CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216
DOI: 10.3303/CET2081124

Selection of Working Medium and Model for Brayton Cycle at Different Heat Source Temperatures

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The Brayton cycle system has a wide range of applications, including ship waste heat utilization, space reactors, sodium-cooled fast reactors, megawatt nuclear power systems and aerospace. The circulating temperature and circulating medium also vary with the specific application environment. The heat source temperature is usually between 700 K and 2,100 K. The commonly used working medium includes SCO_2, helium and nitrogen. At present, the research and analysis of some parameters in a given working fluid and temperature are applied to specific engineering. According to the environment temperature and working medium, based on MATLAB software, the numerical model of the Brayton cycle under different working conditions is established. In addition, other calculation software is used for programming calculation to obtain the analysis results of temperature change conditions and the comparison of different conditions, providing reference and selection basis for the application of Brayton cycle in practical engineering, so that the most suitable Brayton cycle working medium and cycle model can be selected under specific conditions. The influence of changing the heat exchanger into phase change heat exchanger on the instability of the heat source is analyzed. In this paper, the thermal efficiency curves between 716 K and 2,116 K of the heat source of Brayton cycle for helium, SCO_2 and nitrogen under four different cycle efficiencies were calculated, and the thermal efficiency curves of Brayton recompression cycle for helium, SCO_2 and nitrogen under different extraction ratios were calculated. And the temperature changes of four different models in three working media (helium, nitrogen and SCO_2) with thermal cycle efficiency were compared.

1. Introduction

In power station, the Brayton cycle is a common efficient way to generate electricity. Fu et al. (2014) mentioned a Brayton cycle of nitrogen improves the generation efficiency by 0.69 - 0.85 %. In addition, helium and SCO_2 are also common working materials used in the Brayton cycle. At present, what is applied to specific projects is the study and analysis of some parameters under a specific condition (Ahn et al., 2015), in which the working fluid and temperature are given. Dyreby et al. (2014) provided a numerical modelling method for SCO_2 Brayton cycles using formulas to build thermodynamic models of the key components in the cycle system. Deng developed a dynamic model of SCO_2 recompression cycle utilized in marine sway condition and analyzed transient responses of cycle parameters (Deng, et al.,2019), and combined it with phase change heat exchanger for research (Deng, et al.,2019). Siddiqui analyzed the energy and exergy of SCO_2 Brayton cycles in a cascade arrangement with a secondary cycle (Siddiqui, et al., 2018). In this paper, according to the ambient temperature and working medium, a numerical model of Brayton cycle using different working fluids in different working temperature zones based on MATLAB software has been developed, and other calculation software is used for programming and calculation to obtain the analysis results of the temperature variable conditions and the comparison of different working conditions, to provide reference and selection basis for applying the Brayton cycle to practical projects. Such as calculated the helium, SCO_2 and nitrogen Brayton cycle under four different model cycle efficiency between the heat source temperature is 716 K to 2,116 K change curve, helium, SCO_2 and nitrogen in different extraction ratio of Brayton recompression cycle with the heat of the efficiency curve of temperature change, there are three kinds of working media (helium and nitrogen and SCO_2) in four different

Paper Received: 08/05/2020; Revised: 20/06/2020; Accepted: 20/06/2020
Please cite this article as: Zhang L., Deng T., Ma T., Zeng M., Wang Q., 2020, Selection of Working Medium and Model for Brayton Cycle at Different Heat Source Temperatures, Chemical Engineering Transactions, 81, 739-744 DOI:10.3303/CET2081124

models change with heat cycle efficiency of the contrast. It allows us to discover which working medium can be selected and which cycle model can be used to achieve the highest efficiency in a particular temperature range.

2. Numerical Model

In this paper, four Brayton cycle models are selected, which are the basic model, the backheating model, the recompression model and the reheat model.

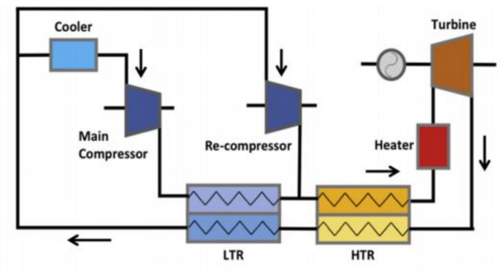


Figure 1: Typical layout of recompression Brayton cycle.

Figure 1 shows the layout of a typical recompression Brayton cycle. The thermophysical properties of working medium were obtained from the reference fluid performance (REFPROP) provided by the National Institute of Standards and Technology of the United States. Design parameters, same as the text Sandia laboratory experiment, of this work are shown in Figure 2. It is assumed that all parts of the cycle, including the turbine, main compressor, recompressor, regenerator, valves, and piping, are well insulated. The numerical model utilized in this article is used to develop different layouts of the Brayton cycle, including ordinary cycle, backheating cycle, compression cycle and reheat cycle calculation model. The model has been validated using the experimental data of the Sandia laboratory, the USA.

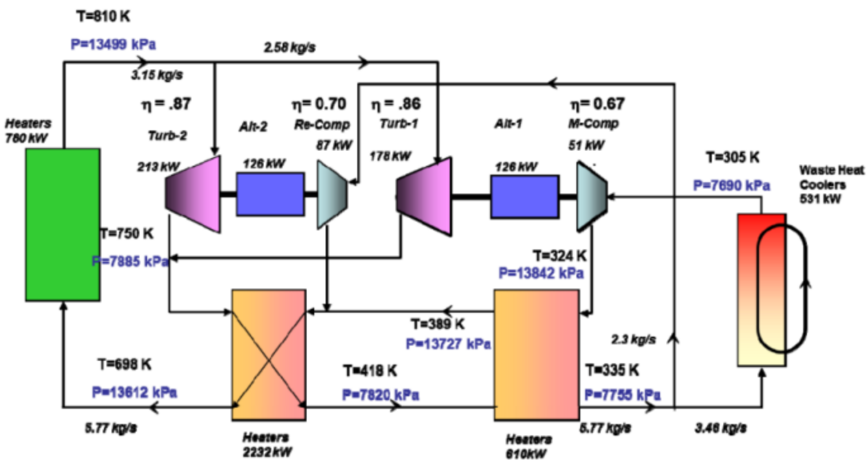


Figure 2: Schematic diagram of the Sandia recompression Brayton cycle experiment.

Cycle parameters including the extraction ratio of the compressor and turbine import and export temperature and pressure, the efficiency of the regenerator, and as the known parameters such as pressure loss were considered as different working temperature conditions of the cycle model. Under the same input parameters using MATLAB and REFPROP calculated heat absorption capacity of 781.45 kW, with the experimentally measured heat absorption capacity of 780 kW is only 0.19 % (Pasch et al., 2012). It is considered that the model, calculation method and process constructed in this paper have real reliability.

3. Results and Discussion

Under the condition that the specific experimental parameters of the verification model are used as the initial conditions, the important parameters of some commonly used Brayton circulating working media are calculated for varying heat sources under different circulating models.

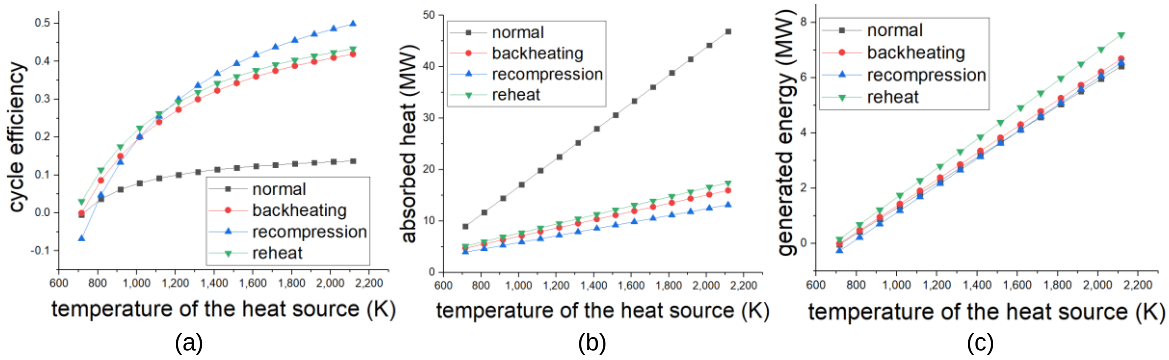


Figure 3: The variation of important cycle parameters of helium Brayton cycle under four different models: (a) Change in cycle efficiency; (b) Change in heat absorption; (c) Change in generated energy.

As shown in the figure above, for the helium Brayton cycle, the heat absorption of an ordinary cycle is much higher than other models, followed by the reheat cycle, the backheating cycle and the recompression cycle. In terms of power generation, the power generation of each cycle is roughly similar, among which the power generation of reheat cycle is more than that of other models.

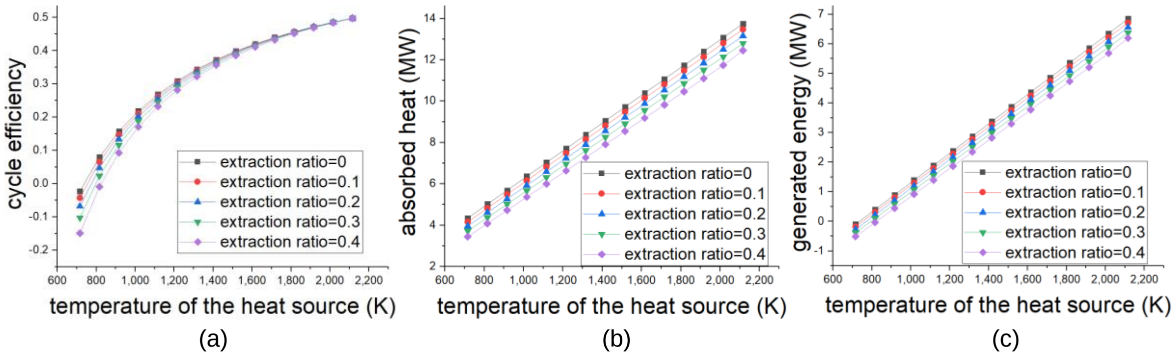


Figure 4: The change of the key parameters of the helium Brayton recompression cycle under different extraction ratios with the temperature of the heat source:(a) Change in cycle efficiency; (b) Change in heat absorption; (c) Change in generated energy.

As shown in the figure above, when the heat source temperature is low, the lower the extraction ratio, the higher the cycle efficiency. However, when the heat source temperature is high, the extraction ratio has almost no effect on the cycle efficiency.

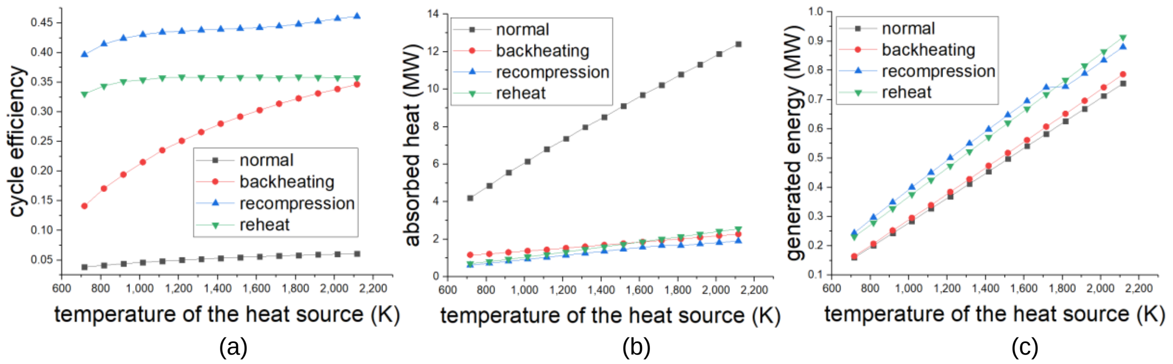
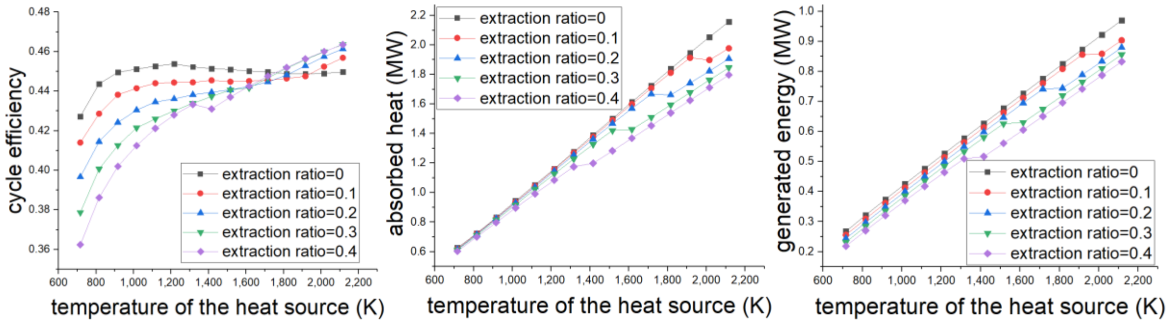


Figure 5: The variation of important cycle parameters of SCO_2 Brayton cycle under four different models:(a) Change in cycle efficiency; (b) Change in heat absorption; (c) Change in generated energy.

Different from helium, SCO_2 has a large difference in cycle efficiency between different models. The cycle efficiency of the basic model changes little with the temperature of the heat source and remains below 7.5 %.

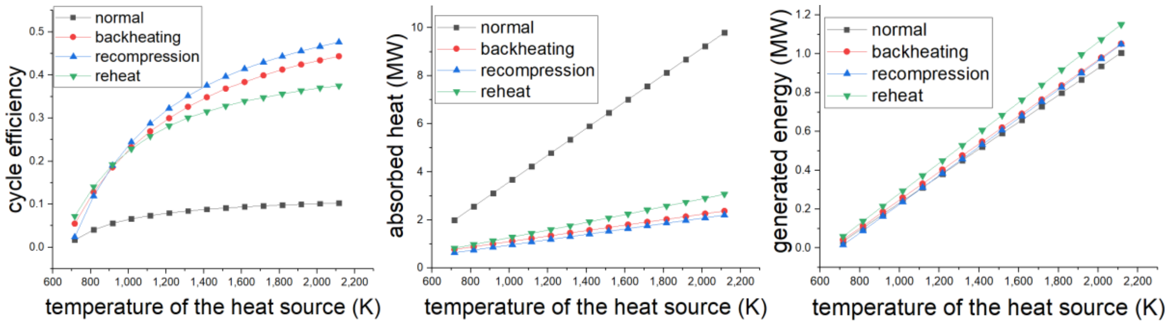
And the cycle efficiency of the recompression model is still higher than reheat, and reheat is higher than backheating. With the increase in temperature, the recompression Brayton cycle's efficiency can reach about 45 %, which is a considerable efficiency value. The model backheating is much less efficient than reheating at first, but as the temperature of the reservoir increases, the two are almost equal after 2,000 K. From the point of view of cycle efficiency, the recompression model is still the preferred model of SCO_2 as working medium. For heat absorption, all the models except the basic cycle control the heat absorption to a low level, and for the generating capacity, again, reheat the most, compression a little bit less, backheating and normal the least.



(a) (b) (c)

Figure 6: The change of the key parameters of the SCO_2 Brayton recompression cycle under different extraction ratios with the temperature of the heat source: (a) Change in cycle efficiency; (b) Change in heat absorption; (c) Change in generated energy.

It can be seen that when the temperature of the heat source is lower than about 1,700 K, the lower the extraction ratio is, the circle efficiency is higher; when the temperature of the heat source is higher than about 1,900 K, the higher the extraction ratio is, the higher the circulation efficiency is; and when the temperature of the heat source is around 1,800 K, the lower the circulation efficiency is almost equal. With the increase of the extraction ratio, the heat absorption and power generation decrease gradually.



(a) (b) (c)

Figure 7: The variation of important cycle parameters of nitrogen Brayton cycle under four different models:(a) Change in cycle efficiency; (b) Change in heat absorption; (c) Change in generated energy.

As can be seen from the above figures, in the nitrogen Brayton cycle, when the temperature of the heat source is low (below 900 K), the efficiency of the ordinary cycle is still much lower than that of other cycles, and the efficiency does not increase significantly as the temperature of the heat source increases. In the other three cycle models, when the heat source temperature is lower (less than 900 K), the cycle efficiency of the reheat model is higher than that of the reheat model than that of the recompression model. When the heat source temperature is above 1,000 K, the recompression model has the advantage of efficiency up to about 50 %, followed by the model of bringing back the heater, followed by the reheat model. For different models, the other three models have lower heat absorption than the ordinary model, and from the perspective of heat absorption, the reheat model is higher than the backheating model, and the recompression model the least. The four models are close in generating capacity

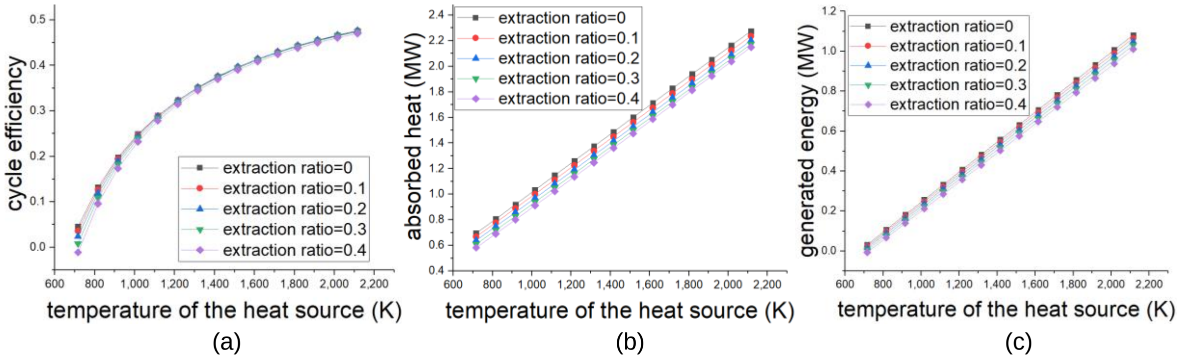
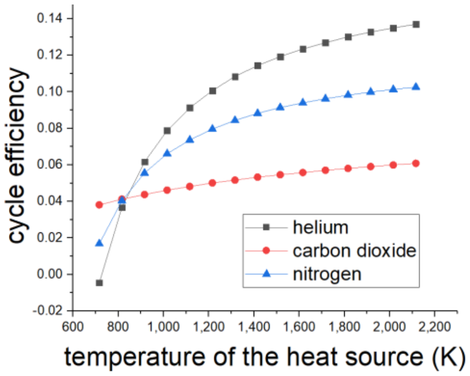
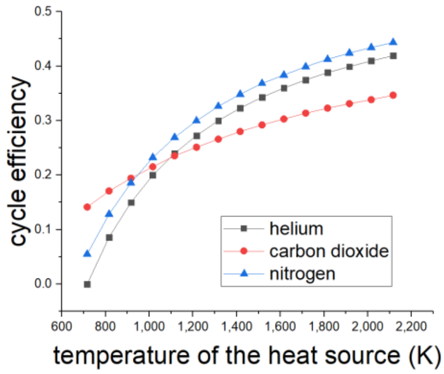


Figure 8: The change of the key parameters of the nitrogen Brayton recompression cycle under different extraction ratios with the temperature of the heat source:(a) Change in cycle efficiency; (b) Change in heat absorption; (c) Change in generated energy.

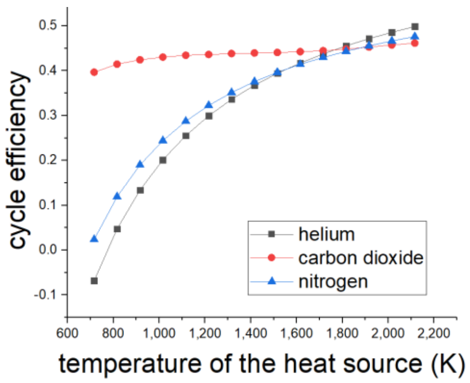
From the above figures, it can be seen that the same two working medium meet the law that the higher the extraction ratio is, the lower the efficiency. However, as the temperature of the heat source increases, the cycle efficiency of each model are very close. For heat absorption and power generation, the higher the extraction ratio, the lower the value.



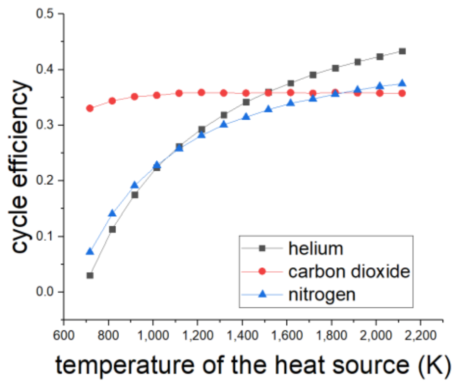
(a) Normal



(b) Backheating



(c) Recompression



(d) Reheating

Figure 9: Comparison of working media under different Brayton cycle models

As shown in the figure above, the efficiency of the three working media is almost equal to 4 % at the temperature of the heat source of more than 800 K. In the case that the heat source temperature is gradually increasing, helium gas is more advantageous than SCO_2 in the normal cycle model. For the backheating model, nitrogen is always slightly more efficient than helium and has an advantage at higher temperatures (above 1,000 K), and SCO_2 has an advantage at lower temperatures (below 1,000 K). The heat source temperature has less influence on the efficiency of CO_2. For the recompression model, the SCO_2 shows great advantages, it is very stable in all temperature ranges and maintains the ideal efficiency of more than 40 %, while the inert gas has lower efficiency in the low-temperature region and anti-ultra-SCO_2 efficiency in the case of ultra-high temperature (more than 1,800 K). For the reheat model, the SCO_2 still shows stable efficiency in the whole temperature range and is stable at the appreciable efficiency value of about 35 %. When the heat source temperature is lower than 1,500 K, supercritical CO_2 has advantages, while when the heat source temperature is higher, the inert gas is more efficient.

4. Conclusion

In this work, four numerical models of the Brayton cycle are calculated in MATLAB software. Besides, In this paper, three kinds of commonly used Brayton circulating working medium are taken as the research object, and the changes of the key parameters of the circulation are discussed when the cold source temperature is fixed and the heat source temperature is changed in the commonly used range. It provides the most suitable and efficient reference for the users of the Brayton cycle to select the most suitable model and working medium under the specific conditions required. The main conclusions can be summarized as follows:

(i) For the three working media, the overall efficiency of the Brayton recompression cycle model is higher than that of the other three models at different heat source temperatures. The efficiency of the basic model is generally much lower than that of the other three and does not vary much with the temperature of the heat source (all below 15 %). However, by comparing the heat absorption and power generation of each model, it can be found that the reason for the inefficiency of the ordinary model is that the ordinary model has higher heat absorption than other models. For power generation, there is little difference between the models.

(ii) Since the Brayton cycle recompression model has a higher overall efficiency than other models, the key factor extraction ratio is taken as the research object to study the variation of Brayton cycle efficiency with the temperature of the heat source when the extraction ratio is 0, 0.1, 0.2, 0.3, and 0.4. For the inert gases helium and nitrogen, the cycle efficiency always decreases with the increase of the extraction ratio. When SCO_2 is used as a working medium, the lower the extraction ratio is, the higher the efficiency is.

(iii) The performance of different working medium under the same model is compared, among which the extraction ratio adopted by the recompression model is 0.2. It can be easily found that the SCO_2 in each model always presents the characteristic of stable efficiency relative to the inert gas. The heat source temperature ranges from 700 K to 2,100 K, and the efficiency is always stable at a relatively ideal value. Under the condition of the low temperature of heat source, each model shows the characteristic of higher efficiency of SCO_2. When the heat source temperature is in the ultra-high range, and the inert gas starts to show its superiority, and the cycle efficiency is higher than SCO_2.

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