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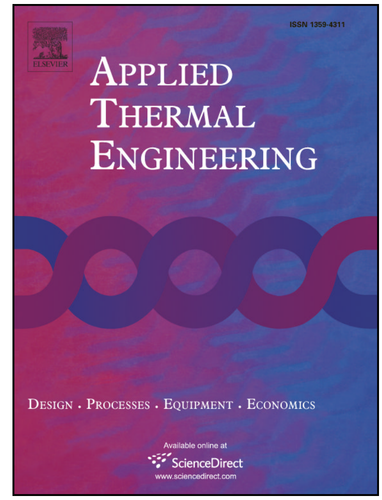

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Navid Khallaghi, Dawid P. Hanak, Vasilije Manovic

PII: S1359-4311(18)34930-5
DOI: https://doi.org/10.1016/j.applthermaleng.2019.03.033
Reference: ATE 13462

To appear in: *Applied Thermal Engineering*

Received Date: 10 August 2018
Revised Date: 10 October 2018
Accepted Date: 6 March 2019

Please cite this article as: N. Khallaghi, D.P. Hanak, V. Manovic, Staged oxy-fuel natural gas combined cycle, *Applied Thermal Engineering* (2019), doi: https://doi.org/10.1016/j.applthermaleng.2019.03.033

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Applied Thermal Engineering, Volume 153, May 2019, pp. 761-767
DOI: 10.1016/j.applthermaleng.2019.03.033

Staged oxy-fuel natural gas combined cycle

Navid Khallaghi, Dawid P. Hanak, Vasilije Manovic*

Clean Power Engineering, Energy and Power, School of Water, Energy and Environment, Cranfield University, Bedford, Bedfordshire, MK43 0AL, UK

*Corresponding author: *Dawid P. Hanak, d.p.hanak@cranfield.ac.uk*

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Abstract

Exhaust gas recirculation (EGR) in conventional natural gas-fired oxy-combustion cycles is required to maintain the combustion temperature at an allowable level. However, EGR is not beneficial from the system performance perspective. It is difficult to achieve in oxy-fuel cycles due to the high pressure and increased pressure drop in such systems. Consequently, alternative options to control the combustion temperature need to be considered. In this study, staged oxy-fuel natural gas combined cycle (SOF-NGCC) was proposed, which does not require EGR, and its feasibility was evaluated. A process model was developed in Aspen Plus in order to evaluate the thermodynamic performance of the proposed system and to benchmark it against the Allam cycle and conventional NGCC. The optimum net efficiency of the proposed cycle (47.63–51.32%) was shown to be lower than that for Allam cycle (54.58%) and the conventional NGCC without post-combustion capture (PCC) (56.95%). However, the SOF-NGCC is less complex and requires smaller equipment than the Allam cycle. This is mostly because the combined volumetric flow rate into expanders in both topping and bottoming cycles is approximately 25% of that estimated for the Allam cycle. Moreover, with a backpressure of 35 bar, no further compression is required prior to the CO_2 purification unit.

Key Words: Carbon capture, oxy-combustion cycle, natural gas, exhaust gas recirculation, staged combustion, supercritical CO_2 cycle

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The final published version (version of record) is available online at DOI:Published by 10.1016/j.applthermaleng.2019.03.033. Please refer to any applicable publisher terms of use.

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1. Introduction

Environmental targets are causing governments to express keen interest in methods to reduce carbon emission risks and impacts to thus hold the global average temperature increase to well below 2°C [1]. Among available options to reduce carbon emissions, carbon capture and storage (CCS) is regarded as the most promising and the least cost-intensive solution for the power sector [2–4]. However, improvement of existing CCS options (pre-combustion, post-combustion and oxy-combustion) in terms of efficiency and costs is imperative in the near future.

Oxy-combustion technology was proposed as a means to produce relatively pure CO_2 for enhanced oil recovery (EOR) [5]. This technology is based on combustion of fuel in the presence of high-purity O_2 and partially recycled exhaust gas (to moderate the flame temperature, as combustion in high-purity oxygen would result in intolerably high temperatures in the combustors).

In general, the concept of exhaust gas recirculation (EGR) in gas turbines was originally used to decrease NO_x emissions since recirculating exhaust gas to the combustion chamber decreases the combustion temperature. Furthermore, in the conventional gas turbine (GT) with post-combustion capture (PCC), EGR is used to compensate for the low partial pressure of CO_2 in the flue gas, resulting in a lower capture energy requirement [6,7] The effects of applying EGR on cycle performance and cost have been studied extensively [8–10]. Compared to a GT integrated with PCC without EGR, implementation of EGR results in 30% reduction in capital cost of the capture system. Moreover, the overall specific capital cost and incremental capital cost would decrease by 9% and 19%, respectively, using 50% EGR [11]. Li et al. [12] showed that utilisation of EGR results in reduction of the absorber feed stream mass flow by 51% if the recirculation ratio increases to 50%. They also compared four different methods of increasing CO_2 concentration in the exhaust gas: (1) EGR; (2) humidification; (3) supplementary firing; and (4) external firing. The obtained results showed that from the viewpoint of electrical efficiency, EGR seems to be the most efficient among these methods [13].

However, the emphasis of most studies is on air-fired natural gas combined cycle (NGCC) integrated with PCC where EGR is applied to compensate for the low partial pressure of CO_2 in the exhaust gas. Conversely, in gas-fired oxy-combustion cycles,

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the exhaust gas mainly comprises steam and CO_2 and the moisture can be easily separated by condensing, leaving a concentrated CO_2 stream. Consequently, in GTs operating under oxy-combustion conditions, the main reason of using EGR is to keep the combustion temperature within allowable levels. Therefore, the concept of EGR has different roles depending on the type of technology. However, EGR causes some drawbacks, especially for gas-fired oxy-combustion cycles, as it increases the complexity of the system and, due to the high pressure and increased pressure drop in such cycles, EGR is more difficult to achieve.

Burner operation under non-stoichiometric conditions has been studied by Becher et al. [14]. They used controlled staging with non-stoichiometric burners (CSNB) to moderate the combustion temperature while reducing the recycle gas flow ratio. The feasibility of controlling combustion temperature by adjusting the burner stoichiometry was also investigated by Bohn et al. [15]. They reduced the EGR by 50% while the flame temperature remained at the same level as that of air-blown combustion or an oxy-combustion with 70% EGR. Furthermore, Gopan et al. [16] proposed a staged, pressurised oxy-combustion (SPOC) cycle for coal-fired oxy-combustion without EGR and demonstrated an efficiency improvement of almost 6% compared to that of a conventional oxy-combustion plant [17]. In the SPOC process, which is presented in Figure 1, both combustion products and excess O_2 are diluents.

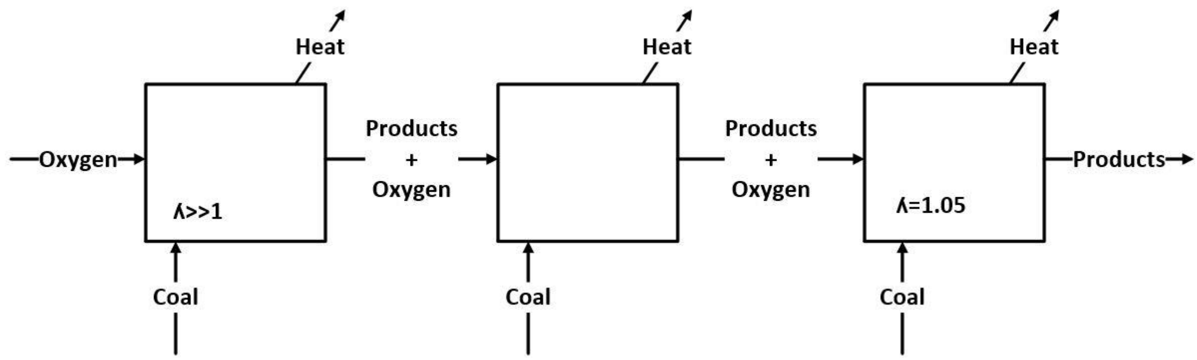

Figure 1. Depiction of staged pressurised oxy-combustion concept [16]

It should be noted that the previous study [16] mainly explored staged combustion in the case of coal-fired oxy-combustion. However, such concept has not been applied to NG-fired cycles and has not been integrated with any power generation scheme. Therefore, in this work, the concept of the staged pressurised combustion cycle is

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integrated into the s-CO_2 cycle and proposed for the NG-fired oxy-combustion cycle that is expected to achieve high-efficiency at low CO_2 emissions. Two different cycles (conventional NGCC and Allam cycle) are considered as reference cases for benchmarking and evaluation of the newly proposed cycle. The process model of the proposed cycle is developed in Aspen Plus®, and the optimal net efficiency is estimated based on parametric analysis. Finally, the thermodynamic feasibility of the new cycle is evaluated and the results are compared with those of the reference cycles.

2. Process description and simulation

The Allam cycle and conventional NGCC are selected as reference cycles in this study. The performance analysis of the Allam cycle is taken from Scaccabarozzi et al. [18]. The layout of the conventional NGCC and its operating parameters are taken from Biliyok et al. [19]. The SOF-NGCC comprises two different cycles: (1) NG-fired staged-combustion cycle; and (2) s-CO_2 cycle. Although neither simulation nor experimental data are available on the performance of the novel NG-fired staged-combustion cycles, the s-CO_2 cycle model used in this study was validated with data from Moisseytsev and Sienicki [20] and presented in Hanak and Manovic [21]. In order to enable a fair comparison between SOF-NGCC and the reference cycles, this study considers the same fuel composition and fuel rate for SOF-NGCC and conventional NGCC as in Scaccabarozzi et al. [18]. Therefore, the conventional NGCC has been refined to operate under a changed fuel composition. Finally, the values for the mechanical efficiency of the turbomachinery used in simulations of SOF-NGCC are also taken from [18].

2.1. Conventional natural gas combined cycle

A 440 MW NGCC plant is used as a reference case. It comprises a gas turbine and a three-pressure-level steam cycle with reheat. Further details of this cycle are provided by Biliyok et al. [8,19]. The main input/design data of the cycle are summarised in Table 1.

Table 1. NGCC plant input and design data.

Parameter	Value
Fuel flow rate (kg/h)	59470
Turbine inlet temperature (°C)	1425
Gas turbine inlet pressure (bar)	20.68
HP turbine inlet pressure (bar)	124
IP turbine inlet pressure (bar)	28.65
LP turbine inlet pressure (bar)	4.45
Condensate pressure (bar)	0.04
Superheated steam temperature (°C)	565
Reheated steam temperature (°C)	558
Ambient temperature (°C)	15

2.2. Allam cycle

The Allam cycle, which is also known as the NetPower cycle, is one of the near-zero-emissions gas-fired oxy-combustion cycles that, in addition to high net efficiency, deliver high-purity CO_2 at supercritical conditions ready for geological storage. It comprises one high-pressure CO_2 turbine and a multi-stage compression system with intercooler to pressurise the CO_2 to the required pressure. Scaccabarozzi et al. [18] showed that the optimal maximum pressure of the Allam cycle is in the range of 260–300 bar. Operating at this pressure and using CO_2 as a working fluid provides the opportunity of producing high-purity CO_2 at a high pressure and, as a result, there is no need of any further CO_2 purification [22]. The maximum net efficiency estimated for this system with complete CO_2 capture and almost no other air pollutants is estimated to be 59% [23], 55.10% [24] and 54.58% [18,24].

2.3. Staged oxy-fuel natural gas combined cycle

Figure 2 shows a schematic of the SOF-NGCC, which consists of three main parts: (i) cryogenic air separation unit (ASU); (ii) power section, which comprises a gas turbine and a supercritical CO_2 (s-CO_2) turbine; and (iii) CO_2 purification unit (CPU). The entire amount of oxygen required to ensure complete combustion enters into the first combustion stage, whereas natural gas enters into each of three combustion stages with almost the same feed rate. The combustion products of the first combustion stage along with unconsumed oxygen act as a diluent for the second combustion stage. In addition, to keep the combustion temperature at an allowable

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level, excess heat is extracted from the combustion stages to pre-heat the CO_2 stream of the s-CO_2 cycle. This process continues until all the oxygen is consumed in the last combustion stage. The exhaust gas, which is mainly composed of steam and CO_2, drives the turbine to generate power. The flue gas then passes through a heat exchanger and transfers heat to the oxygen, fuel and CO_2 streams of the s-CO_2 cycle. The water vapour is easily separated and the remaining CO_2 is sent to the CPU to be readied for storage.

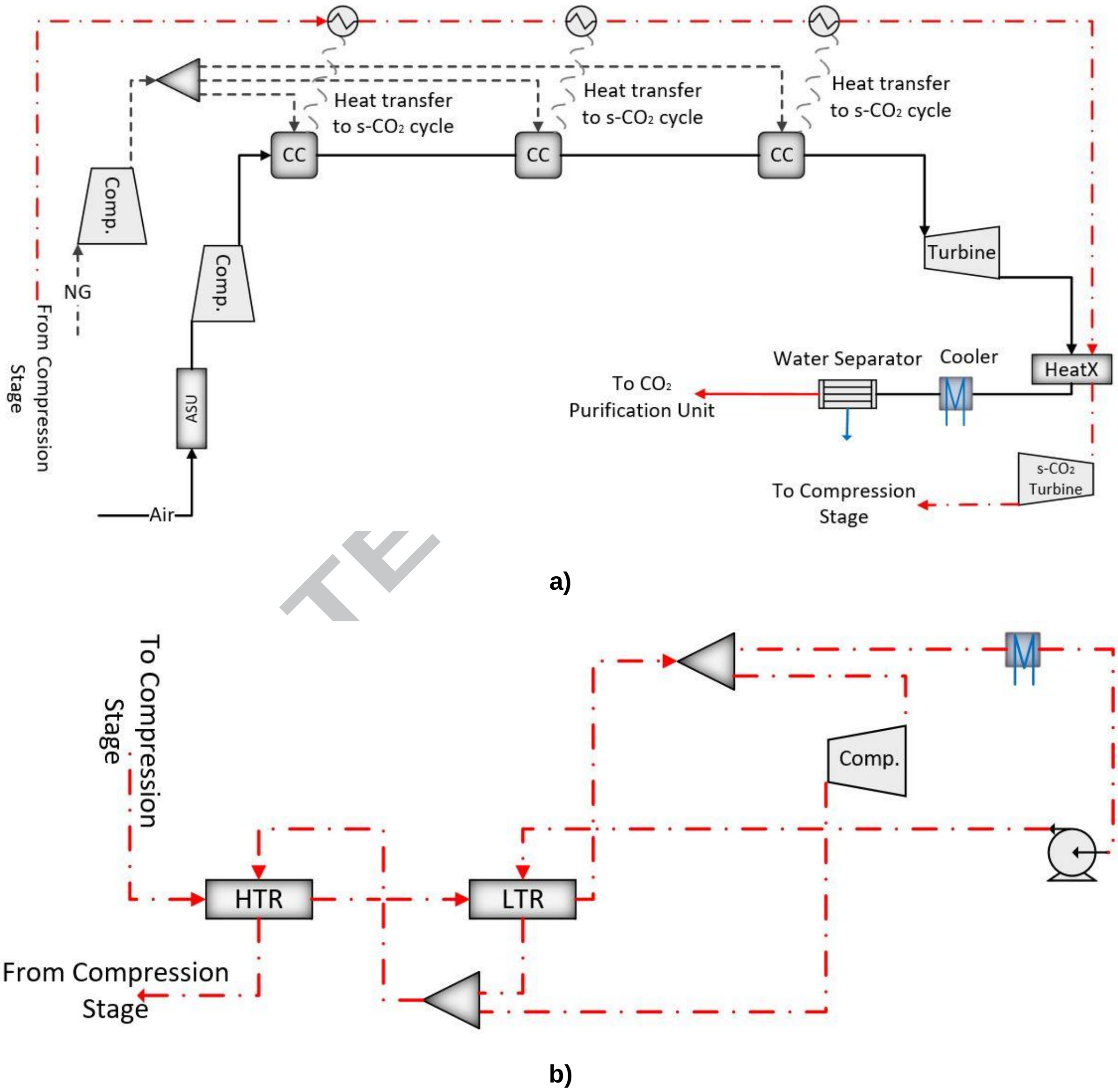

Figure 2. Schematic of SOF-NGCC a) power section of SOF-NGCC and b) compression trail of s-CO_2 cycle. ASU – air separation unit.

In the bottoming cycle, the s-CO_2 stream is first pressurised to 300 bar and then preheated in a low-temperature recuperator (LTR) and high-temperature recuperator (HTR), as well as SOF combustor, before entering the high-pressure CO_2 turbine.

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2.4. Model development

A process model of a conventional NGCC, which is considered as a benchmark in this study, was developed in Aspen Plus® and described in detailed by Biliyok et al. [8,19]. The simulation for the SOF-NGCC is carried out using Aspen Plus®. The package used for thermodynamic property estimation is the Peng Robinson equation of state. The combustion chambers are simulated by the Gibbs reactor (*RGibbs*), available in the Aspen Plus® model library. All heat exchangers are modelled using the *MHeatX* block and designed based on the assumption that the minimum temperature approach of the heat exchangers is 5°C. All turbines are modelled as individual turbine sections using the *Compr* block. The ASU is a standard double-column cryogenic unit with the high- and low-pressure column operated at 5.6 and 1.3 bar, respectively, and filled with 350Y structured packing [25]. The ASU delivers oxygen at 95% purity, which is associated with the minimum energy consumption for a cryogenic ASU [26]. The properties of the natural gas feed stream and other key assumptions regarding the turbomachinery used along with initial simulation parameters for the SOF-NGCC are summarised in Table 2.

Table 2. Main assumptions and turbomachinery properties for simulation

Natural gas composition and conditions [18]	**Value**
Methane ($\%_{vol}$)	89
Ethane ($\%_{vol}$)	7
Propane ($\%_{vol}$)	1
Butane ($\%_{vol}$)	0.1
Pentane ($\%_{vol}$)	0.01
CO_2 ($\%_{vol}$)	2
N_2 ($\%_{vol}$)	0.89
Temperature (°C)	15
Pressure (bar)	70
Turbomachinery efficiency [18]	**Value**
Isentropic efficiency of vapour-phase compressor (%)	90
Isentropic efficiency of turbine stages (%)	89
Polytropic efficiency of natural gas compressor (%)	85
Polytropic efficiency of main ASU compressor (%)	85
Hydraulic efficiency of dense-phase pump (%)	85
Initial SOF-NGCC operating parameters	**Value**
Combustion pressure (bar)	300
Combustion temperature (°C)	1300
Turbine backpressure (bar)	35
s-CO_2 turbine inlet temperature (°C)	700
s-CO_2 turbine inlet pressure (bar)	300
s-CO_2 turbine backpressure (bar)	75
Recompression split fraction (-)	0.3

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3. Results and discussion

The performance summary for the SOF-NGCC, considering initial design parameters, is shown in Table 3. The SOF-NGCC has a net power output of 358.41 MW, with a net efficiency of 46.65%. It needs to be highlighted that the bottoming s-CO_2 cycle generates most of the gross power output in the SOF-NGCC (90%). As can be observed, a considerable share of generated electrical energy is used for the compression stage (compressor and pump) in the s-CO_2 cycle and oxygen separation in the ASU. The power requirements of the s-CO_2 compression stage together with O_2 production and compression are 162.68 MW and 99.89 MW, respectively, which account for 21.17% and 13% of the total system energy input, respectively.

Table 3. Performance summary of SOF-NGCC

Component	Value
High-pressure turbine (topping cycle) (MW)	62.61
s-CO_2 turbine (bottoming cycle) (MW)	567.3
Natural gas compressor power consumption (MW)	4.18
Air separation unit power consumption (MW)	58.74
O_2 compression power consumption (MW)	41.15
s-CO_2 compression stage power consumption (MW)	162.68
CO_2 purification power consumption (MW)	4.75
Thermal energy input (MW)	768.31
Net power output (MW)	358.41
Net efficiency (%)	46.65

A sensitivity analysis is performed in order to explore the influence of the key parameters and to optimise the SOF-NGCC process to be compared with the reference cycles.

3.1. Sensitivity analysis

The performance of each thermodynamic cycle can be improved by several factors, especially by increasing the operating temperature and pressure at the turbine inlet. Therefore, in this section, in order to evaluate the influence of different key parameters on the SOF-NGCC performance, a sensitivity study is performed. The following cycle parameters are varied to analyse their effects on cycle performance:

- Split fraction
- s-CO_2 cycle (bottoming cycle) turbine inlet conditions
- Topping cycle turbine inlet conditions

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In the s-CO_2 cycle, the specific heat of the cold-side flow is higher than the specific heat of the hot-side flow in the recuperator [27]. To compensate for this difference, to reduce waste heat and to achieve higher thermal efficiency, the s-CO_2 stream after the LTR is split into two parts, one of which is pressurised without heat rejection [28], as shown in Figure 2b. Figure 3 shows the effect of the split fraction on cycle performance.

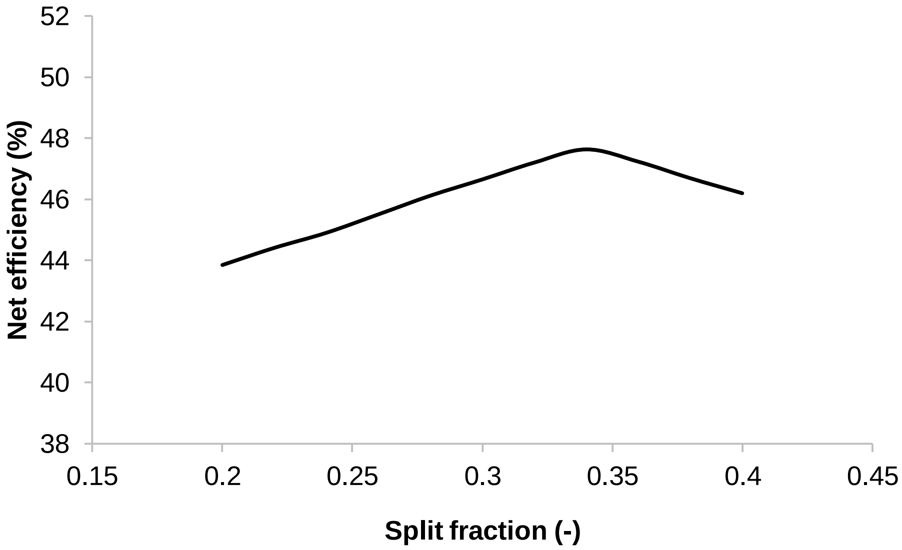

Figure 3. Effect of split fraction on the net efficiency

The split fraction varies from 0.2 to 0.4, indicating the fraction of total flow entering the HTR. From Figure 3 it can be seen that the maximum efficiency occurs when the split fraction is 0.34. This indicates that 66% of the supercritical CO_2 enters the LTR after the splitter. This is because, at the split fraction of 0.34, the heat capacity rates on both sides of the LTR are equal.

The effect of the s-CO_2 turbine inlet pressure and temperature on the net efficiency of the cycle is presented in Figure 4, which indicates that the net efficiency of the cycle is proportional to the s-CO_2 turbine inlet temperature and pressure. It can be seen that the correlation with temperature is nearly linear while with the pressure is second order (Figure 4b). The highest temperature of the s-CO_2 cycle in this study is set at 700°C with an efficiency of 47.63%, considering the cost and lifetime of the materials under high-pressure and high-temperature conditions. However, further development of materials for high-temperature application would enable even higher efficiencies. For instance, in the case of operation at 800°C, the efficiency would be 51.32%. On the other hand, the analysis of the net efficiency trend in Figure 4a

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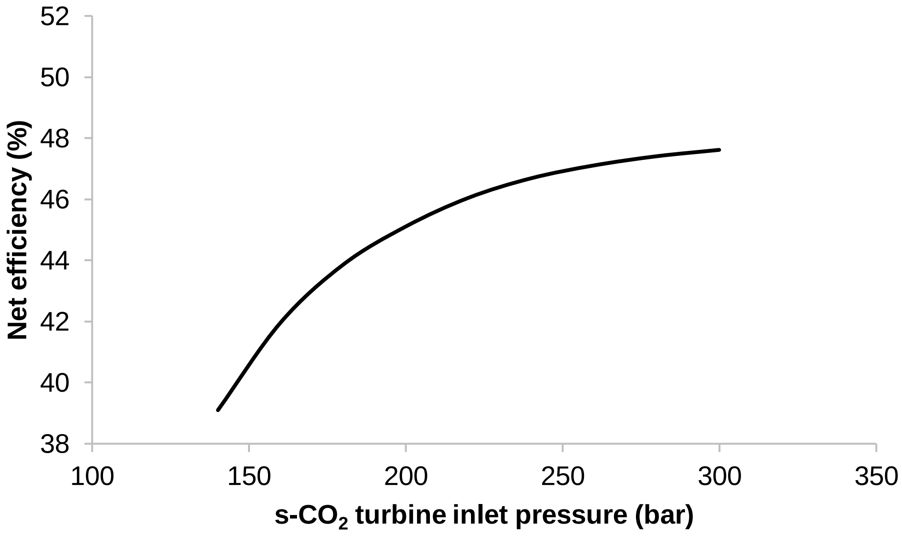
indicates that an increase in turbine inlet pressure from 140 bar to 200 bar has a more-pronounced effect on the cycle performance (efficiency increases from 39.1% to 45.12%) than that from 200 bar to 300 bar (efficiency increases from 45.12% to 47.63%). It needs to be highlighted, however, that such linear and non-linear trends for temperature and pressure, respectively, are in agreement with the results reported for s-CO_2 cycles in different applications [29–32].



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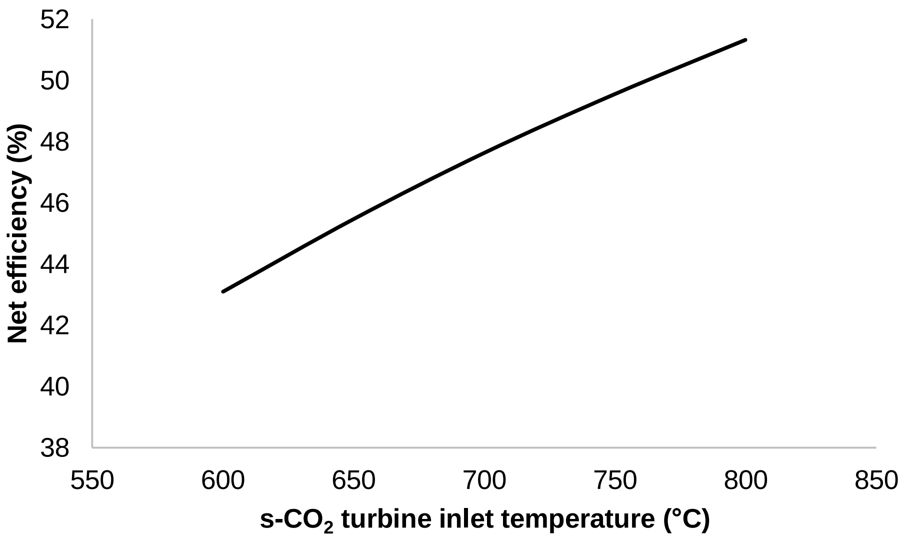

a)

Figure 4. Effect of s-CO_2 turbine inlet a) temperature and b) pressure on the net efficiency

To investigate the effect of topping cycle turbine inlet conditions on cycle performance, turbine inlet temperature (TIT) is varied from 950°C to 1250°C (upper value that the turbine blades, due to current material limitations, can withstand). In

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addition, ten cases for turbine inlet pressure in the range of 120–300 bar and five cases for the turbine outlet pressure: 35 bar, 40 bar, 45 bar, 50 bar and 55 bar, are considered, while all other design parameters and assumptions are kept constant. Figure 5 reveals that the net efficiency of the SOF-NGCC is directly proportional to TIT, as the turbine expansion work increases at higher TIT. On the other hand, as the fuel consumption and TIT for the s-CO_2 cycle are kept constant, the lower TIT for the topping cycle results in less heat available for the recuperation. Therefore, a lower CO_2 mass flow rate is required to keep the s-CO_2 TIT constant at 700°C. Consequently, less power output from the s-CO_2 turbine is available. In addition, an increase in the turbine inlet pressure from 120 bar to 240 bar was shown to have a significant effect on the net efficiency. However, since higher combustion pressure increases the power consumption associated with NG and oxygen compressors, only small gains in the net efficiency were observed for higher pressures.

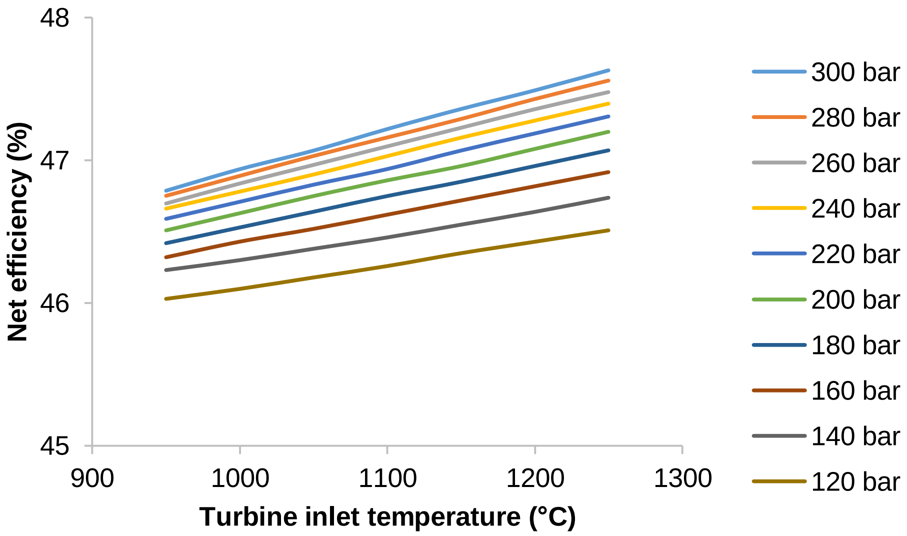

Figure 5. Net electric efficiency of the SOF-NGCC as a function of turbine inlet temperature

Figure 6 illustrates the effect of turbine backpressure at each turbine inlet pressure. It can be concluded from Figure 6 that, at a certain turbine inlet pressure, the cycle net efficiency decreases with turbine outlet pressure increment. Although lower CO_2 compression work is required at higher turbine backpressure, it has a more significant negative effect on turbine power output since the mass flow rate entering the turbine is higher than that entering the CPU after water separation.

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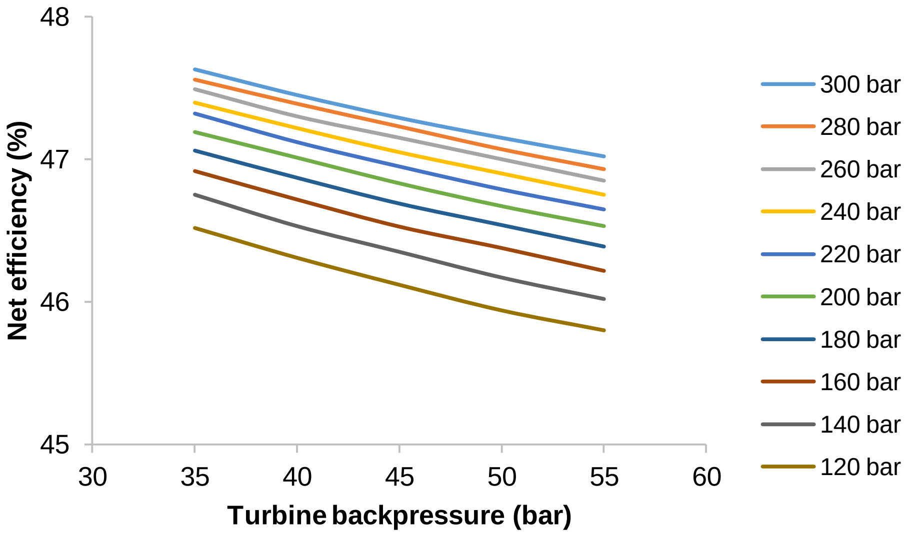

Figure 6. Net electric efficiency of the SOF-NGCC as a function of turbine inlet pressure and backpressure

Working under 300 bar increases compactness of the components. Because no cooling flow is used in the SOF-NGCC, working under high temperature (1250°C) is intolerable. Figure 5 shows that the efficiency difference between 950°C and 1250°C at 300 bar is only 0.84%. Moreover, efficiency at 120 bar and 950°C (46.03%) is 1.6% less than at 300 bar and 1250°C. Furthermore, at a backpressure of 35 bar (Figure 6), the efficiency of the cycle at 300 bar is 47.63%, which is only around 1% higher than the efficiency at 120 bar (46.52%). Therefore, working at 950°C at 300 bar and even 120 bar are worth considering due to reduced complexity, higher achievability and lower cost.

3.2. Performance comparison

The overall performance of the three system configurations is summarised in Table 4. The same natural gas input (59470 kg/h) is used for all three cycles. The analysis shows that the SOF-NGCC has a net power of 365.94 MW with a net efficiency of 47.63%. As indicated above, the net efficiency can increase to 51.32% (394.26 MW) if the TIT in the s-CO_2 is increased from 700°C to 800°C. The maximum efficiency of the Allam cycle based on Scaccabarozzi et al. [18], takes place at a TIT between 1150°C to 1200°C, and at turbine inlet pressure between 260 bar and 300 bar. Regarding the simulation results in Scaccabarozzi et al. [18], the Allam cycle has higher power output (419.31 MW) and higher net efficiency (54.58%) in comparison

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with the SOF-NGCC. On the other hand, the NGCC has higher net power and net efficiency than the other two cycles due to lack of the ASU and CPU, 437.6 MW and 56.95%, respectively. Implementation of the CPU has a large negative effect on the cycle performance. This is because on retrofit of amine-based post-combustion capture to a conventional NGCC, which results in an efficiency penalty of 8.7% points, the CPU results in a 1.7%-point drop in the net efficiency of the entire system [33].

Table 4. Performance comparison between SOF-NGCC, Allam cycle and NGCC

Component	**SOF-NGCC (Case 1)**	**SOF-NGCC (Case 2)**	**Allam cycle**	**NGCC**
High-pressure turbine power output (MW)	62.61	62.61	622.42	27.88
Intermediate-pressure turbine power output (MW)	-	-	-	46.15
Low-pressure turbine power output (MW)	-	-	-	78.6
Gas turbine power output (MW)	-	-	-	590.1
s-CO_2 turbine power output (MW)	587.68	602.72	-	-
Natural gas compressor power consumption (MW)	4.18	4.18	4.18	-
Air separation unit power consumption (MW)	58.74	58.74	85.54*	-
Air/O_2 compression power consumption (MW)	41.15	41.15	*	303.823
Recycle gas compression power consumption (MW)	-	-	111.15*	-
s-CO_2 compression stage power consumption (MW)	175.53	162.22	-	-
CO_2 purification power consumption (MW)	4.75	4.78	-	-
Thermal energy of feedstock (MW)	768.31	768.31	768.31	768.31
Net power output (MW)	365.94	394.26	419.31	437.6
Net efficiency (%)	47.63	51.32	54.58	56.95

* Oxygen compression power consumption in Allam cycle is included in O_2 power consumption (O_2 pressure from the ASU is 120 bar) and recycle gas compression power consumption
Case 1 - SOF-NGCC with s-CO_2 cycle TIT of 700 °C
Case 2 - SOF-NGCC with s-CO_2 cycle TIT of 800 °C

However, the volumetric flow rate into the expanders, compressors and heat exchangers is another factor which affects the component size used in these cycles and, in turn, affects cost analysis estimation. By applying staged combustion, there is no need of EGR in such system, which results in extremely reduced volumetric flow rate than systems with EGR. Moreover, fewer components, such as compressors and pumps which are used to pressurise recirculating gas to combustion pressure are needed. Although the Allam cycle is more efficient than the SOF-NGCC, in terms of component size and cost the SOF-NGCC seems to be much more affordable than the Allam cycle. Compared to conventional NGCC integrated with PCC in which the exhaust gas needs to be pressurised after condensation to be ready for the CPU, in

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the SOF-NGCC as the turbine backpressure is 35 bar, further compression is not needed. A comparison of volumetric flow rate into the expanders, recirculating compressors and heat exchangers is summarised in Table 5.

Table 5. Comparison of SOF-NGCC and Allam cycle in terms of volumetric flow rate

Component	**SOF-NGCC (Case 1)**	**SOF-NGCC (Case 2)**	**Allam cycle**
	m^3/s	**m^3/s**	**m^3/s**
Expander	1.4	1.4	~83.1
s-CO_2 expander	18.6	18.7	-
Recirculation compressor	-	-	~1.06
Main heat exchanger	23.0	23.6	~143.8
s-CO_2 heaters	15.9	16.4	-
High-temperature recuperator	55.9	55.4	-
Low-temperature recuperator	30.6	28.3	-

4. Conclusions

The aim of this study is to analyse the effect of EGR elimination by applying staged-combustion in oxy-combustion cycles and recommend the new cycle, which is comparable with other available and proposed cycles, such as a conventional NGCC and Allam cycle. Therefore, a brief description of NGCC, Allam cycle and SOF-NGCC was presented. A parametric study was conducted by varying the inlet turbine conditions of both the topping and bottoming cycles of SOF-NGCC, and the HTR/LTR split fraction. Then, the optimal efficiency of the SOF-NGCC was compared with the other cycles in terms of performance and mass flow rate.

It was found that conventional NGCC has the highest net efficiency of 56.95%, due to its lower power requirement, as there is no ASU or CPU. This is followed by the Allam cycle (54.58%), and the SOF-NGCC (47.63–51.32%). However, in terms of component size and complexity, the SOF-NGCC is much smaller and simpler. The volumetric flow rate into the expander in the Allam cycle is almost 4 times higher than that in the SOF-NGCC and some components, such as compressors and pumps, are not necessary in the SOF-NGCC due to EGR elimination. Furthermore, with a turbine backpressure of 35 bar, no additional compression is required prior to the CPU. Finally, the effect of working temperature and pressure on the efficiency of SOF-NGCC is small, as at 120 bar and 950°C the efficiency drops by only 1.6% compared to working at 300 bar and 1250°C. These factors are expected to result in a profound reduction in the cost of the SOF-NGCC.

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Highlights

- Exhaust gas recirculation enables temperature control in oxy-fuel turbine cycles
- EGR increases system complexity and is difficult to achieve at high pressure
- Staged oxy-fuel combustion natural gas cycle is proposed to alleviate the need for EGR
- SOF-NGCC is shown to achieve the net efficiency of 47.63–51.32%
- SOF-NGCC is less complex and requires smaller equipment than the Allam cycle

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