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Review Article

Innovative power generation systems using supercritical CO_2 cycles

Qian Zhu*

The IEA Clean Coal Centre, 176 Upper Richmond Rd, London SW15 2SH, UK

*Corresponding author. E-mail: qian.zhu@iea-coal.org

Abstract

Supercritical carbon dioxide (sCO_2) power cycle is an innovative concept for converting thermal energy to electrical energy. It uses sCO_2 as the working fluid medium in a closed or semi-closed Brayton thermodynamic cycle. The sCO_2 power cycles have several benefits such as high cycle efficiency, small equipment size and plant footprint (and therefore lower capital cost) and the potential for full carbon capture. Achieving the full benefits of the sCO_2 cycle depends on overcoming a number of engineering and materials science challenges that impact both the technical feasibility of the cycle and its economic viability. For example, the design and construction methods of turbomachinery, recuperator and high-pressure oxy-combustor pose significant technical challenges. Other R&D needs include material selection and testing, and optimized power cycle configuration. Over the years, particularly in the last decade, R&D efforts have been growing worldwide to develop sCO_2 cycle technologies for power generation. Significant progress has been made in developing sCO_2 cycle power systems. Some small, low-temperature sCO_2 Brayton cycle power systems are starting to emerge in the commercial market, and a natural gas-fired demonstration power plant using a sCO_2 cycle called the Allam Cycle is under construction. This article describes the sCO_2 cycles for applications in power generation from fossil fuels and reviews the recent developments in sCO_2 power cycle technologies.

Key words: supercritical CO_2 cycle; Brayton cycle; power generation; energy efficiency; CO_2 capture

Introduction

Supercritical carbon dioxide (sCO_2) power cycle uses sCO_2 as the working fluid medium in a Brayton thermodynamic cycle. The Brayton cycle is the same cycle run by natural gas turbines. In an sCO_2 Brayton cycle, the CO_2 is kept at supercritical conditions throughout the cycle. Therefore, unlike a Rankine cycle, a Brayton cycle operates in a single phase and no condensation or phase change occurs. sCO_2 has many unique properties that make it an ideal working fluid. CO_2 is non-explosive, non-flammable, non-toxic, thermally stable and readily available at low cost. CO_2 has a relatively low critical pressure of 7.4 MPa and critical temperature of 31°C. Consequently, CO_2 can be compressed directly to supercritical pressures and heated to supercritical state at moderate conditions. In a heat engine, this can facilitate obtaining a good thermal match with the heat source in a wide temperature range such as high-temperature fossil fuel combustion and low-temperature geothermal energy. On the other hand, the critical temperature is not too low to make it difficult to cool the working fluid sufficiently because of the lower limit set by the terrestrial ambient temperature. Therefore, an sCO_2 Brayton cycle has a great potential for high efficiency since a large temperature difference is available and it is compatible with air cooling. CO_2 near its critical point becomes more incompressible, and hence, the compression work can be decreased substantially leading to high cycle efficiency. In its supercritical state, CO_2 is also nearly twice

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as dense as steam. The high density and volumetric heat capacity of sCO_2 with respect to other working fluids make it more energy dense. Consequently, the size of all the system components such as the turbine and heat exchangers can be considerably reduced, which leads to a smaller plant footprint. An sCO_2 cycle operates in a single phase, reducing the complexity of the system. As a result, an sCO_2 power cycle could require lower capital investments, lower operation and maintenance costs and therefore result in cheaper electricity.

There are two types of Brayton cycles: the open cycle that is heated directly using a combustor and the closed cycle that is heated indirectly using a heat exchanger (or heater). In the closed cycle, working fluid is circulated in a closed loop and is heated indirectly with an external heat source, similar to the operation of a steam Rankine cycle. Gas turbines usually operate on an open cycle in which the fuel gas and air mixture enter the compressor at the beginning. Heat is generated by combustion of fuel gas in air and the combustion gas leaving the turbine is discharged. The sCO_2 power cycle operates in a manner similar to other turbine cycles, but it uses CO_2 as the working fluid in the turbomachinery. Two primary approaches to electricity generation power cycles using sCO_2 as the working fluid have been investigated: indirectly heated, closed-loop sCO_2 cycle and semi-closed, directly fired, oxy-fuel cycle. In a simple closed-loop Brayton cycle, CO_2 (the working fluid) is heated indirectly from a heat source through a heat exchanger (heater), similar to the way steam would be heated in a conventional boiler. Energy is extracted from the CO_2 as it is expanded in the turbine. The CO_2 exiting the turbine is then cooled in a heat exchanger (cooler) to the desired compressor inlet temperature. After compression to the required pressure, the CO_2 is sent back to the heater to complete the cycle. In an improved version of the simple cycle, a recuperator is added between the turbine exhaust

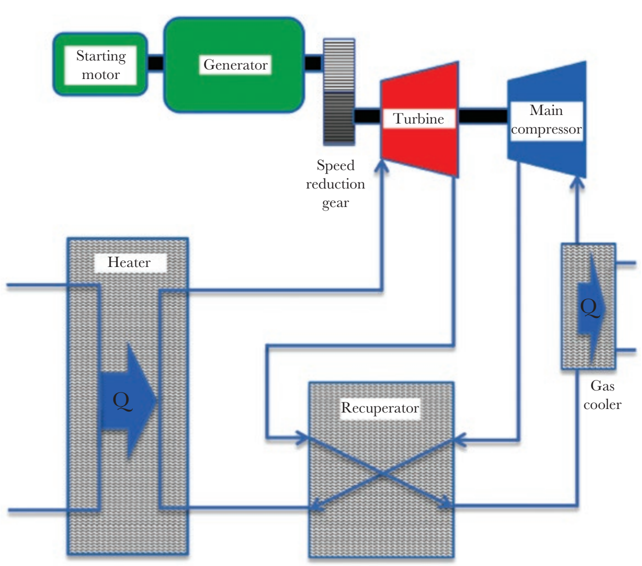

Fig. 1 A recuperated closed Brayton cycle [1]

and the compressor exhaust as shown in Fig. 1. Introducing a recuperator in the cycle improves the cycle efficiency because a portion of the sensible heat in the turbine exhaust is recuperated and used to preheat the working fluid prior to entering the heat source and therefore, reduces the amount of heat loss in the CO_2 cooler. For high-temperature applications, a recompression sCO_2 cycle is generally selected. Fig. 2 shows a recompression cycle. The differences between the recompression and recuperated cycle lie downstream of point H. In the recompression cycle configuration, the low-pressure CO_2 stream exiting the recuperator is split into two. One portion is cooled in the CO_2 cooler and is then compressed in the main compressor before being heated in the low-temperature recuperator. The other stream bypasses the CO_2 cooler and is compressed in the re-compressor to the maximum cycle pressure. It is then mixed with the stream exiting the low-temperature recuperator and the mixture passes through a high-temperature recuperator and the CO_2 heater. With this cycle layout, the heat capacity between the hot and cold sides of the recuperator is better matched and hence, the overall efficiency of the recuperator is improved. It is claimed that at the optimal pressure ratio for maximum cycle efficiency, the efficiency of the recompression cycle is over 5% points higher than the recuperated cycle [1]. There are many other variations of indirectly heated, closed sCO_2 power cycles using different compression, reheating and other cycle configurations such as pre-compression, intercooling and split expansion to increase the efficiency of the cycle or to adapt to particular applications. However, it may be that the optimum cycle configuration for power generation has not yet been identified.

Fig. 3 shows the configuration of a directly heated oxy-fuel combustion sCO_2 cycle proposed by US DOE's NETL [2]. Fuel is burned in relatively pure and near stoichiometric oxygen in the combustor, and the resulting stream that contains mainly CO_2 and H_2O is used to drive the turbine. The remaining heat in the stream exiting the turbine is recuperated, and the stream is then further cooled to condense the water out, leaving a stream of high concentration CO_2. A portion of the CO_2 is compressed to the desired pressure. The cooled and compressed CO_2 passes through the recuperator to be preheated, and it is then recycled back to the combustor as combustion diluent. The remainder of the CO_2 is ready to be compressed for storage.

The range of potential applications for the indirectly heated, closed sCO_2 cycle is broad since it can be used in essentially any application that currently uses a Rankine cycle including nuclear, solar, thermal power, geothermal, waste heat and fossil fuel combustion. Semi-closed, directly fired, oxy-fuel Brayton cycles are well suited to natural gas or coal-derived syngas oxy-combustion applications and have the additional benefit of facilitating CO_2 capture. Semi-closed, directly fired oxy-fuel sCO_2 cycles can potentially achieve significantly higher cycle efficiencies than the indirectly heated cycles as a much higher turbine inlet temperature can be attained in a directly fired cycle.

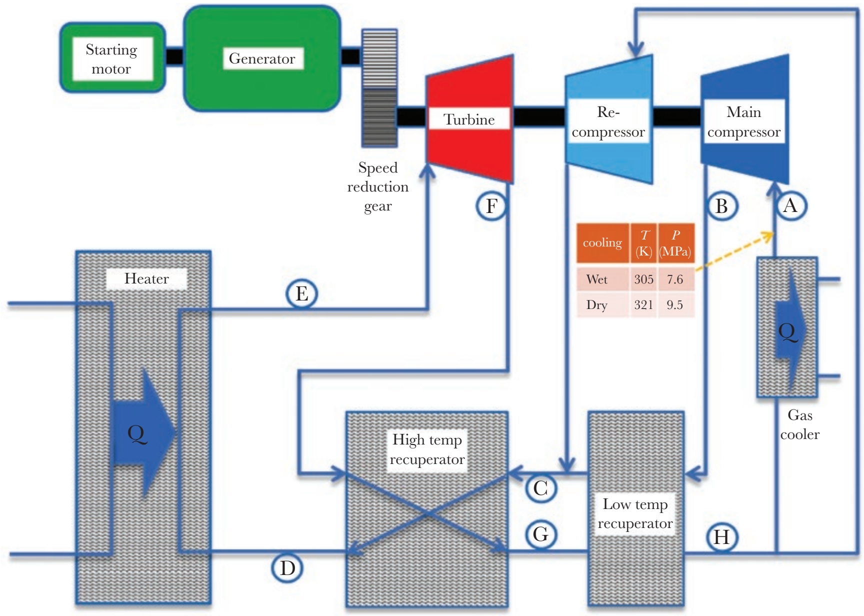

Fig. 2 A recuperated, recompression closed Brayton cycle [1]

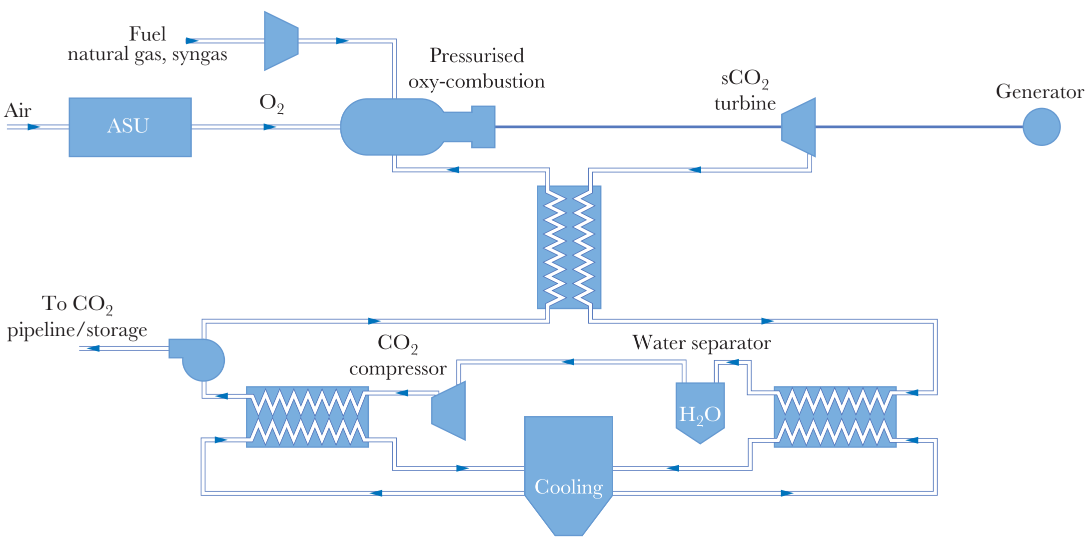

Fig. 3 A potential configuration of a directly heated oxy-fuel combustion sCO_2 cycle [2]

1 Technical challenges

Components used in sCO_2 power cycles are radically different from those used in steam Rankine and gas Brayton cycles, but they are considered to be well within the capabilities of existing engineering and manufacturing processes. In general, components such as power generation subsystem, heat rejection subsystem, plant control systems and instrumentation are considered mature technologies. However, the development of control methods and design optimization of these components for a given application may be required. Equipment for compression and pumping of sCO_2 is already used in the oil and gas industry for other applications, and so the compression technology required for the sCO_2 cycle is considered mature and presents little risk. However, several aspects of the sCO_2 cycle still require significant R&D. For example, although the fundamentals of, and engineering tools for, turbine design are mature and reliable, there is limited operational experience of sCO_2 power turbines and associated turbomachinery at any scale or under conditions relevant to commercial operation. The high density, high pressure and rapidly changing properties of CO_2 near the critical point, such as density, viscosity and acoustic properties, represent a relatively new and different regime for turbomachinery design. Particular challenges include materials and coatings, seals, bearings, corrosion, erosion and blade cooling, especially in applications with an elevated turbine inlet temperature.

Another major technical challenge in the development of sCO_2 power cycles is the designs of low-cost and compact recuperators. Recuperator designs must account for high temperatures and high pressures (with inlet temperature in excess of 700°C and pressure up to 30 MPa) as well as high-pressure differentials between streams. A major constraint is to design a heat exchanger with minimal pressure drop across the system while pursuing effective high heat transfer. Due to the heavy heat duty required, compact heat exchangers (CHE) are selected for recuperators because of their relatively high surface area to volume ratio (typically >700 m^2/m^3). Work is needed to develop and improve the designs and metallurgical and fabrication processes in a cost-effective manner. Some specific issues for directly fired systems also need to be addressed, such as corrosion and erosion due to the presence of water and other pollutants from the combustion products [1, 3].

Perhaps a more significant challenge is developing the oxy-combustor for high-pressure operation. A directly fired sCO_2 combustor resembles a conventional gas turbine combustor, but the pressure will be much higher than in conventional gas turbines. With pressures of the order of 30 MPa and high energy densities, issues such as injector design, wall heat transfer and combustion dynamics will play a challenging role in combustor design for which there is little current experience. Tests and computer modelling are needed to develop oxy-combustor designs for natural gas and syngas (from coal gasification) that ensure complete combustion and uniform wall temperatures and minimize hot spots in the combustor [1, 4].

Material selection for components such as turbines and heat exchangers is challenging as they are exposed to sCO_2 at high temperature and pressure, and materials have not commonly been tested under these conditions. The temperature and pressure can be up to 700°C and 30 MPa, respectively, for the proposed indirectly heated, closed sCO_2 power cycles and 1150°C and 30 MPa for directly fired, semi-closed sCO_2 power cycles. The effects of material interactions with sCO_2 under particular operating conditions and environments with respect to specific applications can affect the design, reliability and lifetime of essentially all system components. Uncertainties about materials reliability include carburization and sensitization, high-temperature corrosion, erosion, creep and thermal fatigue. While pure, dry CO_2 is virtually inert at temperatures of <500°C, previous studies have shown corrosion and internal carburization of steels and nickel alloys occurred in CO_2 environments at high temperatures, particularly in the presence of even small quantities of water (ppm levels) and/or other contaminants [5–7]. R&D is needed on the long-term corrosion and carburization behaviour and maximum use temperature of these alloys to identify degradation mechanisms and to predict the useful life. For directly fired, semi-closed sCO_2 cycles, the impurities such as H_2O, O_2 and SO_x resulted from combustion of fuel will present in the working fluid and may affect corrosion rates, and thus, oxidation/corrosion data in these conditions are needed.

Other R&D needs include identifying the optimum cycle configuration and design, system integration and new control methods. Fundamental studies, computer modelling and assessment of the performance and cost of the sCO_2 cycles and individual components are also essential.

2 Recent developments

2.1 Turbomachinery

Over the years and particularly in the last decade, there have been increasing R&D efforts worldwide on sCO_2 power cycles. There have been a large number of R&D programmes in which many companies, universities and research institutes have participated to develop sCO_2 cycle technologies for power generation. Several small-scale closed-loop sCO_2 test facilities (up to 1 MW in size) have been built, and tests are conducted to determine the feasibility of sCO_2 power conversion systems and the performance of turbomachinery components and heat exchanger [8–13]. The designs and fabrication of laboratory-scale sCO_2 turbomachinery including the bearings, seals and alternator have been developed and validated. The sCO_2 turbines and compressors have performed close to the design value and have operated effectively above and below the critical temperature [8–13]. Therefore, it is anticipated that there will not be major surprises in the turbomachinery design and operating efficiency as the technology is scaled up to higher power levels.

In October 2016, the US DOE awarded up to US$80 million for a 6-year project to design, build and operate a 10-MWe sCO_2 pilot test facility. The test facility is scheduled to be operational in 2020, and the project participants include the Gas Technology Institute (project lead), the Southwest Research Institute (SWRI) and General Electric Global Research (GE-GR). GE-GR has been working on the turbomachinery design and fabrication. Following detailed studies and analyses of the system-level impacts of each configuration, the researchers at GE-GR identified the best design to be pursued. The studies included detailed aero-design, generator selection, gearbox selection, compressor wheel selection (off-the-shelf), sealing system designs, rotor-dynamics and bearing designs for each design as well as overall costs. A second option has been selected as a back-up, which has not only a significantly lower technical risk but also lower scores on the criteria list. The design team primarily focused on the axial turbine design with shaft speed, mass flow rate, leakage requirements and efficiency targets as boundary conditions [14]. The complete design of the 10-MWe high-pressure, high-temperature sCO_2 turbine is shown in Fig. 4.

Since 2012, Toshiba (Japan) has been developing an sCO_2 turbine and combustor for NET Power's Allam Cycle demonstration plant. The Allam Cycle is a semi-closed, recuperated, oxy-combustion trans-critical sCO_2 power cycle. The design essentially combines gas turbine and steam turbine technologies. The turbine has an inlet pressure of 30 MPa and an inlet temperature range of 1100–1200°C. This turbine inlet temperature is not high for gas turbines, but it is very high for steam turbines. Similarly, the pressure of this

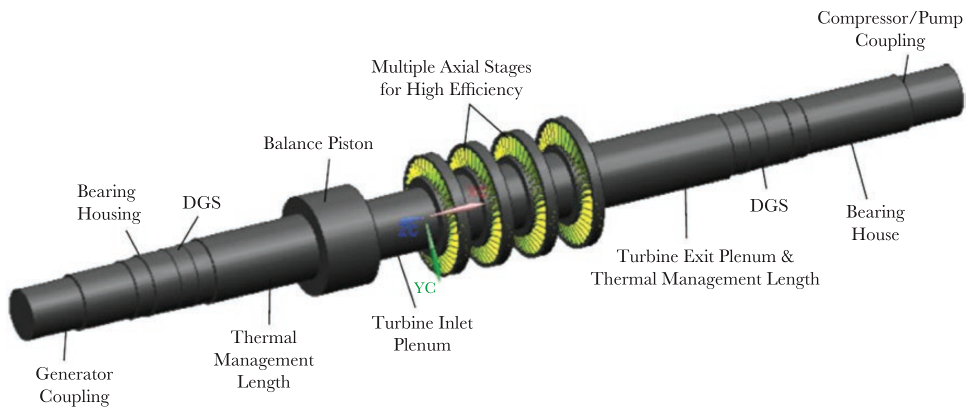

Fig. 4 The 10-MWe high-pressure, high-temperature sCO_2 turbine design by GE-GR [14]

cycle does not surpass that of advanced steam turbines, but it is extremely high for gas turbines. The sCO_2 turbine operates at a low-pressure ratio (between 6 and 12), and the pressure at the turbine exit is 3 MPa. Therefore, only a single high pressure (HP) turbine is needed compared to a steam turbine that consists of HP, intermediate pressure (IP) and low pressure (LP) sections. To cope with the high turbine inlet temperature, cooling designs and thermal barrier coatings adopted from gas turbine technology were used. Toshiba, in cooperation with NET Power, has also developed a proprietary turbine control system [15, 16]. This turbine was built and delivered to the construction site of the demonstration plant in November 2016. The turbomachinery and key sub-components such as seals, bearings, rotors and shafts for application in sCO_2 power cycles are also being developed and tested by other companies and research institutes around the world.

2.2 Heat exchangers

Several types of CHE are developed for operating in high-temperature, high-pressure petroleum and chemical processes, and some innovative CHE designs are identified as good candidates and are being investigated for use in sCO_2 power cycles. The Printed Circuit Heat Exchanger (PCHE) has been in operation in very high-pressure oil, gas and chemical processes for decades, and it has been the most widely used recuperative type of heat exchanger for testing sCO_2 power cycle development. They are able to withstand pressures of over 60 MPa, and temperatures ranging from cryogenic to 900°C with close temperature approach (www.heatric.com). PCHEs are plate-type CHE in which flow channels are chemically etched into thin, flat metal plates. The etched plates are stacked together with a prescribed arrangement configuration and diffusion bonded to create a high-integrity solid block. Headers, nozzles and flanges welded to the block constitute the whole of the heat exchanger. PCHEs can adopt various configurations taking advantages of the etching and diffusion bonding process to create geometries for optimal performance for a given application [17]. PCHEs are used in SNL's sCO_2 test loop for the cooler and recuperators applications and in Echogen's EPS100 heat engine as well as in NET Power's Allam Cycle demonstration power plant. While robust PCHE can be produced for sCO_2 recuperator applications, this type of heat exchanger (HE) is expensive. Also, it has been reported that a typical PCHE could fail in 300–800 complete thermal cycles or fail closer to 200 cycles if operating under severe thermal transient conditions [18]. Work is ongoing to understand how to design for, and how to predict, thermal fatigue in these units and to improve designs and fabrication methods of PCHE to optimize efficiency and reduce cost.

Another CHE under development is the plate-fin heat exchanger (PFHE). The traditional brazed PFHEs have been widely used as gas turbine recuperators and have proved their integrity in the extreme environment of a gas turbine. They can withstand high-temperature and high-temperature differentials (higher than those of sCO_2 cycles), rapid thermal transients but moderately high pressures and moderate differential pressures (<1.5 MPa). PFHE can be made with relatively large channels to provide a low pressure drop in viscous fluids like liquid sodium [19]. In the last decade, extensive development of recuperators for advanced nuclear reactors and helium Brayton cycles projects have resulted in an expanded design for higher pressures and pressure differentials.

A different plate-fin design approach has been taken, which can adapt both brazed and diffusion bonding methods. This concept is being considered for application in the sCO_2 power cycle and for the sCO_2 heaters. A conceptual design for these applications has been developed [19], but it needs to be tested and verified.

Funded by the US DOE under the SunShot Initiative, Brayton Energy has developed a design of an sCO_2 solar receiver for use in a 10-MWe concentrated solar power recompression sCO_2 cycle. The receiver design incorporates several innovative and unique characteristics such as a cell with a dense matrix of extended heat-transfer surfaces in the form of densely packed folded fins brazed within an external shell. The high-density folded fins encapsulated in a hermetic boundary surface also provide tensile structural support to the high-pressure working fluid. The sCO_2 receiver is designed to operate under conditions of 25 MPa pressure, an outlet temperature of 750°C and an efficiency of 54% [20]. Brayton Energy has been working to develop a manufacturing plan for producing the required absorber cells and receiver components that are robust, reliable, repeatable and cost-effective.

Other types of CHE such as cast metal heat exchangers (CMHE) and ceramic, microchannel heat exchangers are also under development. The CMHE concept is based on the interconnectivity of the flow channels proposed for advanced PCHE surfaces with new construction methods [18]. Casting has long been used to reduce the cost of a component by reducing the number and complexity of the fabrication steps involved. The developers believe that CMHE hold great potential for sCO_2 HE and HE components as they could offer a performance similar to, or better than, PCHE but at less than a fifth of the cost while allowing for greater flexibility in options for materials and channel geometries. Constructing the highly interconnected channel spaces of these surfaces produces a casting core more like a perforated plate with manageable aspect ratios between each interconnection. This type of casting core can be slotted into polymer-bound sand or investment casting moulds to produce a heat exchanger in a single casting operation. However, there is limited industrial experience with similar fabrication techniques, and therefore, more work is needed. The most critical challenge to be addressed in developing CMHEs will be in finding methods and techniques for removing casting core material from the finished block. The next major challenge will be the castability of various HE channel geometries, which is highly dependent on the specific design of the unit and material involved [18].

The ceramic-based HEs can withstand operating temperatures that far exceed those of conventional metallic alloys. The main advantages of ceramic materials over traditional metallic materials in CHE construction are their extremely high-temperature stability, low material cost and excellent resistance to corrosion and chemical erosion. A US company has recently developed microchannel designs and manufacturing methods to produce scalable ceramic HEs that the developer claims are cost-effective and highly reliable with a high heat-transfer efficiency, low pressure drop and are suitable for large-scale power cycle applications [21]. The major obstacles to the improvement of ceramic HEs mainly lie in their intrinsic brittleness in tension, difficulties in shaping and sealing and thus high manufacturing costs. They cannot withstand large thermal gradients and are susceptible to thermal shock failure except silicon carbide and silicon nitride. Therefore, major researches are focused on less brittle ceramics forms such as composite ceramics. Work is also needed to test and analyse the performance, reliability, durability and environmental effects of sCO_2 on materials.

2.3 Combustor

Toshiba has been developing an oxy-fuel combustor for NET Power's 25-MWe Allam Cycle demonstration power plant. The Allam Cycle requires oxy-fuel combustion at ~30 MPa and 1150°C turbine inlet temperature. A 5-MWt test rig was built to test high-pressure combustion. Due to the use of oxygen instead of air, NO_x formation is not a concern and hence, flame temperatures can be selected for best performance, operability and durability. Initial tests show that the combustor has a good operability over a wide range of O_2/CO_2 ratios (15–40% O_2 by mass) and the metal temperatures of the combustor are close to their predicted values, proving the feasibility of the design concept. With successful testing, Toshiba developed a high-pressure combustor, which attained the required pressure of 30 MPa in 2013. The scaled demonstration combustor will be tested using the facilities of the demonstration plant before being commissioned as an integrated part of the complete combustion turbine assembly [22].

Other developers are also working on a supercritical oxy-combustor. Researchers at the University of Texas (USA) have developed a conceptual design for a natural gas-fuelled, oxy-fuel combustor for a 300-MWe turbine. The design is based on a liquid oxygen (LOX)/methane rocket engine and has two major advantages: (i) the use of existing and established LOX/methane engine technologies and (ii) a modular design that can be modified to be compatible with current or similar power turbine layouts. The analysis conducted by the researchers showed that with this design, uniform mixing of the working fluids and stable combustion could be achieved in the combustor [23].

SWRI, in partnership with Thar Energy, LLC, has been working to develop a high inlet temperature supercritical oxy-combustor suitable for a natural gas- or syngas-fuelled sCO_2 power cycle with a target plant efficiency of 52% (LHV, low heating value). System design and thermodynamic analyses have been conducted to determine the optimum cycle configuration and combustor design parameters such as inlet temperature, pressure and mass flow. A kinetic model has been developed, and initial evaluation of the combustion kinetics at combustor inlet conditions was carried out. An auto-ignition-based combustor design has been developed, and bench-scale testing is being performed. Further design studies using parametric computational fluid dynamics (CFD) simulation, cooling flow simulation and structural simulation will be carried out, and a demonstration scale oxy-combustor will be designed [24].

A swirl-type supercritical oxy-combustor for solid fuel was also designed and developed at SWRI. The combustor development focused on flow path and combustion optimization using computer models to simulate the flow through the combustor and to provide initial assessment of the coal combustion reactions in the flow path. The design effort included the initial combustor mechanical layout, initial pressure vessel design and the conceptual layout of a pilot-scale test loop [25]. Tests are needed to validate the feasibility of these designs.

2.4 Materials

Extensive tests have been conducted worldwide to identify materials compatible with high-temperature, high-pressure sCO_2 operation and the performance requirements of individual components. A large number of studies are available on creep, corrosion, oxidation and carburization behaviours of alloys [26–38]. These tests were typically conducted in pure CO_2 and generally in a temperature range of 400–750°C and pressure up to 20–25 MPa with exposure time ranging from a few hundred to 8000 h. Many of the tests were carried out on Cr-containing iron-based alloys, but tests on, for instance, Ni-based alloys and Fe- or Ni-based alumina-forming alloys were also performed. Studies on welding of superalloys and coating techniques for material applications in sCO_2 power systems are also underway. Results from these studies indicate that, in general,

- the degradation due to corrosion, oxidation and carburization of the tested materials in sCO_2 is insignificant at temperatures < 500°C;
- the corrosion/oxidation rate of the tested materials increases with increasing temperature whereas the sCO_2 pressure has minimal effects;
- high concentrations of chromium and nickel significantly increase the corrosion resistance of steel alloys and higher-alloyed materials perform better than lower-alloyed materials in high-temperature sCO_2. The corrosion/oxidation rate generally decreases with increasing Cr concentration of the alloy, and austenitic steels are more resistant to sCO_2-induced corrosion than ferritic-martensitic steels within the test temperature range.

Previous R&D work were mainly focused on closed sCO_2 cycles for applications such as nuclear and solar power, and hence, most material testing was carried out in pure CO_2. However, in both closed and semi-closed, oxy-combustion sCO_2 cycles, it is expected that some low levels of impurities such as O_2, H_2O, hydrocarbons and NO_x/SO_x (fossil-fuelled, semi-closed cycles) will be present. Studies are currently ongoing to investigate the impact of the impurities on the stability, creep and corrosion properties of the structural materials. Initial results from laboratory tests show that the tested materials exhibit higher corrosion resistance when low levels of O_2 and H_2O are present. This may be attributed to the higher oxygen partial pressure that promotes the formation of protective oxide scales [39, 40]. Additional work is needed to understand better the material interactions with sCO_2 under operating conditions and their compatibility in sCO_2 power systems and to generate data needed for the design and construction of key components.

2.5 Other developments

Progress has also been made in areas such as computer modelling and piping configuration. A number of computational models have been developed around the world for fundamental studies and analyses such as the chemical kinetics of sCO_2 combustion, thermal dynamics of heat transfer, development and refinement of cycle control strategies, performance and economic analysis and comparison of sCO_2 cycles. These models provide useful tools for studying and designing sCO_2 power cycles and the individual components.

3 Commercial and emerging sCO_2 power cycles

The selection and design of the optimum sCO_2 power cycle configuration depend on the given application. Two pathways have been explored for power generation from coal: directly heated close Brayton cycle and indirectly heated semi-closed sCO_2 cycles.

3.1 Echogen heat engine

The first commercial 8 MWe closed sCO_2 Brayton cycle heat engine EP100, developed by Echogen Energy Systems, was brought to the market in 2014. It turns waste heat from various industrial processes to electricity and operates at relatively low temperatures.

A recuperated closed condensing Brayton cycle with multiple stages of recuperation and heat extraction from the primary heat source is employed by EPS100. The EPS100 uses two separate turbines. One, the 'drive turbine' is connected directly to the compressor, while the other 'power turbine' is coupled to a generator for power generation. The power turbine operates at a constant speed. The turbo-compressor speed can be varied independently over a wide range to maintain the optimal flow rate for the fluid loop for the given heat source and coolant conditions. Fig. 5 shows a simplified cycle layout of the EPS100. The heat energy of the exhaust stream from industrial processes or gas turbines is recovered through a waste heat exchanger (sCO_2 heater) by heating a flow of compressed sCO_2. Downstream of the sCO_2 heater, the heated sCO_2 flow is split into two main streams. Approximately two-thirds of the flow is directed to the power turbine, while the remainder is directed to the drive turbine that provides the shaft power for the main sCO_2 compressor. The sCO_2 streams exiting from the power turbine and drive turbine pass through recuperators to preheat the CO_2 stream from the main compressor before being cooled, compressed and then sent to the sCO_2 heater to complete the cycle. The power turbine has a single-stage radial design. The recuperators and CO_2 coolers (condenser) are all of the PCHE type, while the sCO_2 heater has a shell and finned tube design [41].

Echogen can now provide standard heat engines scalable from 1 to 9 MWe (net). On the basis of the EPS100 system, Echogen has also completed a conceptual design of a 10-MWe sCO_2 test facility for the US DOE Nuclear Energy Group. Echogen is currently working with EPRI to develop integrated solutions for coal-fired power plants using sCO_2 power cycles as part of an ongoing US DOE-funded project.

Conceptual designs of utility-scale coal-based closed sCO_2 cycle power plant including designs for key

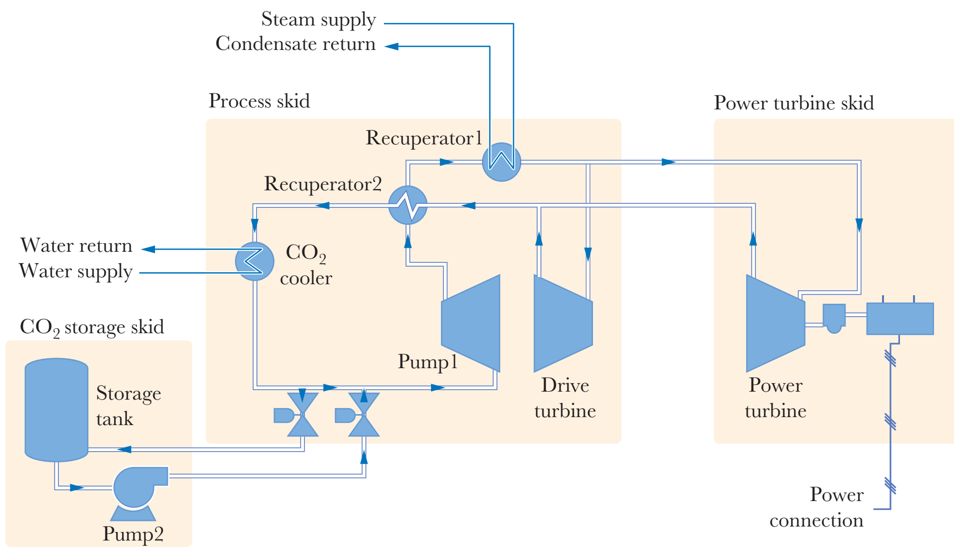

Fig. 5 Process flow diagram of the EPS100 [41]

components such as boilers, heat exchangers and compressors have been developed by several developers [42–45]. However, the viability of these designs needs to be tested and validated.

3.2 Allam cycle

An sCO_2 oxy-fuel power cycle has the potential for almost 100% CO_2 capture. Several R&D programmes are ongoing to develop a fossil fuel oxy-combustion sCO_2 cycle power generation system such as the Supercritical Transformational Electric Power crosscut initiative in the USA. The R&D of directly fired, semi-closed oxy-combustion sCO_2 cycle for power generation is most advanced in the development of Allam Cycle [16].

The Allam Cycle is a semi-closed, recuperated, oxy-combustion trans-critical CO_2 power cycle. The Allam Cycle is a trans-critical CO_2 cycle because the pressure of the working fluid exiting the turbine is around 3 MPa, which is below the critical pressure of CO_2. The core process, as shown in the yellow area in Fig. 6, is a gas-fired, high-pressure, low-pressure ratio cycle, operating with a single turbine that has an inlet pressure of ~30 MPa and a pressure ratio of 10. A pressurized gaseous fuel is burned in the oxy-combustor at ~30 MPa. Combustion takes place in the presence of a hot oxidant flow containing a mixture of O_2 and recycled CO_2 as a diluent for combustion temperature control. The exhaust flow exiting the combustor is expanded through a turbine to ~3 MPa, reducing in temperature to >700°C. Following the turbine, the exhaust flow enters a recuperator where it is cooled to >70°C by transferring heat energy to the high-pressure CO_2 recycle stream. Exiting the recuperator, the turbine exhaust flow is further cooled to near ambient temperature at which any water contained in the flue gas is condensed and separated, resulting in a stream of predominantly CO_2. The CO_2 stream is compressed to the high pressure required and is then split into two. The recycle CO_2 stream returns to the recuperator and is reheated to temperatures exceeding 700°C. It is then mixed with oxygen and fed to the combustor. The other stream containing high-purity CO_2 at high pressure is ready to be exported via pipeline for storage or utilization. This net export is ~5% of the total recycle flow, meaning most of the process inventory is recirculated [16, 46].

The optimum high pressure for operation of the system is between 20 and 40 MPa, while the optimum pressure ratio is in the range of 6–12. This means that the CO_2 recycle compressor inlet pressure will be below the CO_2 critical pressure of 7.4 MPa. In the recycle CO_2 compression system, a conventional single- or two-stage compressor first raises the pressure to ~8 MPa. The supercritical CO_2 is then cooled to near ambient temperature in the compressor after-cooler. Its density at this point will be >700 kg/m^3. The sCO_2 is then compressed to the pressure required using a multistage centrifugal pump.

It is important to use a high turbine inlet temperature to achieve a high net cycle efficiency. However, this temperature is limited by the maximum allowable temperature (700–750°C) of the turbine exhaust entering the hot end of the recuperator. This maximum allowable temperature is determined by the operating pressure of the recuperator and the allowable stress level for construction materials. This leads to a typical turbine inlet temperature constraint in the range of 1100–1200°C.

Almost all the heat of the turbine exhaust flow can be recuperated within the Allam Cycle. Some of the additional heat required could be met with the recovery of low-grade heat of the co-located air separation unit, further enhancing the system efficiency. An Allam Cycle is simple, using only a single gas turbine with an oxy-fuel combustor, heat exchangers and compressors/pumps. Consequently,

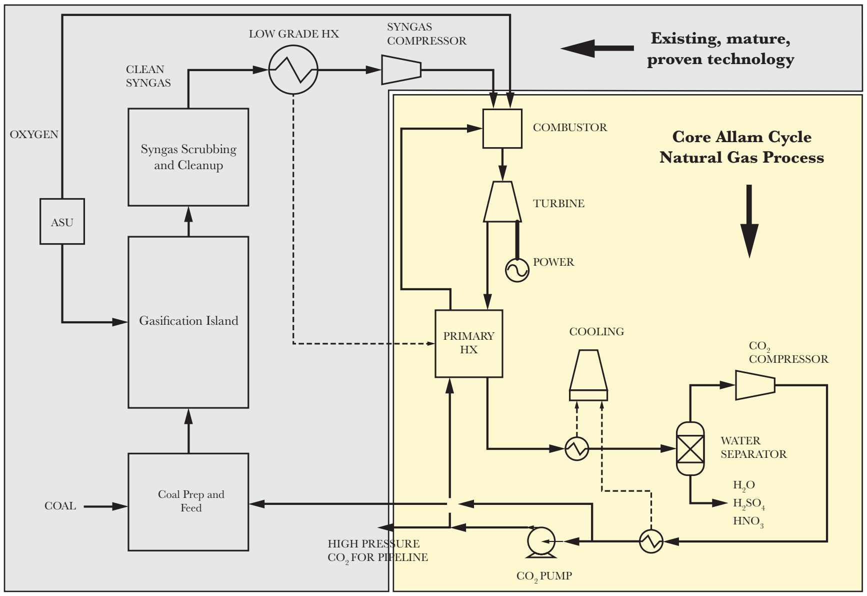

Fig. 6 A simplified block flow diagram of the Allam Cycle coupled with a coal gasification system [47]

an Allam Cycle power system can achieve a high plant efficiency with full carbon capture, have a reduced balance of plant requirement, a small footprint and lower costs. Under development for over 7 years by 8 Rivers Capital (USA), the Allam Cycle can use a variety of hydrocarbon fuels including natural gas and syntheses gas (syngas) derived from gasification of coal, oil-refining residuals and biomass with target net efficiencies of 51% (LHV) for coal and 59% (LHV) for natural gas, and full carbon capture [16, 46, 47].

Specific development of the natural gas-fuelled Allam Cycle has been undertaken by NET Power, a subsidiary of 8 Rivers Capital. NET Power is currently building a 50 MWt (25 MWe) natural gas demonstration power plant in La Porte, TX, USA, scheduled to be commissioned in 2017. The aim of the plant is to demonstrate the characteristics of the cycle and verify the design and operation of the integrated power generation system and individual components. The plant will be a fully operational, grid-connected power plant containing all key system components. The demonstration process will match the operating conditions of the core Allam Cycle and the expected commercial temperatures and pressures. Tests will be carried out to validate performance, control methodology, operational targets and component durability. Furthermore, it will undergo full evaluation of the cycle operability including start-up, shut-down, load following, emergency operation and partial-load operation, as well as reliability and safety. Meanwhile, a full-scale, 300-MWe gas-fuelled Allam Cycle commercial plant has been under development and is currently in the design phase. Several commercial partners are already engaged and potential sites for the plant are being vetted.

In parallel to the natural gas-fuelled Allam Cycle, a coal-based Allam Cycle power system is also under development. This system, fuelled with coal-derived syngas, integrates a core Allam Cycle with a commercially available coal gasifier. The operating conditions of a coal-fuelled Allam Cycle will be the same as those used in the natural gas version. Several additional operations are required in order to utilize coal. The coal is first prepared by grinding and the pulverized coal is fed into an oxygen-blown gasifier. The syngas produced is cooled and then passes through scrubbing and clean-up systems to remove particulates and possibly other combustion by-products before entering the Allam Cycle. Four additional R&D needs have been identified for commercialization of the coal-fuelled Allam Cycle: (i) selection of the appropriate gasification process; (ii) handling of corrosion and erosion from impurities found in coal-derived syngas; (iii) methods of contaminant removal from the system; and (iv) development of the Allam Cycle combustor for low calorific value and hydrogen-containing fuels. An Allam Cycle coupled with a slurry-feed gasifier with water quench cooling provides a simpler process that has lower capital cost and higher reliability. Most of the particulates in the syngas are also removed during the quenching process. The gas stream after quench cooling has a temperature typically ranging from 200 to 300°C and is saturated with moisture (steam). The latent heat of the steam in the syngas can be recuperated and transferred into the Allam Cycle, improving the system efficiency. The developer is currently focusing on the development of a post-combustion process for SO_x and NO_x removal due to its advantages of higher efficiency and lower cost. An assessment of potential corrosion problems using this approach is being carried out, with particular focus on the lower temperature regions of the plant where water condensation and, hence, acid precipitation may occur [46]. This work is ongoing.

4 Conclusions

The sCO_2 power cycles hold great potential for providing alternative power generation systems that can achieve higher plant efficiency and full carbon capture at lower costs. However, there are some outstanding technical issues to be resolved. Extensive R&D activities have been conducted and are still ongoing to develop sCO_2 cycle for power generation. Significant progress has been made so far in many areas such as developing the design and construction of the key components, identifying materials suitable for application in sCO_2 power cycles, identifying the optimum sCO_2 cycle configuration for power generation and establishing computational models for fundamental studies and system analysis. Some small, low-temperature sCO_2 Brayton cycle power systems are starting to emerge in the commercial market. The commercial operation of Echogen's heat engines proves the technical and economic viability of sCO_2 cycles for power generation. However, a lot more needs to be done before a full coal-based sCO_2 cycle power generation system, either indirectly or directly fired, can be developed and commercialized with confidence. If solutions can be found to resolve all the technical challenges in developing the sCO_2 power cycles, they could offer major opportunities for future power generation from coal in a carbon-constrained world.

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