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[1]Adel Bojeldain *, [2]Shahat Mohammed
[3]ABDELGADER ALKAREMI, and [4]FATHALLA BAKAR

Department of Mechanical Engineering, College of Technical Science, Derna, Libya
adelbojelain@gmail.com*
1- https://orcid.org/0009-0008-9261-4283
2- https://orcid.org/0009-0003-9769-8803
3- https://orcid.org/0009-0004-0998-7961
4- https://orcid.org/0009-0004-7826-3369

Abstract

The performance of conventional steam power plants is still severely limited by heat losses in the exhaust gas. This study proposes a waste-heat recovery concept for the Derna Steam Power Plant based on a supercritical carbon dioxide (sCO_2) closed Brayton cycle. The goal is simple. Get more power out of the boiler exhaust stream without burning more fuel. The fundamental mass- and energy-balance equations were used to model the thermodynamic behavior by numerical simulation in Engineering Equation Solver (EES). It was discovered by means of a detailed parametric analysis that the operating conditions strongly affect the performance of the cycle. The highest net work and the highest overall efficiency are obtained at 76.8 bar and 75.8 bar, respectively. The maximum thermal efficiency is achieved at about 230 bar. Temperature settings also count for a lot. Lowering the compressor inlet temperature and raising the exhaust-heat temperature from 300 °C to 500 °C increased the net power output from 2050 kW to over

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant
http://www.doi.org/10.62341/istj-vol39-2-ar30

4344 kW and increased the thermal efficiency from 22.8% to 32.01%, which reduced the back-work ratio. The above results provide solid support for the technical feasibility of the proposed scheme. Therefore, more attention should be paid to the practical implementation of the Derna plant, with more detailed economic assessments and exploration of integration with renewable energy sources.

Keywords: supercritical carbon dioxide; closed Brayton cycle; Derna Steam Power Plant.

تحليل الأداء الحراري والبارامتري لدورة ثاني أكسيد الكربون فوق الحرج لاسترجاع حرارة العادم بمحطة درنة البخارية

عادل بوجلدين*، شحات محمد، عبدالقادر الكريمي، فتح الله بكار
قسم الهندسة الميكانيكية، كلية العلوم التقنية، درنة، ليبيا
*adelbojelain@gmail.com

الملخص

تُمثل الفواقد الحرارية في غازات العادم تحدياً كبيرا يحد من كفاءة محطات توليد الطاقة. حيث تناقش هذه الدراسة تقييم أداء دورة "برايتون" المغلقة باستغلال ثاني أكسيد الكربون فوق الحرج (sCO_2) كمائع تشغيل لاسترداد الطاقة المهدرة من عادم الغلاية بمحطة درنة البخارية، بهدف توليد قدرة كهربائية إضافية دون استهلاك وقود إضافي. ولتحقيق ذلك، تم إنشاء نموذج رياضي ومحاكاة رقمية باستخدام برنامج حل المعادلات الهندسية (EES)استناداً لقوانين حفظ الكتلة والطاقة ضمن دراسة بارامترية شاملة. أظهرت النتائج استجابة عالية للمتغيرات التشغيلية؛ حيث تحددت القيمة المثلى للضغط المنخفض عند 75.8 بار لتحقيق أقصى كفاءة و76.8 بار لتحقيق أقصى شغل صاف، بينما بلغت الكفاءة الحرارية ذروتها عند ضغط عالٍ يناهز 230بار. وأسهم تخفيض حرارة دخول الضاغط ورفع حرارة العادم من 300°C إلى 500°C في إحداث قفزة نوعية؛ إذ أن الشغل الصافي تضاعف من 2050 كيلو وات إلى أكثر من 4344 كيلو وات، وارتفعت الكفاءة الحرارية من 22.8% إلى 32.01% مع انخفاض في نسبة الشغل

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

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العكسي. وتؤكد هذه النتائج الموثوقية والتفوق التشغيلي للنظام المقترح، موصية بجدوى تطبيقه فعلياً بمحطة درنة البخارية، وإجراء تحليل حراري متقدم ودراسة جدوى اقتصادية، فضلاً عن بحث آفاق دمج المنظومة مع مصادر الطاقة المتجددة لتعزيز الاستدامة.

الكلمات المفتاحية: ثاني اكسيد الكربون فوق الحرج؛ دورة برايتن المغلقة؛ محطة درنة البخارية.

1. Introduction

Energy availability to the world is one of the indicators of industrialization, economic progress, and sustainable development. Human desires to maintain themselves, their families, and their communities, and to enhance their quality of life, fuel the need for energy. Anticipated to reach seven billion, the world population will drive an increase in global energy consumption. Energy is the main driving force of the economic growth in modern times, as human progress has been bonded to the ability to exploit its sources and to convert them into useful forms (Breeze, 2019). Conventional power plants, which depend on fossil fuels such as coal, oil, and natural gas, as well as nuclear energy, have dominated the global energy scene for decades. The chemical or nuclear energy is transformed into thermal energy, and these plants generate steam to turn turbines that are coupled to electrical generators (Twidell et al, 2015). These plants are distinguished by their capacity to generate continuous and consistent baseload power and a high energy density that needs relatively modest land areas (Breeze, 2019). The current trend toward the development of sophisticated thermodynamic cycles is due to the increased need for higher energy conversion efficiencies and lower emissions. Among these, the supercritical carbon dioxide (sCO_2) Brayton cycle is regarded as a promising technique owing to its unique features, including high density and low viscosity, leading to excellent thermal performance over a broad temperature range.

In this sense, several past research studies have addressed the analysis and development of this cycle. Akbari et al. (2014) did the thermodynamic and economic research for the optimization of a combined cycle with a topping sCO_2 cycle and a bottoming Organic Rankine Cycle (ORC). The findings showed that this combination

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant
http://www.doi.org/10.62341/istj-vol39-2-ar30

enhances the overall power production by around 15%. It showed the significance of choosing intermediate operating conditions to prevent the expensive cost of heat exchangers. When considering its integration with renewable energy, Padilla et al. (2015) offered an exergy study in which the "recompression" configuration is the one with the maximum efficiency, and they said that the solar receiver is responsible for more than 68% of the exergy destruction. On another note, a critical review by Zhu et al. (2017) confirmed the promising potential of the cycle as a competitive alternative to the Rankine cycle by proving its viability in high-temperature waste heat recovery (above 450 °C) despite the technical challenges related to withstanding pressures up to 300 bar. To build cascaded heat recovery systems, Hou et al. (2018) devised a quadruple-level hybrid system. The introduction of the sCO_2 cycle as an intermediary step eliminated the pinch point issue and improved the total thermal efficiency by 3.12%. Moreover, Zhang et al. (2023) studied the use of the cycle in renewable energy applications. The cycle was shown to be better in Concentrated Solar Power (CSP) plants with efficiencies higher than 50%, but with limited use for low-temperature geothermal resources. In the industrial context, numerical modeling by Carapellucci et al. (2024) showed that the integration of the sCO_2 cycle with an ORC for exhaust waste heat recovery boosts the efficiency by 5%–12%. Finally, a comparison with the work of Maksimov et al. (2024) was performed, allowing a confirmation of the great superiority of the sCO_2 cycle in contrast to the steam and organic Rankine cycles in terms of specific power output when high-temperature sources are included.

The review demonstrates a scientific agreement on the high efficiency of the sCO_2 cycle at high temperatures and that its integration provides an ideal hybrid configuration for optimizing energy recovery. Despite this impressive academic achievement, there are still practical hurdles in operation when trying to implement these technologies in existing power plants. This is the case of the Derna Steam Power Plant, which is based mostly on a typical Rankine cycle whose thermal efficiency constraints have reached a plateau, resulting in the loss of a large part of the thermal energy of the fuel in the form of exhaust gases vented into the

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant
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environment. Existing heat recovery mechanisms in the boiler, i.e., the economizer and the air preheater, are installed, but the gases still leave the economizer with high-quality thermal energy, often higher than 300°C. This is a squandered technical opportunity to obtain more electrical power than just heating the air. Here is the real technical dilemma in the integration of an advanced technology such as the sCO_2 cycle to utilize this surplus: deciding on the precise engineering trade-off between extracting the maximum possible mechanical work to drive the extra turbine and keeping the combustion air temperature high enough when entering the boiler to ensure stable combustion and to avoid acid corrosion in the stack. This is especially important since the continued thermal waste leads to a rise of the specific fuel consumption and a decrease of the total efficiency, as well as an increase of the carbon emissions per produced megawatt.To fill this technological gap, this research aims to investigate and analyze the performance of the supercritical carbon dioxide (CO_2) Brayton cycle as a novel technology to recover the waste heat from the Derna Steam Power Plant exhaust gases and convert it to usable energy. To this end, the study seeks to establish the thermodynamic properties of the exhaust gases in order to define the system's input boundaries. Subsequently, an integrated numerical simulation model is developed in Engineering Equation Solver (EES) software to evaluate key performance indicators such as net power and thermal efficiency. Finally, the research includes a detailed parametric study to find out the best operating conditions (like the operating pressure, compression ratio (pressure ratio), and turbine inlet temperature), which ensure the best cycle efficiency without affecting the basic operational stability of the power plant.

2. The Targeted Power Plant Description

The proposed system in Figure 1 is based on the integration of the supercritical carbon dioxide sCO_2 Brayton cycle as a topping heat recovery cycle to use the exhaust gasses leaving the economizer at the Derna Steam Power Plant whose temperature is more than 300 °C, representing a substantial energy loss in the boiler system as established in a previous study (Bojeldain et al, 2022).

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

http://www.doi.org/10.62341/istj-vol39-2-ar30

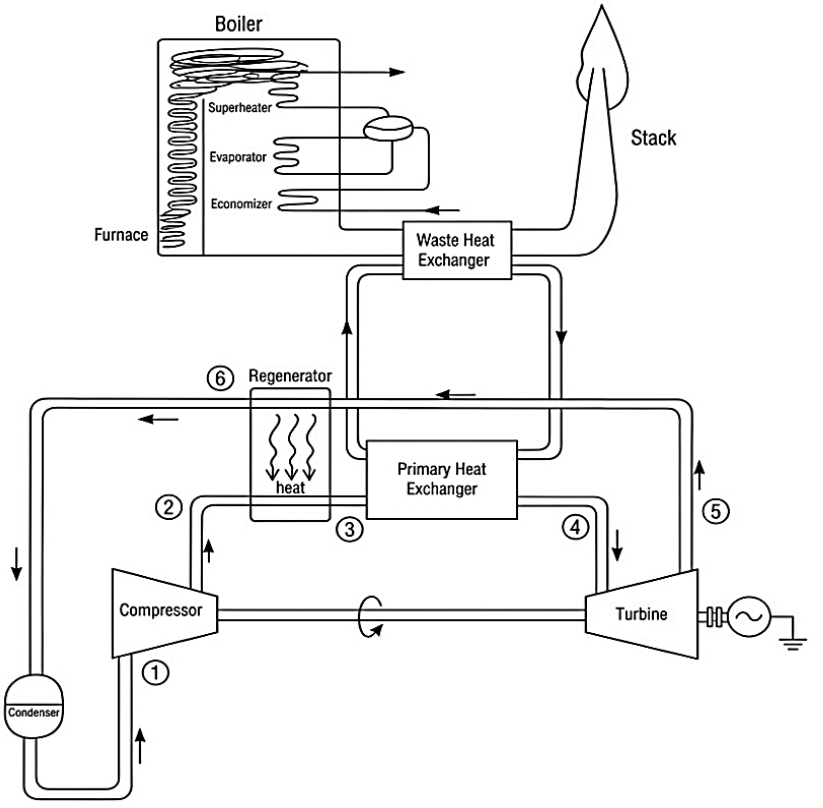


Fig. 1. Configuration of the proposed plant.

The engineering system is constituted by a primary heat exchanger (PCHE) for the heat exchange between the exhaust gasses and the working fluid sCO_2, an advanced turbine for the generation of further mechanical work, a condenser and a cooler to set the fluid state close to the critical point before entering the compressor and a compression cycle that enhances the overall efficiency. The integration is intended to strike a fine balance between the maximum extraction of additional electrical power and the safe temperatures of the combustion air so as not to have any detrimental influence on the stability of the boiler and no acid corrosion in the stack. The particular operation conditions of the power plant are given in Table 1 below.

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant
http://www.doi.org/10.62341/istj-vol39-2-ar30

Table 1. Operating conditions of the power plant.

Operating condition	Value
Flue gas mass flow rate	60.3kg/s
Exhaust gas temperature after the economizer	318 ºC
Stack gas temperature	130 ºC
High pressure	200 bar
Low pressure	75 bar

3. Methodology

The performance of the proposed supercritical carbon dioxide sCO_2 Brayton cycle for waste heat recovery from the exhaust gasses of the Derna Steam Power Plant was assessed through the development of a complete mathematical model and an integrated numerical simulation using the Engineering Equation Solver (EES) software. The basic model is based on applying the general conservation rules of mass and energy to each component of the system during steady-state operation. Where the mass continuity equation reflects the equality of the intake and output mass flow rates according to the formula:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

Calculating the whole energy balance by the equation from the first law of thermodynamics:

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{2}$$

The initial phase of the application of these rules was the determination of the inputs of the heat recovery system by specifying the thermodynamic parameters of the exhaust gasses leaving the economizer of the Derna plant. This includes the mass flow rate and the temperature over 300 °C to guarantee correct computation of the available heat for recovery via the main heat exchanger. This was then followed by the full mathematical modeling of the cycle components. The heat exchanger was

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant
http://www.doi.org/10.62341/istj-vol39-2-ar30

modeled for the calculation of the exchanged heat transfer rate taking into consideration the pinch point calculation to guarantee that no temperature crossover occurs. In addition, the quantity of heat rejected via the condenser was estimated to bring the working fluid back to its suitable condition. Meanwhile, the created and consumed work were calculated based on the expansion and compression efficiencies and the intake and output pressures.
For assessing the efficiency of the system, the governing equations were coded to determine the key performance indicators (KPIs) such the net power production and the thermal efficiency of the additional cycle. Finally, the parametric analysis tools of EES software were used to find the optimum operating conditions by analyzing the effect of changing the main operating parameters such as maximum operating pressure, compression ratio and turbine inlet temperature on the overall efficiency and net power output while meeting the operational constraints set to maintain the combustion stability of the base plant and prevent acid corrosion in the stack.

Assumption:

- Steady-state operation.
- Considering carbon dioxide sCO_2 as a real fluid.
- Maintaining the exhaust gas temperature above the dew point to prevent corrosion.
- Assuming an efficiency of 85% for both the compressor and the turbine.
- Assuming a heat exchange efficiency of 90% between the exhaust gases and the working fluid.

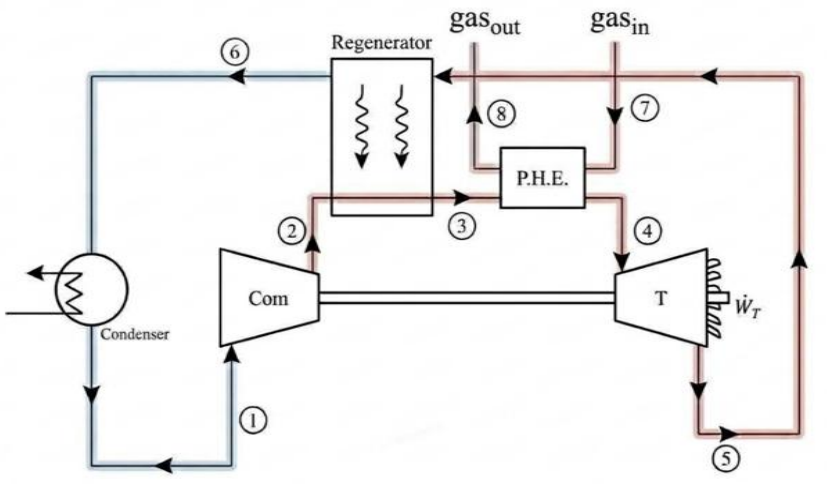
4. Results and Discussion

This section summarizes the findings of the simulation and the parametric research carried out to assess the performance of the proposed sCO2 cycle, operating in a pressure range between 75 bar (low pressure) and 200 bar (high pressure). The aim of this presentation is to do the sensitivity analysis of the main performance characteristics, i.e. the thermal efficiency and the net power output, against the alteration of the driving operating parameters of the

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

http://www.doi.org/10.62341/istj-vol39-2-ar30

system. The parameters include operating pressures , Turbine Inlet Temperature and exhaust gas characteristics i.e. temperature and mass flow rate. The findings are interpreted by graphical figures and explanatory tables to show the thermodynamic patterns and their effect on energy transfer and consumption in the components. This discussion is helpful to learn more about the plant behavior and to find the best operation settings that guaranty the maximum efficiency and reliability feasible. According to the schematic design and the state points specified in Figure 2 and Table 2.



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Fig. 2. Schematic diagram of the proposed plant.

Table 2. Operational data of the proposed plant.

State point	T (°C)	P (bar)	h (kJ/kg)	s (kJ/kg·K)
1	32	75	-144.1	-1.206
2	86.67	200	-113.3	-1.193
3	150.4	200	17.07	-0.857
4	303	200	224.4	-0.436
5	208.2	75	144	-0.413
6	97.47	75	13.6	-0.722
7	318	1.013	598	6.393
8	165.4	1.013	440.4	6.085

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

http://www.doi.org/10.62341/istj-vol39-2-ar30

The results of the numerical simulation obtained by solving the thermal equilibrium equations presented in the methodology section using Engineering Equation Solver (EES) are shown in Table 3.

Table 3. Results of the Engineering Equation Solver (EES).

$\dot{m}_{sCO_2}$ (kg/s)	45.83
$\dot{m}_{gas}$ (kg/s)	60.3
$\dot{w}_c$ (kW)	1411
$\dot{w}_t$ (kW)	3687
$\dot{w}_{net}$ (kW)	2276
$\dot{Q}_{in}$ (kW)	9503
bwr %	38.28
η_{th} %	23.95

The impact of raising the low side pressure (74-78 bar) on the thermodynamic performance of the cycle is shown in Figure 3.

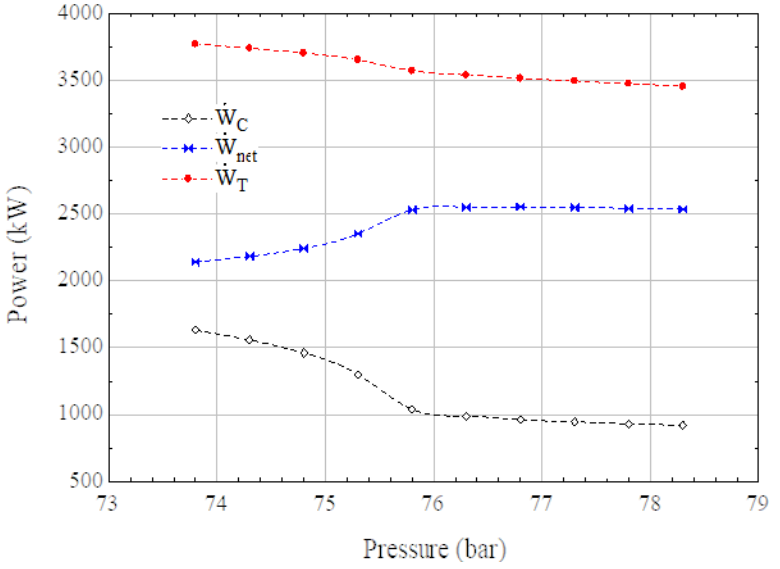


Fig.3. Effect of varying the low pressure on the compressor work, turbine work, and the plant's net work.

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

http://www.doi.org/10.62341/istj-vol39-2-ar30

The increase in pressure decreases the compressor work, because of the enhanced thermophysical characteristics of the fluid at the critical point, and at the same time reduces the turbine work, because of the lowered expansion ratio. The net work production achieves an operational maximum at a pressure of around 76 bar because of the combination of these two trade-off effects and then levels off progressively thereafter. Therefore, the research shows that the ideal low side pressure exists, which may guaranty the increase of net work production without deterioration of turbine expansion performance.

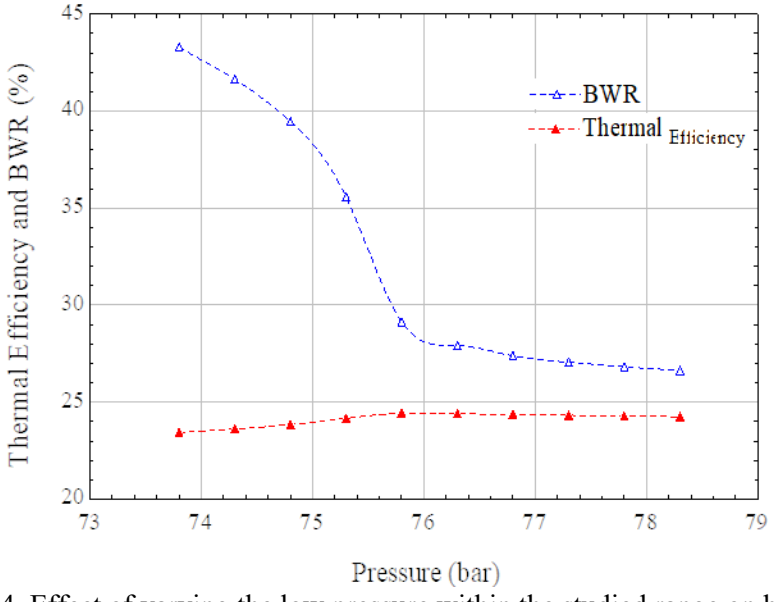


Fig.4. Effect of varying the low pressure within the studied range on both the plant's thermal efficiency and (BWR).

Figure 4 shows the impact of the low side pressure on the thermal efficiency and Back Work Ratio (BWR). The thermal efficiency is optimum at 75.8 bar because of decrease in compression work and increase in net work production, then it levels off progressively thereafter. In contrast, the BWR displays a continuous decrease at 75 bar, driven by the abrupt variations in the thermophysical characteristics of the fluid close to the sCO_2 critical point, and then a gradual stabilization at higher pressures. This large drop in the

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

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BWR implies an increase in the performance of the cycle because the ratio of compressor work to turbine work is reduced.
As shown in Figure 5, raising the high pressure in the range of 160–250 bar results in a proportionate increase in both compressor and turbine work. The work of turbine increases with the rise in the enthalpy difference but the compressor work requirements are lesser than the increase in turbine work. So, the net work of the plant is continuously increasing. Thus, increase in high pressure increases the power production. However, the ideal operating pressure of the plant should be determined by simultaneous consideration of the thermal efficiency and the back work ratio.

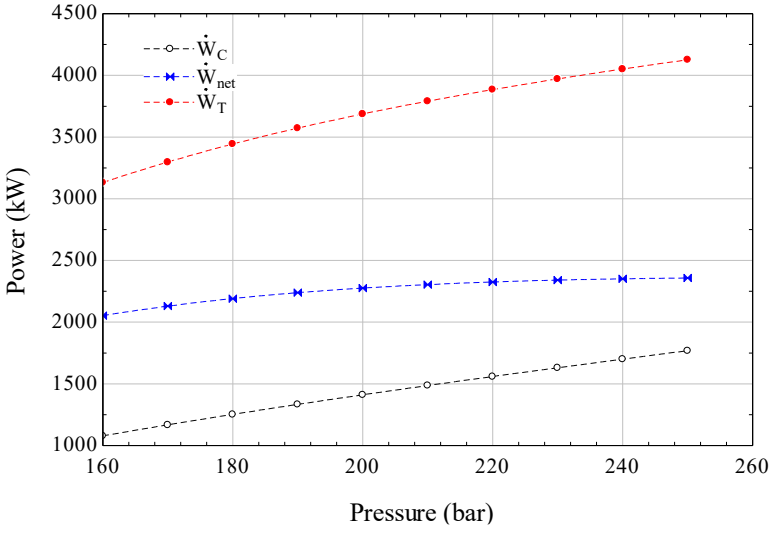


Fig.5. Effect of varying the high pressure on the compressor work, turbine work, and the plant's net work.

Figure 6 illustrates that the thermal efficiency of the plant increases steadily up to around 230 bar and then levels off asymptotically as the pressure continues to rise up to 250 bar due to the balanced enhancement in work production. Meanwhile, the back work ratio increases almost linearly (from 35% to over 43%) with the increasing of the compressor power consumption, which takes a

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

http://www.doi.org/10.62341/istj-vol39-2-ar30

growing part of the power output of the turbine. So, the results indicate that the operating pressure range is the optimal operational pressure, as it yields the best compromise between the rising thermal efficiency and the adverse effect of a high back work ratio.

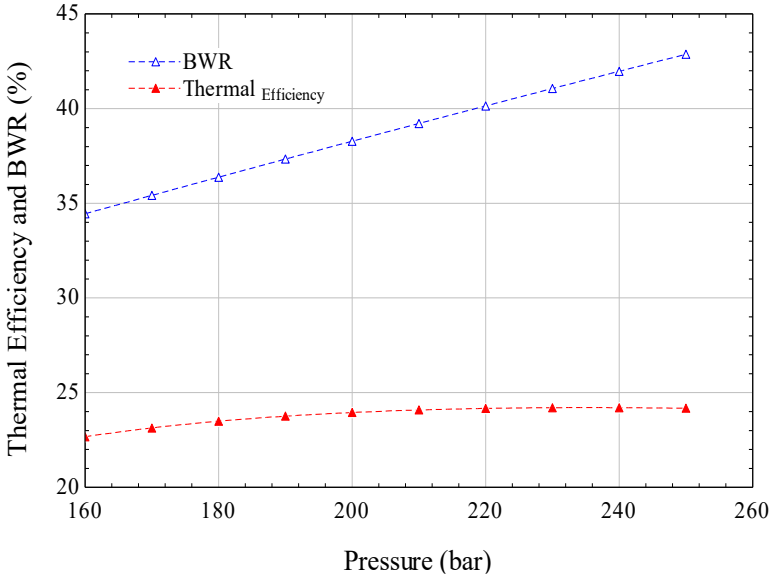


Fig.6. Effect of varying the high pressure on both the plant's thermal efficiency and back work ratio.

Figure 7 demonstrates that compressor work is consistently increased with the rise of the compressor intake temperature (from 31°C to 40°C) which is above the marginal gain of turbine work. Since this extra turbine work is not enough to balance the increasing compression needs, the plant's net work steadily declines. Hence it can be stated that high intake temperatures have a negative influence on the overall performance, which leads to a decrease in the net power production of the plant.

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

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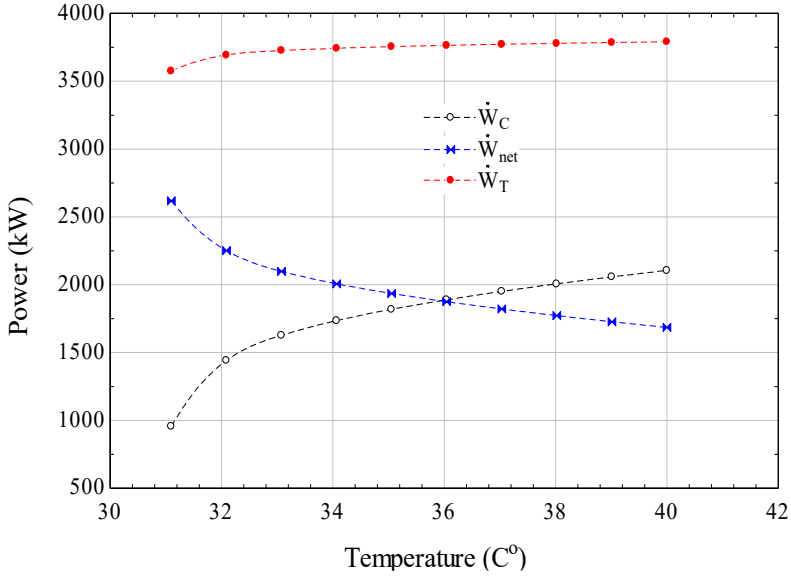


Fig. 7. Effect of varying the compressor inlet temperature on the compressor work, turbine work, and the plant's net work.

The impact of changing the compressor input temperature from 30.1°C to 40°C on the thermal efficiency and back work ratio (BWR) is shown in Figure 8. The findings show an obvious negative association with progressive decrease of thermal efficiency and significant and continuous rise of back work ratio. Thermodynamically this tendency may be explained by the fact that the greater the fluid temperature at the compressor input, the higher the effort needed to perform the compression process. However, the increased turbine work due to the higher cycle enthalpy is not sufficient to make up for the increased power consumption of the compressor. The compressor work increases at a quicker rate than the net work. One obvious result is that the compression process takes an increasing percentage of the unit's total gross power (thus explaining the increasing back work ratio). This finally causes the thermal efficiency of the plant to degrade.

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

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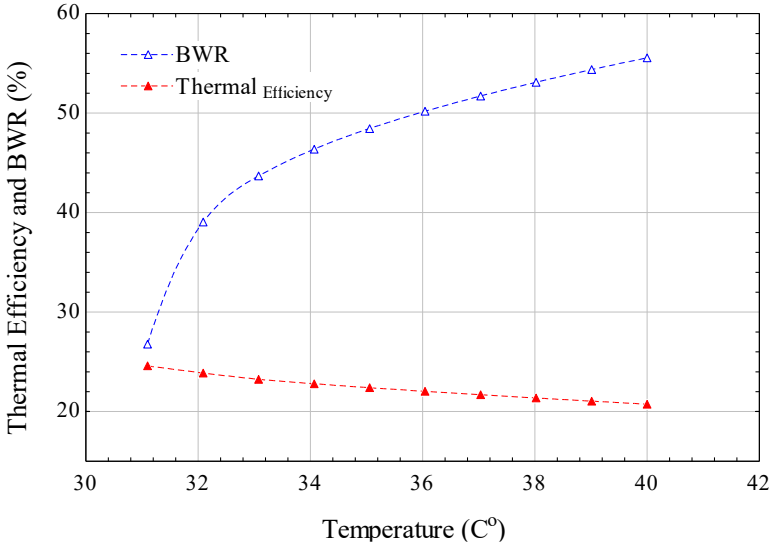


Fig. 8. Effect of varying the compressor inlet temperature on the thermal efficiency and back work ratio.

Figure 9 depicts the influence of different exhaust gas temperatures on mechanical performance parameters of the plant, including compressor work, turbine work and net work. The findings show a direct proportionality of these factors with the increase of the temperature, but with different growth rates. Compressor work shows a little, steady rise, due to higher heat transfer rates in the system, but turbine work increases considerably. The major performance gain of the turbine is due to the increased availability of thermal energy (enthalpy) at higher temperature which directly increases the power produced by the turbine. The net work of the plant increases quasi-linearly since the increase in turbine work is much more than the increased compressor demand. These data show the very favorable effect of increasing the exhaust gas temperatures so as to optimize the net power of the cycle. This validates the thermodynamic feasibility of using high temperature exhaust sources to improve the performance of the system.

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

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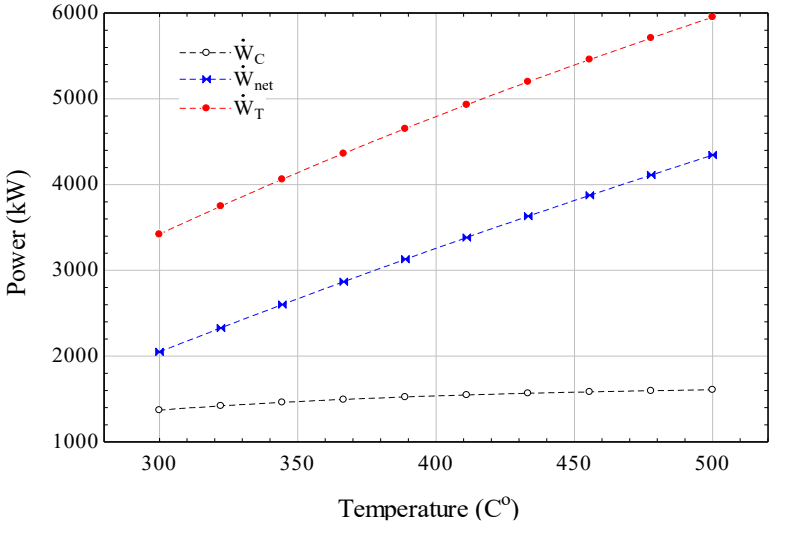


Fig. 9. Effect of varying the exhaust gas temperature on the compressor work, turbine work, and the plant's net work.

The trends of Figure 10 show the double favorable impact of raising the exhaust gas temperature (from 300°C to 500°C) on the overall plant performance. The increase in accessible thermal energy and the increase in net work caused a significant improvement in thermal efficiency (from 22.81% to 32.01%). This was accompanied by a dramatic decrease in the back work ratio (from 40% to 27%) indicating that the fraction of power spent internally was lowered. Thus, the use of high-temperature exhaust gasses is an effective means of increasing the cycle efficiency and enhancing its general performance characteristics.

As shown in Figure 11, the increase of the exhaust gas flow rate (in the range from 0.1 to 1.0) has a quasi-linear, directly proportionate influence on all the work values throughout the cycle. The higher rate of thermal energy transfer to the working fluid increased the turbine power (3687 kW) at a rate higher than the equivalent increase in work required by the compressor. This positive deviation led to a significant increase in the net work of the plant (from 228 kW to 2276 kW) proving the crucial relevance of managing the flow

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant

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of exhaust gasses as a basic pillar for enhancing the overall system performance.

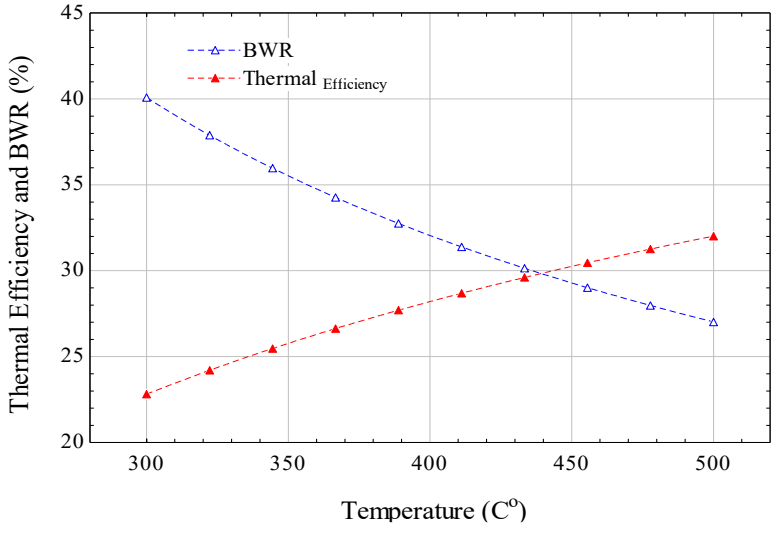


Fig. 10. Effect of varying the exhaust gas temperature on both the thermal efficiency and back work ratio.

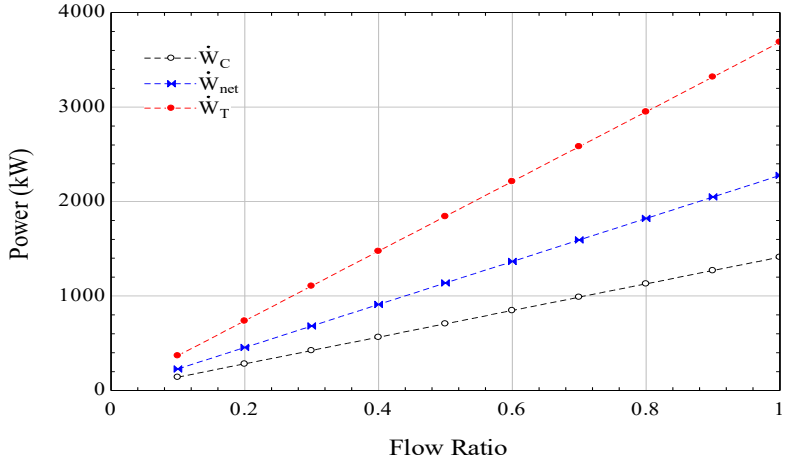


Fig. 11. Effect of varying the exhaust gas flow rate on the compressor work, turbine work, and the plant's net work.

Thermodynamic Analysis and Parametric Study of a Supercritical sCO2 Closed Brayton Cycle for Waste Heat Recovery at Derna Steam Power Plant
http://www.doi.org/10.62341/istj-vol39-2-ar30

Figure 12 shows that, regardless of the exhaust gas flow rate, there is a significant stability in the thermal efficiency (23.95 %) and in the back work ratio (38.28 %). It can be concluded that in the range tested, the work and heat terms increase proportionally with the flow rate, without significantly influencing the energy recovery efficiency. This means the influence of this variable is reduced to the increase of total power production capacity of the plant, without any influence on the main thermal performance parameters.

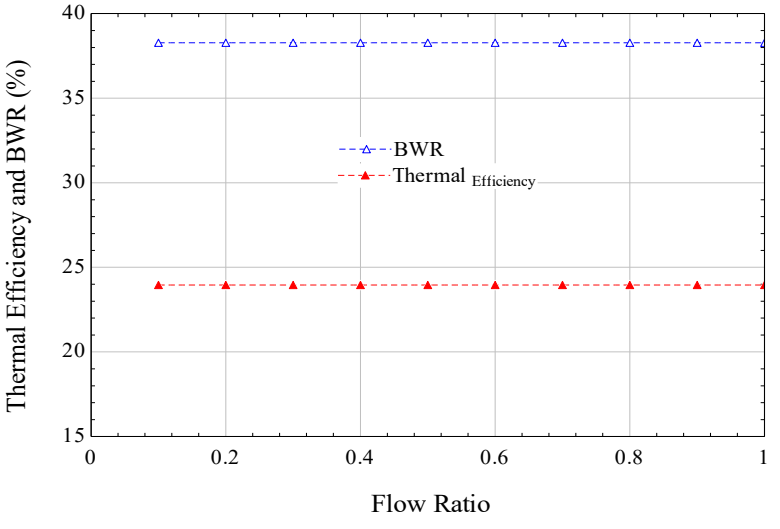


Fig. 12. Effect of varying the exhaust gas flow rate (Flow Ratio) on the cycle's thermal efficiency and back work ratio.

5. Conclusion

The detailed thermodynamic study of the performance of the proposed supercritical carbon dioxide (sCO_2) power plant cycle against the variation of the basic operational parameters leads to the following scientific conclusions:

1. Effect of low operating pressure: Low pressure is an important factor in determining the performance of the cycle. An ideal working point was found at around 76 bar, when the plant reaches its maximum limits for net work and 78 bar for thermal efficiency, followed by a progressive leveling off. Any

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variation away from this number results in a stabilization rather than a sharp deterioration in overall performance because of the stable expansion process in the turbine.

2. Effect of high operating pressure: The continuous increase of high pressure helps to maximize the net work and overall capacity of the plant in a linearly proportionate ratio. However, thermal efficiency is characterized by a continuous slight increase and its highest value is reached at a pressure of around 230 bar, as it keeps rising steadily. This behavior is caused by the balanced enhancement in work production despite the increased compressor work needs and the increased back work ratio (BWR).
3. Compressor inlet temperature impact: Results showed a significant negative effect on overall performance of high fluid temperature at compressor intake. The rise in input temperature leads to a large increase in power consumption during the compression process at the price of net work, thereby diminishing thermal efficiency. Hence, the design and operational choice of the cycle should be carried out at the minimum compressor inlet temperature for the purpose of improving thermodynamic indicators.
4. Effect of exhaust gas temperature: Exhaust temperature is the most important variable that affects the energy recovery efficiency. Increasing the temperature from 300°C to 500°C caused a dramatic rise in net work and a significant improvement in thermal efficiency (from around 22.8% to 32.01%). This increase was accompanied by a continuous decrease in the back work ratio (from 40% to 27%), which proved the efficacy of higher temperature in improving the energy conversion and the efficient use of the available thermal content.
5. Effect of exhaust gas flow rate: With the increase of the flow rate, the produced power and net work of the plant are amplified in a quasi-linear connection, which indicates that a direct capacity scaling is there. However, this variable was completely independent of the thermal properties of the cycle,

http://www.doi.org/10.62341/istj-vol39-2-ar30

and had no fundamental influence on the thermal efficiency and the back work ratio which were stable in the range investigated.

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