycle coupled with various types of reactor system. The results indicated that the S–CO_2 power system was most suitable for GFR, SFR and LFR. Benjelloun et al. [59] developed thermodynamic and economic models of direct and indirect S–CO_2 recompression cycle to investigate the system performance. The results showed that compared with the indirect system, the capacity of the direct cycle increased by 13 MW. Besides, Ahn et al. [60] designed a S–CO_2 recompression cycle applied in SFR and analyzed the dynamic performance of S–CO_2 cycle with the partial load. It was found that when the load was less than 50%, the surge margin of main compressor would drop sharply.

As for the fossil fuel, various power plant vendors and operators are studying S–CO_2 cycle design for application to coal power plants [43,61]. Compared with the conventional power conversion system, innovative layouts of S–CO_2 cycle can achieve a high thermal efficiency as well as capture and store CO_2. On this basis, Bidkar et al. [62] investigated the 50 MW and 450 MW power plants with the employment of S–CO_2 power cycle. The study indicated that the intercooling and reheating processes could improve the thermal efficiency of the coal-fired plant. Moullec [43] evaluated the conceptual design of a S–CO_2 cycle integrated with post-combustion CO_2 capture process for a coal-fired power plant. The net plant efficiency of the overall system was 41.3%. On the other hand, when S–CO_2 cycle is used for coal-fired power plant, the increased flow rate causes extremely large boiler pressure drops, and the energy extraction of residual flue gas becomes difficult. Aiming at these issues, Xu et al. [63] proposed a partial flow strategy to yield boiler module design. Both flow rate and length for each module are cut to be half, reducing pressure drop to 1/8 of that with total flow mode.

For the waste heat recovery, the majority of researches still focus on theoretical analysis. Marchionni et al. [64] conducted a techno-economic comparison among several different S–CO_2 power cycles, such as simple recuperation, recompression, reheating cycles. The results proved that the simple recuperation S–CO_2 power cycle appeared to be the most suitable choice for the recovery of medium to high waste heat, because of its lower initial investment and acceptable performances. With the aim to recover the waste heat of shipboard, Yu et al. [65] proposed a combined system coupling CO_2 power cycle and refrigeration cycle to simultaneously produce power and cooling. Thermodynamic and economic models were developed to conduct energy, exergy and economic analysis. The obtained results indicated that the energy and exergy efficiencies of the proposed system were respectively 42.42% and 39.05% under design conditions. The corresponding average energy cost was 9.28 $/GJ. As for the experimental system, a 50 kW S–CO_2 testing facility for waste heat recovery has been designed at Brunel University London [66].

Nowadays, various types of fuel cell such as proton-exchange membrane fuel cell (PEMFC), molten-carbonate fuel cell (MCFC) and solid-oxide fuel cell (SOFC) have been designed and constructed. The corresponding temperature varies from 80 °C to 1000 °C [67]. For the high exhaust temperature of MCFC (600 °C–700 °C), it's a great opportunity to apply S–CO_2 cycle to utilize the exhaust heat. Thus, scholars focus on the integration of S–CO_2 with the MCFC. Bae et al. [68] compared the performance of MCFCs comprising with the S–CO_2 recompression cycle, the simple regenerative S–CO_2 cycle. The result indicated that the application of recompression cycle had better performance. Sanchez et al. [69] compared the performance of air Brayton cycle and S–CO_2 Brayton cycle applied to MCFCs. The results indicated that the efficiency of S–CO_2 cycle is increased by 11% than air cycle under the same turbine inlet temperature of 650 °C.

For the geothermal energy, the main advantage of adopting S–CO_2 cycle is to simplify the system structure and reduce the investment costs of power plant. At present, the main research is the theoretical analysis of S–CO_2 comprising geothermal energy. For instance, based on the cycle optimization to maximize the geothermal power output of overall system, Ruiz-Casanova et al. [70] compared the thermodynamic performance of four different S–CO_2 cycles. The results showed that the intercooling and recuperator cycle had the highest performance. The corresponding power output, energy and exergy efficiencies are 779.99 kW, 11.51%, and 52.49%, respectively.

From the above reviews, it can be found that although there are extensive researches on various applications of S–CO_2 power cycle, the existing researches mainly conduct the theoretical analysis of S–CO_2 cycle integrating with different heat sources. At the present stage, experimental systems are being designed for some applications. The corresponding progresses are still far from building the commercial S–CO_2 power plants.

4.2. Cycle configurations and modeling

In order to improve the cycle performance of S–CO_2 and avoid the temperature crossover in the recuperators, various system configurations have been developed. The derivation of most used configurations is shown in Fig. 9. Generally speaking, different cycle configurations are preferred for different specific applications. Several efforts have been made to compare the performance of various configurations in a specified application scenario [71]. For instance, Wang et al. [72] applied different S–CO_2 configurations into solar power tower systems. By calculating the efficiency, the specific work, and the temperature difference of molten salt across the solar receiver, performances were comprehensively compared for different S–CO_2 cycles. It was concluded that efficiency of the intercooling cycle was the highest. For the waste heat recovery, Manente and Fortuna [73] conducted a systematic comparison between traditional and novel layouts with dual expansion. The obtained results indicated that the cycle efficiency of the most advanced layout reaches 17.8%–28.5%, which is 5.8%–9.5% higher than the traditional layouts. In fact, the selected cycle configuration must be matched to heat sources, so as to achieve the highest thermal to electrical conversion efficiency in balance with economic objectives and operational, safety, and emission

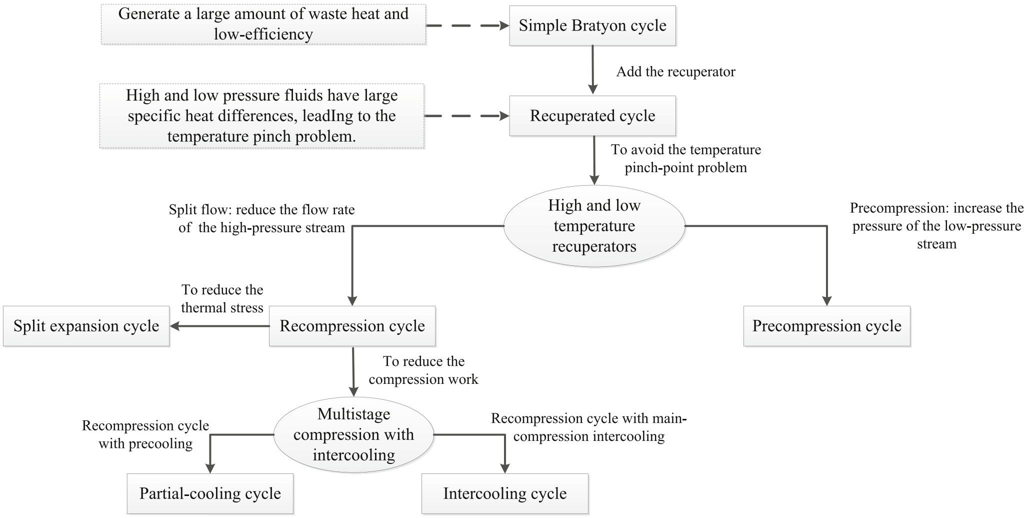

Fig. 9. Configuration derivation of typical S–CO_2 cycles [72].

requirements. The optimal cycle configurations are usually dependent on the maximum and minimum S–CO_2 temperatures, pressure ratio, type of heat source, energy storage requirements, splitting ratio, and economics. However, it should be noted that although there are numerous configurations of S–CO_2 cycle, there is still lack of systematic methodology to design and analyze S–CO_2 cycles driven by different heat sources under variable condition and transient operation.

Besides developing different cycle configurations of S–CO_2, constructing cogeneration systems is also a way to further improve the efficiency. Due to the fact that the outlet temperature of the recuperator is around 200 °C, a large amount of heat from S–CO_2 cycle can be utilized by adding a bottoming cycle. In general, the bottoming cycle can be transcritical CO_2 Brayton cycle [74–78], ORC [49,79–81], Kalina cycle [82], and organic flash cycle [83]. The corresponding schematic diagrams and T-s charts of the four cogeneration systems have been summarized and compared by Liu et al. [4]. It's thought that the bottoming cycle can greatly reduce the heat sink temperature, and the cogeneration system can generate more power with less fuel. At present, the researches on the cogeneration system are in the stage of conceptual design and theoretical analysis. Before commercialization, more works are required to investigate the component design and manufacture, the system operation and control in the future.

In order to analyze the performance of S–CO_2 cycle, thermodynamic models have been widely established under certain assumptions. For the energy model, it's based on the first law of thermodynamics. In the system model, component models are usually required to determine the involved work and heat. Although there are various configurations of S–CO_2 cycle, the basic components generally consist of compressor, turbine, heater, recuperator and gas-cooler. For the compressor and turbine, a simple isentropic efficiency model is used to characterize the component performance [46,84,85]. As for the recuperator, it's usually assumed as a counter-flow heat exchanger. The recuperator can be modeled by an effectiveness or conductance. Both models discretize the heat exchanger to account for the variation of physical properties and solve for the conditions that result in the specified effectiveness or conductance [86]. Furthermore, in the effectiveness model, a minimum temperature difference is also enforced to constrain the performance of the recuperator by imposing "realistic" physical bounds [87,88]. On the other hand, for the heater and gas-cooler, pinch point models are always applied to determine the minimum temperature differences of heat exchangers. After finishing the energy analysis of S–CO_2 cycle, the exergy analysis is followed based on the second law. By accurately quantifying the entropy generation of each component, the exergy analysis can predict the irreversibility of the component level, and help to find the critical components, causes and locations of thermodynamic losses as well as the optimum operating conditions, so as to maximize the output work [54,89–91]. For these two models, the used equations have been summarized in Ref. [4].

Besides the employment of thermodynamic models, the exergoeconomic model is also used to calculate the exergy cost per unit flow by revealing the cost formation process based on the exergy analysis and economic analyses on the system components. Cost indicators such as the levelized cost of energy (LCOE) [88,92,93], the capital cost per net power (CCPP) [94] and the total cost (sum of capital investment cost, total exergy destruction cost and environmental impact cost) [95] are determined for different S–CO_2 cycles. On the other hand, in order to obtain a higher efficiency at a lower cost, key cycle parameters such as the turbine inlet temperature, the compressor inlet pressure and the pinch temperature difference of heat exchanger are usually optimized. The optimization method includes GA, non-dominated sorting genetic algorithm II (NSGA-II), direct search (DS), and golden-selection search (GSS) [4]. However, it should be noted that the above models belong to static analysis on the S–CO_2 power cycle. Dynamic models for components and overall system are being developed under off-design condition. Thereafter, control strategy needs to be proposed to keep the high-efficient and safety operation of S–CO_2 system.

4.3. CO_2-based mixtures

Besides configuring different structures for S–CO_2 power cycle, another way to improve the cycle performance is to use the CO_2-based mixture as working fluid. Compared with the pure fluid, the CO_2-based mixture can adjust the critical point of CO_2 by adding different gases. The direction and range of the critical point variation of CO_2 depend on the mixed component and its amount. So far, a few researches have been conducted to discuss the feasibility and performance of the supercritical CO_2-based mixture power cycle [96–105]. For example, Sandia National Laboratories performed experimental tests on the compatibility of CO_2 mixtures with the turbomachinery and the compressor operation in the supercritical region of mixtures [96]. Jeong et al. [101,102] developed a supercritical cycle model, based on the mixture properties. They investigated the performance of a supercritical CO_2-based mixture cycle, which was applied to the power conversion of SFR. It was found that the mixtures of CO_2—He, CO_2-Xe and CO_2-Kr had an increase in the total cycle efficiency, when the inlet temperature of main compressor is 1 K above the critical temperature of mixtures. Thereafter, Hu et al. [99] analyzed the performance of a nuclear reactor integrated with the CO_2-based mixture cycle. The obtained results indicated that the adoption of CO_2—He and CO_2-Kr could increase the cycle efficiency and decrease the amounts of heat transfer in the heat temperature recuperator and low temperature recuperator. Guo et al. [104] analyzed the thermodynamic performance of four different Brayton cycles using CO_2 mixtures in the molten salt solar power tower systems. The used mixtures were CO_2-Xe (0.7/0.3) and CO_2-butane (0.95/0.05). From the obtained results, it can be concluded that adding xenon into S—CO_2 cycle could obviously improve the overall thermal efficiency and exergy efficiency, while the effects of butane as an additive were converse. Furthermore, Yu et al. [100] comprehensively compared recompression cycle performances of seven mixtures (CO_2-Xe, CO_2-Kr, CO_2—O_2, CO_2-Ar, CO_2—N_2, CO_2-Ne, CO_2—He) at different CO_2 mass fractions. The results showed that the performance order of mixtures generally coincides with the descending or ascending order of corresponding critical temperatures. On the other hand, in engineering application of Brayton cycle, S—CO_2 will be inevitably mixed with the gas impurities. Therefore, Vesely et al. [97] investigated the effect of gaseous admixtures on the cycle efficiency at a fixed inlet temperature of main compressor. They found that all researched mixtures except CO_2—H_2S had negative effects on the cycle efficiency and net power output. Thereafter, they examined the effect of different impurity compositions on the performance of various cycle components at different inlet temperatures of main compressor [98].

From the above reviews on CO_2-based mixtures, it can be seen that the existing researches mainly focus on the thermodynamic cycle analysis of CO_2-based mixture. Few researches are conducted to investigate the CO_2-based mixtures by simultaneously considering the thermodynamic performance, economy, heat transfer and so on. Besides, in the existing researches, the required properties of mixtures are from the REFPROP calculation. However, due to the lack of experimental data on some mixtures in the range of cycle temperature, the corresponding accuracy of REFPROP calculation can't be guaranteed. More researches are required to obtain the accurate properties of CO_2-based mixtures in the future work.

4.4. System components

The components of S—CO_2 power system mainly include the turbine, compressor and heat exchanger. The performances of these components are strongly related with the efficiency, safety and operation of S—CO_2 cycle. Thus, the current developments of main components are briefly reviewed here. In the turbine, S—CO_2 expands and converts heat energy into mechanical energy through a series of moving blades. Based on the flow direction of working fluid, turbines can be classified into two types of axial flow and radial flow. The radial flow turbine is further divided into centripetal one and centrifugal one. In general, a turbine is primarily designed by one-dimensional aerodynamic calculation. The corresponding internal flow is then analyzed by three-dimensional (3D) numerical simulation. The related researches have been summarized by Liu et al. [4]. As for the experimental study, turbines have been designed and constructed in the testing systems [106—109]. From the tested turbines and results, it can be found that the axial turbine and centripetal turbine are mostly used. The capacity mainly ranges from 0.5 W to 10 MW, and the rotational speed of the centripetal turbine is the largest within the range of 70000—200000 RPM. Although successful experiments of small-scale S—CO_2 turbines have been achieved, there still exist issues for the development of large-scale turbines. The most common challenges are rotor dynamics, pressure containment, sealing, and transient/off-design operation.

As another turbomachinery, the compressor raises the pressure of S—CO_2 near the critical point. Similarly, there exist axial flow and radial flow compressors, where the radial flow can be classified into centrifugal and centripetal compressors. For the theoretical researches, one-dimensional aerodynamic design, 3D numerical simulation and the loss model are usually employed to analyze the S—CO_2 compression in a compressor [110—112]. Besides, since CO_2 is compressed near the region slight above the critical temperature, a vapor-liquid two-phase flow is easily to occur in the compressor under off-design conditions. In order to describe and validate the two-phase thermodynamic region, numerical simulations have been widely employed [113,114]. Through the simulations, a non-dimensional criterion was established to assess the two-phase flow phenomenon and stability of S—CO_2 centrifugal compressors [115]. As for the experiments, several institutes have constructed and tested different compressors [116—119].The rotation rate, pressure, temperature and flow resistance of the test system are usually recorded. The detailed parameters for the existing experiments on compressors have been summarized by Liu et al. [4]. It was found that most of test compressors belong to the centrifugal compressor, which has the highest isentropic efficiency 84%. The corresponding rotate speed ranges from 45000 to 100000 RPM. The minimum operating temperature and pressure are 32 °C and 7.69 MPa, respectively. Being similar with the turbine, the compressor also faces the challenges of pressure containment and sealing. Besides, for the high-temperature recompressor in the recompression cycle, few researches have been conducted under the operation conditions of recompressor.

As the key component of S—CO_2 cycle, the heat exchanger is responsible for the absorbed and released heat. According to the component functions, the used heat exchangers can be categorized into heater, recuperator and gas-cooler. In order to guarantee the high efficiency and safe operation of S—CO_2 system, the employed heat exchangers should have high performance and reliable mechanical characteristics at operation pressures and temperatures. Due to the fact that the involved heat of recuperator is much higher than those of heater and gas-cooler, the existing researches mainly focus on the recuperator. As one of the compact heat exchangers, the printed circuit heat exchanger (PCHE) is a potential regenerator because of its high heat transfer area and volume ratio. So far, numerous researches have been conducted to investigate the heat transfer of PCHE [120—122]. In general, PCHE is characterized by shapes, cross-sections and structures of the flow channel. Based on the developed semi-empirical models and numerical simulations, different types of PCHE channels have been proposed to enhance heat transfer and reduce pressure drop. Meanwhile, in order to validate the performance of PCHE, experiments have been conducted. The detailed information on the employed PCHE and the operating conditions were provided in Ref. [4]. As for the heater and gas-cooler, the used type of heat exchanger is closely related with the heat source and sink [19,123—125]. The corresponding performance of heat exchanger is not only related with the structure type, but also strongly dependent on the heat transfer fluids. In terms of S—CO_2, there are no general correlations of heat transfer coefficients suitable for the wide ranges of system operation [126,127]. At present, the empirical heat transfer correlations are suitable for ones' own data, but are difficult to be extended beyond the parameters range.

4.5. Experiments

The purpose of the experimental study is to make a demonstration on the steady-state and frequent transient operation of S—CO_2 power system. The obtained experimental results can provide a guide for the commercialization. Compared with the extensive theoretical researches of S—CO_2 cycle, the experimental investigations are less, due to the manufacturing difficulties of the system components and the high temperature and high pressure of the system operation. So far, there exist about ten test loops of S—CO_2 power cycle around the world. These experimental systems were mainly developed in the United States, Korea, Japan and China. The corresponding institutes are Sandia National Lab [128,129], Southwest Research Institute [130,131], Echogen [108], GE [62], Net Power [132,133], Korea Institute of Energy Research [134,135], Tokyo Institute of Technology [136] and North China Electric Power University [137]. As for the parameters and configurations of the established S—CO_2 systems, the interest readers are referred to the previous reviews [4,20,30,31]. In general, the existing experiments mainly employ simple recuperated cycle and recompression cycle. The power capacity ranges from 1 kW to 250 kW, which belong to small-scale test loop. This small test loop usually has a lower efficiency, and sometimes the output parameters are lower than the designed values. Furthermore, Problems related to small-scale turbomachines may not occur for large-scale turbomachines.

4.6. Future development

In order to promote the research on S—CO_2 system, a series of large projects funded by governments are being conducted by different institutes, as summarized in Table 9. From the table, it can be seen that these projects mainly concern the applications of S—CO_2 in solar energy, nuclear reactor and fossil fuel. Although great progresses have been made on the development of S—CO_2 cycle technology during the past two decades, there is still a long way for the applications of S—CO_2 cycles in commercial power plants. The missions of these projects involve developing the key system components, revealing the energy conversion mechanism, and establishing the large-scale experiments. The ultimate targets are to establish successful commercialization of the S—CO_2 cycle with high efficiency.

After reviewing the existing researches and projects, the future development work of S—CO_2 cycle should focus on the following aspects:

(1) Since there is no fixed S—CO_2 cycle that can be suitable for all the heat sources, how to design an efficient cycle configuration for a given heat source is still an open question. Thus, based on the characteristics of different heat sources, a systematic methodology should be proposed to design and analyze S—CO_2 cycles. Besides the stable modeling under design conditions, transient models should be developed to investigate the dynamic behaviors of S—CO_2 system under variable conditions.
(2) Due to the fact that S—CO_2 will be inevitably mixed with the gas impurities in engineering, it's a must to consider these mixtures carefully. Meanwhile, the cycle performance of CO_2-based mixtures should be evaluated comprehensively. Furthermore, in order to guarantee the accuracy of thermodynamic calculation, accurate mixture properties have to be obtained and modeled in the future work.
(3) For the used turbomachinery, much effort should be paid to design and improve the bearings and seals to prevent leakage. Theoretical and experimental researches are required for the large-scale turbomachinery. As for the heat exchangers, general heat transfer correlations should be developed by expanding experimental database covering wide parameters range including pressures, temperatures, heat fluxes and structures of heat exchanger.
(4) Before commercialization, more experiments are required to investigate the performance and system operations of large-

Table 9
State-led projects of S—CO_2 power cycle.

Project	Starting Year	Main institute	Founding source	Target
Sunshot [138]	2011	Sandia National Lab; the Office of Nuclear Energy	Department of Energy, USA	To ensure component readiness for the successful launch of S—CO_2 Cycle; To support the development of a re-configurable and scalable system, allowing the testing of commercially attractive configurations and system components; To establish the foundations for successful commercialization of the S—CO_2 cycle
A Supercritical CO_2—Cooled Small Modular Reactor [139]	2014	the Korea Advanced Institute of Science and Technology	–	To design the reactor core and S—CO_2 power generation system in one vessel; To validate the performances of PCHE and radial turbomachinery; To investigate the dynamic behaviors and design the reactor control
Research on basic theory and key technology of coal-fired S—CO_2 power generation [140]	2018	North China Electric Power University; Xi'an Jiaotong University	Ministry of Science and Technology of China	To solve the energy cascade utilization, thermodynamic cycle optimization of coal-fired S—CO_2 power system; To investigate the energy and mass conversion and transfer mechanism of key cycle components; To develop prototypes of boiler, recuperator and turbine and design a 1000 MW system with efficiency 51%
10-MW Supercritical Carbon Dioxide Demonstration [141]	2019	Southwest Research Institute; the Gas Technology Institute; GE company	Department of Energy, USA	To demonstrate the scalability of S—CO_2 system, and its performance ability; To develop a megawatt-scale, high-efficiency S—CO_2 hot-gas turbo-expander; To optimize recuperator technology for S—CO_2 applications
SCARABEUS [142]	2019	Politecnico di Milano; Vienna University of Technology; The University of Seville	European Union's Horizon research	To demonstrate the application of CO_2-based mixtures to CSP plants; To investigate the thermal stability of the new working fluid at 700 °C for 300 h in real working conditions; To demonstrate the feasibility of the condensation process performed at high (up to 60 °C) ambient temperature

scale $S-CO_2$ power cycle. Meanwhile, aiming at different application scenario, control strategies have to be studied and proposed to assure the efficiency and safety of $S-CO_2$ system under off-design conditions.

5. Concluding remarks

In this work, the development of supercritical CO_2 ($S-CO_2$) Brayton cycle is presented through the bibliometric analysis and research review. Based on the Scopus, scientific publications on the $S-CO_2$ Brayton cycle were analyzed using Bibexcel. It was found that there were 724 papers from 543 institutes and 55 countries during 2000–2019. According to the statistic results of existing publications, United States has become the leading country in this field, followed by China and South Korea. Besides, on the basis of article numbers, the most productive journal, author, and institution were respectively identified as Proceedings of the ASME Turbo Expo, Lee J.I, and Xi'an Jiaotong University. The existing publications were mostly completed by three or four authors. On average, 3.8 authors, 1.7 institutes, and 1.2 countries have participated in each publication. Generally, the researches on $S-CO_2$ Brayton cycle consist of four areas, namely applications of $S-CO_2$ cycle technology, cycle structure of $S-CO_2$, $S-CO_2$ system design and optimization and CO_2-based mixtures. The application of $S-CO_2$ technology occupies the largest share of total articles (48.71%), while only 8.72% of the publications focus on the CO_2-based mixtures.

For the research review, the status of $S-CO_2$ cycle is analyzed from five aspects, namely applications of $S-CO_2$ cycle, cycle configurations and modeling, CO_2-based mixtures, system components and experiments. It's found that most of researches are in the stage of theoretical investigation. So far, there exist only around ten experimental small-scale $S-CO_2$ systems around the world. After analyzing the $S-CO_2$ researches, it's suggested that a systematic methodology to design and investigate $S-CO_2$ cycles should be proposed for different heat sources. Much attention needs to be paid to cycle performance and physical properties of CO_2-based mixtures. Furthermore, it's necessary to clarify the heat transfer mechanism of $S-CO_2$ and improve the bearings and seals of turbomachinery. More experiments are required to investigate the performance and system operations of large-scale $S-CO_2$ power cycle under off-design conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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