CHEMICAL ENGINEERING TRANSACTIONS

VOL. 88, 2021

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188134

Dynamic Study of Load Detachment in Supercritical Carbon Dioxide Brayton Cycle

Lianjie Zhang[a], Jiří Jaromír Klemeš[b], Min Zeng[a,*], Ting Ma[a], Qiuwang Wang[a]

[a] Key Laboratory of Thermo-Fluid Science and Engineering, MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shanxi, 710049, P.R. China.
[b] Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
zengmin@mail.xjtu.edu.cn

The supercritical carbon dioxide Brayton cycle has become the choice of a wide range of users because of its higher efficiency and smaller turbine size, and is often used in space vehicles, sodium cooled fast reactors, Marine power equipment and other energy storage and power generation applications. However, in the process of use, the detachment of the load is a common problem, if not well handled often cause the system to crash. In this paper, based on the software Simulink in MATLAB, the moment of inertia of turbine and generator is regarded as fixed value, the key parameter differential equations of Brayton cycle are derived, and the dynamic recompression and intercooling Brayton cycle models are established. The response parameters of the system after load disconnection and different time tie-back are studied. The responses of key parameters of the system after load detachment were obtained. It was found that the recompression model had higher stability under load detachment and tie-back conditions than the intercooling model, and the length of parameter variation after load detachment was linear. The earlier the tie-back was, the faster the system could restore stability.

1. Introduction

The development and application of SCO_2 power cycle has attracted wide attention in recent years due to its application in different energy industries, especially nuclear power and solar energy (Li et al., 2017). The advantages of this cycle are high efficiency, economical structure and convenience. Traditional steady-state models are no longer suitable for more complex variable conditions and transient studies. (Deng et al., 2019) used the dynamic model of the Brayton cycle of supercritical CO_2 repress to study the influence of high and low temperature regenerators on the dynamic characteristics of the cycle. However, in terms of model building, he simplified the relationship between enthalpy and power of inlet and outlet of the turbine, without considering the change of turbine speed. (Wang et al., 2021) gave a detailed review of the dynamic performance and control strategies of SCBC (supercritical carbon dioxide Brayton cycle). SCBC dynamic simulation model was introduced in detail, and the model of main components of different modelling methods and validation of the system model, finally they introduced the load tracking and control strategies. The content covers most of the current scholars' research methods on SCBC dynamic simulation, but they all simplify the treatment of turbine. (Yang et al., 2021) studied the load variation and matching in the Brayton cycle, and from the perspective of thermal efficiency and exergy efficiency, (Hu et al., 2020) studied the variation of thermal parameters and cycle performance with power generation under partial load, and (Gao et al., 2021) defined the dynamic performance of the SCO_2 Brayton system by simulating the load variation of the grid from 100 to 0 to 100 %. However, (Moisseytsev et al., 2008) proposed that the common failure conditions of SCBC include load detachment, which requires dynamic analysis of the turbine. Other scholars used empirical formulas to predict the turbine speed, ignoring that the actual rotation speed of the turbine in the system is affected by multiple parameters. In this study, the original supercritical carbon dioxide Brayton cycle model is improved, and the turbine module which was previously briefly processed is further refined. The dynamic model of turbine speed is obtained by using the characteristic of turbine's and generator's constant moment of inertia as well as the related energy conservation equation. Compared with the empirical correlation formula used by previous scholars, the changes

Paper Received: 18 May 2021; Revised: 19 July 2021; Accepted: 5 October 2021
Please cite this article as: Zhang L., Klemeš J.J., Zeng M., Ma T., Wang Q., 2021, Dynamic Study of Load Detachment in Supercritical Carbon Dioxide Brayton Cycle, Chemical Engineering Transactions, 88, 805-810 DOI:10.3303/CET2188134

of system parameters after load detachment and tie-back are simulated more accurately. The transient analysis and the comparison of recompression and intercooling models are carried out for the fault condition of load detachment, which can provide guidance for users in actual operation.

2. Numerical model

In this study, the recompression model is adopted, which is the most commonly used and typical one in SCO_2 Brayton cycle.

2.1 Turbomachinery and electric generator

The turbine mechanical model of turbine and compressor is designed based on the thermodynamic principle of turbine machinery. In the compression process of the compressor and the expansion process of the turbine, entropy is considered to be constant. Isentropic efficiency and pressure ratio are assumed to be constant, which only depends on the design parameters of the turbomachinery. When the parameters of the turbine and compressor inlets are given, the parameters of outlet can be calculated according to the condition of isentropic expansion. In addition, considering the intershaft of turbine and compressor, the rotation frequency of both is the same, and the moment of inertia of the two objects is expressed by a parameter, and the rated speed is considered to be the common speed of steam turbine, 3,000 RPM. The generator is connected to the steam turbine, and the moment of inertia should be the same under normal operating conditions.

$$W_T = q \cdot (h_{T,i} - h_{T,o}) \cdot \eta_T \tag{1}$$

$$W_{C1} = q_{C1} \cdot (h_{C1,o} - h_{C1,i}) / \eta_{C1} \tag{2}$$

$$W_{C2} = q_{C2} \cdot (h_{C2,o} - h_{C2,i}) / \eta_{C2} \tag{3}$$

$$J_T \cdot \omega \frac{d\omega}{dt} = W_T - W_{C1} - W_{C2} - P_e \tag{4}$$

$$J_e \frac{d\omega}{dt} = \frac{P_e}{\omega} - F \tag{5}$$

where W_T, W_{C1} and W_{C2} are the powers of the turbine, main compressor and recompressor. q, q_{C1}, q_{C2} are the flow rate of the turbine, main compressor and recompressor. The symbols $h_{T,i}$, $h_{T,o}$, $h_{C1,i}$, $h_{C1,o}$, $h_{C2,i}$ and $h_{C2,o}$ denote the enthalpy at the inlet and outlet of turbine, main compressor and recompressor. η_T, η_{C1} and η_{C2} are the isentropic efficiencies of the turbine, main compressor and recompressor. J_T is the combined moment of inertia of turbine and compressor, and J_e is the moment of inertia of the generator. P_e is the generating power and F is the generator torque, ω is the rotational speed.

When the load disassociates, the generation power P_e is 0, and the speed of the turbine and compressor will increase. After a period of time, the load is connected back. Assuming that elastic collision occurs between the turbine and the generator, the collision energy loss is ignored as follows:

$$\frac{1}{2} J_T \omega_T^2 + \frac{1}{2} J_e \omega_e^2 = \frac{1}{2} (J_T + J_e) \omega_{Tx}^2 \tag{6}$$

Where ω_T is the rotational angular velocity of turbine, ω_e is the rotational angular velocity of generator, and ω_{Tx} is the rotational angular velocity of turbine and generator after collision. Therefore, the turbine speed at the tie-back moment can be expressed as:

$$\omega_{Tx} = \left(\frac{J_T \omega_T^2 + J_e \omega_e^2}{J_T + J_e}\right)^{\frac{1}{2}} \tag{7}$$

2.2 Recuperators

According to the first law of thermodynamics, the hot side and the cold side of the regenerator should be satisfied:

$$q_h C_{p,h} (T_{h1} - T_{h2}) - \dot{Q} = M_h C_{p,h} \frac{d\bar{T}_h}{d\tau} \tag{8}$$

$$q_c C_{p,c} (T_{c1} - T_{c2}) + \dot{Q} = M_c C_{p,c} \frac{d\bar{T}_c}{d\tau} \tag{9}$$

Where q_h and q_c are the mass flow rates of SCO_2 on hot and cold sides, $C_{p,h}$ and $C_{p,c}$ are the specific heat capacities of SCO_2 on the hot and cold sides, T_{h1}, T_{h2}, T_{c1} and T_{c2} are the hot-side inlet temperature, hot-side outlet temperature, cold-side inlet temperature and cold-side outlet temperature of SCO_2, $\dot{Q}$ is the heat transfer

rate in the recuperator, M_h and M_c are the masses of SCO2 on hot and cold sides of the recuperators at the specific time, and which are determined by the design parameters of the recuperators, $\bar{T}_\mathrm{h}$ and $\bar{T}_\mathrm{c}$ are the average temperatures of SCO2 on the hot and cold sides, and τ is time.
The average temperature of SCO2 on each side of the recuperators can be obtained by

$$\bar{T}_h = \frac{1}{2}(T_{h1} + T_{h2}) \tag{10}$$

$$\bar{T}_c = \frac{1}{2}(T_{c1} + T_{c2}) \tag{11}$$

Based on the overall heat transfer equation, $\dot{Q}$ can be calculated by

$$\dot{Q} = KA\Delta T_\mathrm{m} \tag{12}$$

where K, A and ΔT_m are the overall heat transfer coefficient, total heat transfer area and the log-mean temperature difference. The parameters K, A M_h and M_c are obtained from the thermal design calculation under the design conditions.
The numerical relationship between the derivative of the outlet temperature of the hot side and the cold side of the recuperator with respect to time and the derivative of the inlet temperature with respect to time can be obtained by Eqs. (8)-(11):

$$\frac{dT_{h2}}{d\tau} = \frac{q_h C_{p,h}(T_{h1}-T_{h2}) - \dot{Q} - \frac{1}{2}M_h C_{p,h}\frac{dT_{h1}}{d\tau}}{\frac{1}{2}M_h C_{p,h}} \tag{13}$$

$$\frac{dT_{c2}}{d\tau} = \frac{q_c C_{p,c}(T_{c1}-T_{c2}) + \dot{Q} - \frac{1}{2}M_c C_{p,c}\frac{dT_{c1}}{d\tau}}{\frac{1}{2}M_c C_{p,c}} \tag{14}$$

Two inlet temperatures and mass flow rates are set as input signals, and the design parameters are set as constant parameters of the S-function. In Eqs (13) and (14), the two derivatives on the right side are obtained from the derivative block of Simulink outside the S-function and are set as extra input signals. Consequently, every variable in the equations can be calculated by using the four temperatures and the constants.

2.3 Model validation

With the operation of the simulation system, it is found that the system reaches a stable state around 1,500 s. At this time, compared with the experimental values of Sandia Laboratory (Pasch, et al.,2012), it is found that the differences of all key parameters are within the acceptable range:

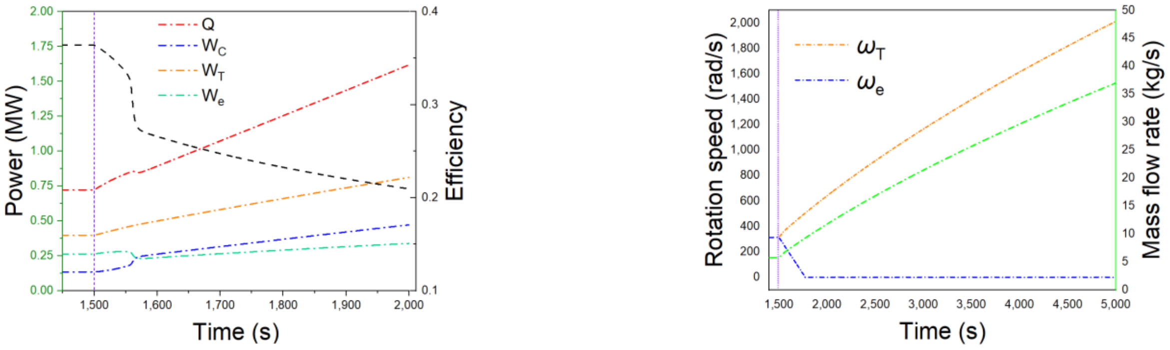
Table 1: Comparison and relative error between simulated steady-state values and experimental values of the recompressed Brayton cycle system

Parameters	Efficiency	Q	W_{C1}	W_{C2}	W_T	W_P
Experimental values	32.31 %	780.0 kW	51.0 kW	87.0 kW	391.0 kW	253.0 kW
Simulation values	36.40 %	723.5 kW	47.3 kW	87.2 kW	397.9 kW	263.4 kW
Relative error	12.67 %	7.24 %	7.33 %	0.28 %	1.76 %	4.10 %
Parameters	$T_\mathrm{C1,i}$	$T_\mathrm{C2,o}$	$T_\mathrm{T,i}$	$T_\mathrm{LTR,C,i}$	$T_\mathrm{LTR,C,o}$	$T_\mathrm{LTR,H,i}$
Experimental values	305.0 K	389.0 K	810.0 K	324.0 K	389.0 K	418.0 K
Simulation values	304.5 K	381.8 K	807.5 K	319.6 K	391.0 K	420.1 K
Relative error	0.15 %	1.86 %	0.30 %	1.36 %	0.51 %	0.51 %
Parameters	$T_\mathrm{LTR,H,o}$	$T_\mathrm{HTR,C,i}$	$T_\mathrm{HTR,C,o}$	$T_\mathrm{HTR,H,i}$	$T_\mathrm{HTR,H,o}$	
Experimental values	335.0 K	389.0 K	698.0 K	750.0 K	418.0 K	
Simulation values	333.6 K	387.2 K	703.7 K	736.6 K	420.1 K	
Relative error	0.43 %	0.46 %	0.82 %	1.78 %	0.51 %	

As shown in Table 1, only the relative error of the cycle efficiency is large at 12.67 %, the relative error of other parameters related to power is within 8 %, and the relative error of parameters related to temperature is within 2 %, these results illuminate that the simulation system of the recompression Brayton cycle is convincing.

3. Results and discussion

In industrial practice, there will be load detachment. In this paper, the parameters of the recompression Brayton cycle model are simulated when the load is detached after the recompression Brayton cycle model reaches stable state.

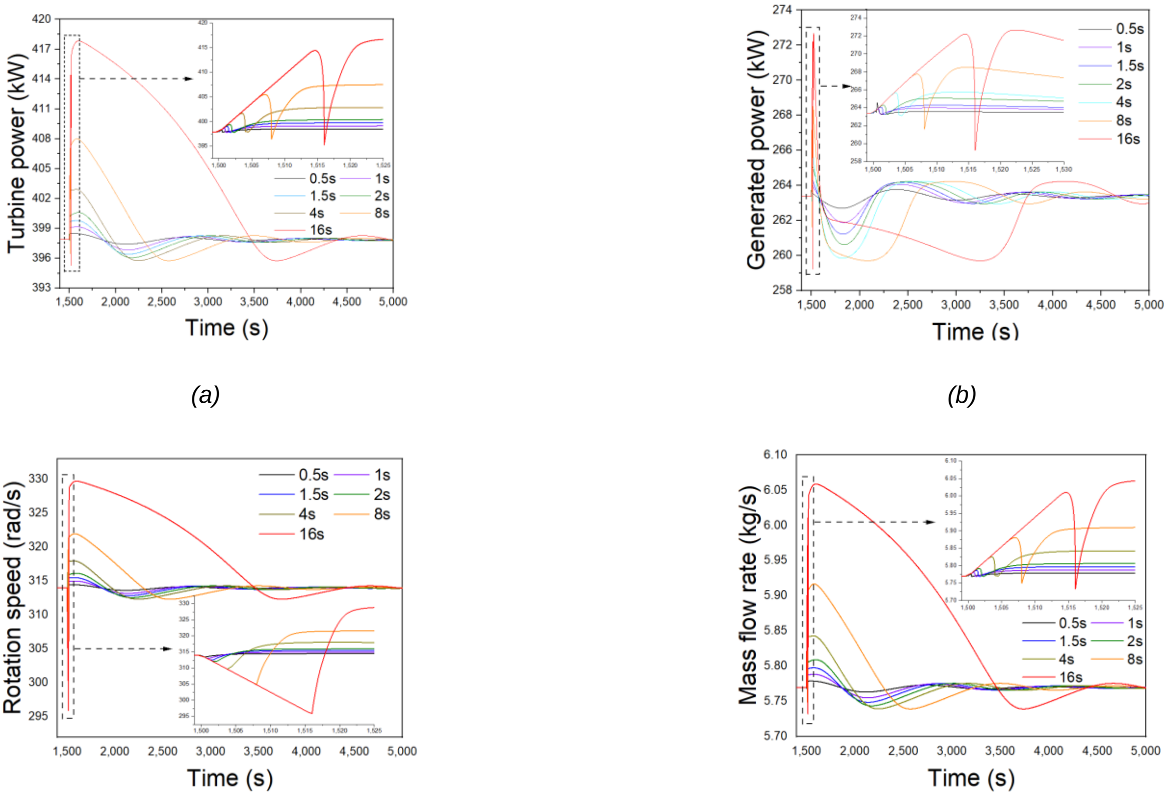


(a) (b)

Figure 1: Parameter response after load detachment in recompression Brayton cycle: (a) Power and efficiency; (b) Temperature; (c) Rotation speed

As can be seen from Figure 1(a), at the moment of load detachment, cycle efficiency began to decrease and the rate of decline became faster; after approximately 70 s, cycle efficiency began to decrease slowly and steadily. Both the compression power and turbine power in the system increased, and the generating power also increased overall, but showed a slightly declining trend during about 60 s to 70 s. In (b), it can be seen that turbine's rotation speed almost rises in a straight line, while generator's rotation speed drops to zero in a straight line, and the system flow is also pushed along and shows a straight rise trend due to the soaring turbine's rotation speed.

However, in industrial applications, this is often found when the load is detached and the load is reconnected in a short period of time. The length of the tie-back time will also have different effects on the system parameters.



(a) (b)

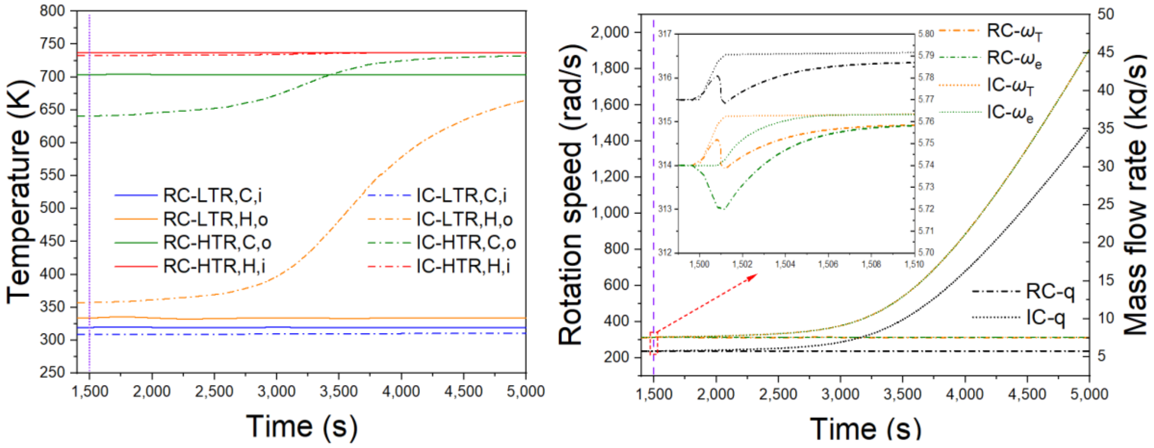
(c) (d)

Figure 2: The influence of the duration of reconnection after load detachment on system parameters in the recompression Brayton cycle: (a) Turbine power; (b) Generated power; (c) Generator's rotate speed; (d) Mass flow rate

It can be seen from (a), and (d) that the variation trends of turbine power, turbine speed and mass flow rate are very similar after load detachment and tie-back. Both increase rapidly in proportion to the length of detachment in an instant and then begin to drop below the initial rating after load retraction and then stabilize at the initial rating before slowly rising back up. It can be seen from the change size that the magnitude of parameter change is proportional to the tie-back time. The longer the separation time is, the longer the time required to return to the stable state after the tie-back is.

In (b), the generation power also increases rapidly after the load is detached, but shows a faster decline rate after the tie-back, and returns to the initial value in a shorter time. However, the time it takes to stabilize to the initial value is longer than that of the turbine power. As for the generator speed in (c), it decreases after the load disconnects and then quickly returns to the stable state with the load tie-back, which is more stable than the turbine speed.

In addition to recompression, the intercooling model is also a very common Brayton cycle model. This model uses two cooling cycles, greatly reducing the compression work and thus increasing the efficiency of the entire cycle. In this paper, we compare the response of various parameters between the recompression model and the intercooling model after 1 s tie-back after load detachment.



(a) *(b)*

Figure 3: Parametric comparison of recompression-intercooling model after load tie-back: (a) Temperature; (b) Rotation speed and mass flow rate

As for the temperature change, it can be seen from (a) that the temperature change of the recompression model is also a rapid recovery to stability, while the temperature of the cold side outlet of the high-temperature regenerator and the hot side outlet of the low-temperature regenerator in the intercooling model have a great change, with the range of change being about 85 K and 300 K respectively, which are about 13 % and 85 % of the original stable temperature. It can be seen from A that the power and heat absorption of the recompression model can return to the stable state after the load unties, while the intercooling model will still gradually appear system imbalance after the load unties and cannot return to the original stable state. Similarly, the turbine, generator speed and mass flow rate of the intercooling model in (b) cannot return to the initial stable state after load tie-back, while the recompression model can return to the stable state. As can be seen from the enlarged figure of the first ten seconds, the rotating speed and mass flow rate in the intercooling model could not return to the original stable state in the future. In the recompression model, due to the existence of the shunt process, the influence on the flow rate is weakened, and the system can be stabilized in a new working condition similar to the original working condition. This also shows that the recompression model is more stable than the intercooling model in the case of load detachment.

4. Conclusions

In this study, the common load detachment situation is simulated by using Simulink in MATLAB and REFPROP. Based on the constant moment of inertia of turbine and generator, the model of mechanical rotation in the system is established. The tie-back duration and the responses of the recompression and intercooling models under this condition were compared. The main conclusions are as follows:

(1) After the load disconnects, the turbine compressor and the heat absorption in the cycle will increase. Except for the HTR cold side outlet temperature, the temperature of other places will rise, the cycle efficiency will

decrease, the turbine speed and mass flow rate will increase steadily, and the generator speed will reach 0 after 250 s.

(2) The power and speed of the turbine and generator also change linearly with the linear increase of the load disconnection time. The shorter the tie-back time, the faster the system will return to a stable state.

(3) The intercooling model cannot return to the stable state after the load untie and tie-back, and the system needs to be stopped urgently. However, the recompression model can return to a new stable state close to the original parameters after the load tie-back, which indicates that the recompression model has better stability performance.

Nomenclature

A – heat transfer area, m^2
C_P – specific heat capacity, J/(kg·K)
F – generator torque, m
h – enthalpy, kJ/kg
J – moment of inertia, kg·m^2
K – overall heat transfer coefficient, W/(m^2·K)
M – mass stored in a heat exchanger at a specific time, kg
P – Power, W
Q – heat absorption, W
q – mass flow rate, kg/s
T – Temperature, K
$\overline{T}$ – the average temperature, K
W – power, W

Greek
ΔT_m – log-mean temperature difference
ω – rotate speed, rad/s
η – isentropic efficiency of turbomachinery, %

Subscribpts
C – cold side
C1 – main compressor
C2 – recompressor
e – electric generator
H – hot side
HTR – high-temperature regenerator
i – inlet
IC – intercooling
LTR – low-temperature regenerator
O – outlet
RC – recompression
T – turbine

Acknowledgements

This work has been supported by the National Key Research & Development Program of China (2018YFE0108900) and the project LTACH19033 “Transmission Enhancement and Energy Optimized Integration of Heat Exchangers in Petrochemical Industry Waste Heat Utilisation”, under the bilateral collaboration of the Czech Republic and the People’s Republic of China (partners Xi’an Jiao Tong University and Sinopec Research Institute Shanghai; SPIL VUT, Brno University of Technology and EVECO sro, Brno), programme INTER-EXCELLENCE, INTER-ACTION of the Czech Ministry of Education, Youth and Sports.

References

Deng T., Li X., Wang Q., Ma T., 2019. Dynamic modelling and transient characteristics of supercritical CO_2 recompression Brayton cycle. Energy, 180, 292-302.

Gao C., Wu P., Liu W., Ma Y., Shan J., 2021. Development of a bypass control strategy for supercritical CO_2 Brayton cycle cooled reactor system under load-following operation. Annals of Nuclear Energy, 151, 107917.

Hu H., Liang S., Jiang Y., Guo C., Guo Y., Zhu Y., Cai H., 2020. Thermodynamic and exergy analysis of 2 MW S-CO_2 Brayton cycle under full/partial load operating conditions. Energy Conversion and Management, 211, 112786.

Li M., Zhu H., Guo J., Wang K., Tao W., 2017. The development technology and applications of supercritical CO_2 power cycle in nuclear energy, solar energy and other energy industries. Applied Thermal Engineering, 126, 255-275.

Moisseytsev A., Sienicki J.J., 2008. Transient accident analysis of a supercritical carbon dioxide Brayton cycle energy converter coupled to an autonomous lead-cooled fast reactor. Nuclear Engineering and Design, 238, (8), 2094-2105.

Pasch J., Conboy T., Fleming D., 2012. Supercritical CO_2 recompression Brayton cycle: completed assembly description. Sandia National Laboratories, Albuquerque, New Mexico, USA.

Wang X., Wang R., Bian X., Cai J., Tian H., Shu G., Li X., Qin Z., 2021. Review of dynamic performance and control strategy of supercritical CO_2 Brayton cycle. Energy and AI, 5, 100078.

Yang J., Yang Z., Duan Y., 2021. Load matching and techno-economic analysis of CSP plant with S–CO2 Brayton cycle in CSP-PV-wind hybrid system. Energy, 223, 120016.