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Transient Characteristic of Supercritical CO_2 Brayton Cycle with PCM System in a High Frequency Oscillating Environment

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The SCO_2 (supercritical carbon dioxide) Brayton cycle has been recommended to the marine industry due to its high efficiency, small volume and low weight. However, the undulation and sway of ships aroused by the wind and sea waves in the marine environment may generate the periodic changes in multiple forces, and finally leading to the unstable performance of the SCO_2 Brayton cycle. Phase change material (PCM) system grabs much attention for its large heat storage capacity and stabilized operation temperature, and has a wide application in the thermal management system, especially for the temperature control of a thermodynamic cycle. In this work, a PCM system is introduced into SCO_2 recompression Brayton cycle in order to reduce the response amplitudes of inlet temperatures in main compressor and recompressor. The transient characteristics of cycle parameters affected by the PCM system in a high frequency oscillating environment are studied. The transient analyses indicate that PCM system is able to control the temperature changes and helpful to enhance the stability of cycle performance.

1. Introduction

SCO_2 (supercritical carbon dioxide) Brayton cycle, coupled with various power applications especially nuclear power and solar energy system, is assumed to have great potential for its high compactness and efficiency. Recently, SCO_2 Brayton cycle system is considered to be applied in marine environment, which has complex and periodic movements, and high frequency forces with such as undulation and sway. Such a high frequency oscillating environment will heavily affect the transient performance of SCO_2 Brayton cycle system. Therefore, a method to control the dynamic performance of the cycle system under periodic disturbances is valuable and indispensable.

Based on previous work, the complex combination of motions in the marine environment could be simplified to three kinds of motions including heaving, pitching and rolling. Among them, the rolling motion was the main influence factor of flow and heat transfer process. Tan et al. (2009) performed experimental studies on heat transfer characteristics for single-phase natural circulation flow under a rolling motion condition, and proved that rolling motion could be regard as a simple harmonic motion in the research of flow and heat transfer.

Being considered as a periodic oscillating condition with high frequency, marine environment indeed affects the SCO_2 Brayton cycle applied on the ship, and probably causes instability of the system. PCM storage system is assumed as a practical energy controlling method to adjust the dynamic performance of cycle system for its simple construction, high density of energy storage, and strong ability of temperature controlling. According to the dynamic performance of SCO_2 Brayton cycle, it could be an effective way to control the instability of the cycle system to set a heat exchanger on the inlet of the compressor.

Many works have been performed to study PCM heat exchanger. Tay et al. (2013) conducted an investigation into characterising and optimising the useful latent energy within a tube-in-tank PCM heat exchanger, and used effectiveness-NTU model to determine its design parameters. Stathopoulos et al. (2015) designed a PCM heat exchanger with plate structure and developed a numerical model using the apparent heat capacity approach and the finite differences method. Allouche et al. (2017) developed a dynamic model of PCM cold storage

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components using in solar-driven air conditioning system, and studied the influence of the solar collector area and the hot storage capacity by simulation. Thierno et al. (2019) analysed the energy efficiency for a solar PVT Loop Heat Pipe system within a novel PCM heat storage exchanger, which had been proved contributing to the 28 % improvement of the overall energy efficiency of the system. Yu et al. (2019) established melting-solidification models of 12 different PCM using in latent energy storage component in organic Rankine cycle system, and found that $LiNO_3$-$KClNaNO_3$ as the chosen PCM could provide with the longest ORC operating duration and the largest total output work. Akanksha et al. (2013) designed a new component with variable aperture coupled with heat exchanger in solar generating system to store unused heat during peak times, and analysed the beat aperture diameter considering with reactor temperature and radiation losses.

However, there is little work about the PCM system applied in SCO_2 Brayton cycle specifically. Since the working fluid SCO_2 has special thermal properties and high working pressure, a new style of PCM storage system using to control the transient performance of SCO_2 Brayton cycle is required. In this work, a novel PCM heat exchanger adapting to SCO_2 Brayton cycle in which the working fluid SCO_2 changes heat with PCM so as to adjust its temperature is performed, , and its dynamic performance under a periodic oscillating condition has been studied by numerical simulation. Moreover, the influences of the PCM heat exchanger on dynamic characteristics of cycle parameters have been discussed.

2. New form of PCM heat exchanger

2.1 Concept of new PCM-SCO_2 HX

A PCM-SCO_2 heat exchanger is demanded to control the transient performance of SCO_2 Brayton cycle in a high frequency oscillating environment. Since the working fluid SCO_2 has a high heat capacity and high pressure (over 8 MPa), the PCM heat exchanger is required not only with high efficiency but also good ability of pressure resistance. Unfortunately, traditional PCM heat exchanger such as tube-in-tank and concentric tube cannot reach such a high performance of heat transfer with limited volume and space due to their relatively low compactness. As the result, a new concept of PCM heat exchanger is designed, referencing the type of PCHE (printed circuit heat exchanger). PCHE is an advanced plate heat exchanger which has high compactness, strong pressure endurance, and high heat transfer capacity. Fig. 1 shows the structure of the new PCM heat exchanger which is called PCM-SCO_2 PCHE. In this conformation, half of the plate sides are designed as shallow rectangular tunnels instead of common tunnels of PCHE which have semi-circular sections and the other parts of plates still remain semi-circular sections. The rectangular tunnels have no exit at both ends to store PCM, while SCO_2 flows in semi-circular tunnels and changes heat with PCM. This PCM-SCO_2 PCHE has high pressure resistance and enough compactness to match the SCO_2 Brayton cycle.

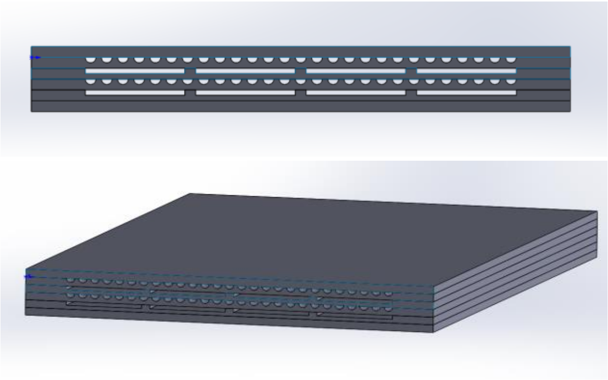


Figure 1: the structure of the PCM-SCO2 PCHE

It is critical to choose suitable phase changing materials for PCM heat exchangers. The PCM stored in PCM-SCO_2 PCHE should have the following advantages: suitable melting temperature, high heat of fusion, and reliable convertibility at repeated phase transformations, high heat conductivity, and the minimum change in volume while melting, chemical stability, nontoxic property, flame and fire safety, availability and cheapness. Considering with the above requirements, two specific kind of PCM are chosen to fulfil the tunnels of PCM-SCO_2 PCHE. To address the low conductivity of the PCM, adding high porosity copper foams is recommended as a direct reinforcement approach, owing to its high thermal conductivity and large specific surface area, which provides a low thermal resistance channel for heat transfer, resulting in the enhancement of thermal storage efficiency and temperature uniformity of PCM according to Li et al. (2018). The melting temperature of the PCM was determined to match the inlet temperature range of the compressors in the megawatt-level SCO_2 Brayton recompression cycle test of Sandia National Laboratory proposed by Pasch et al. (2012). The properties of PCM provided by Jankowski et al. (2014) and copper foams are shown by Table 1.

Table 1: The properties of chosen wax and copper foams

Properties	"Paraffin wax''	Palmitic acid	Copper Foams
Density ρ (kg/m^3)	830.0	941	8930.0
Heat capacity C_p (J/(kg·K))	3.26	2.20	1.5
Thermal conductivity λ (W/(m·K))	0.51	0.17	398.0
Melting temperature T_m (K)	305	333	--
Heat of fusion La (kJ/kg)	251	210	--
Porosity ε(%)	--	--	0.9

2.2 Thermodynamic design

In order to make sure that the design of PCM-SCO_2 PCHE is capable to satisfy the requirement of controlling parameters of SCO_2 fluid, thermodynamic designing calculation is achieved. Several assumptions and simplifications were made as following: (1) the rectangle tunnels are considered fully filled with PCM; (2) the whole heat exchanger remains at the melt temperature of the PCM initially, which specifically equals to the temperature of SCO_2 in the steady working condition; (3) the density of the PCM changes insignificantly during the melting process; (4) the external boundaries are assumed to be adiabatic.

According to the known conditions including parameters of inlet and outlet SCO_2 of the PCM heat exchanger, the heat transfer rate can be calculated based on the first law of thermodynamics:

$$Q_{\mathrm{PCM}} = \dot{m}_{\mathrm{h}} c_{\mathrm{ph}} (T_{\mathrm{in}} - T_{\mathrm{out}}) \tag{1}$$

where Q_{PCM} is the heat transfer rate of PCM; $\dot{m}_{\mathrm{h}}$, c_{ph}, $T_{\mathrm{in}}$and T_{out} are mass low rate, heat capacity, inlet and outlet temperature of SCO_2 in hot side respectively.

Therefore the mass of contained wax in the PCM-SCO_2 PCHE are obtained by:

$$\dot{m}_{\mathrm{PCM}} = Q_{\mathrm{PCM}} / La \tag{2}$$

where La is the heat of fusion of PCM, $\dot{m}_{\mathrm{PCM}}$ is the quality of PCM in unit time

Assuming the stable density of the wax, the required volume for the wax in PCM-SCO2 PCHE can be calculated:

$$\varepsilon \dot{V}_{\mathrm{PCM}} = \dot{m}_{\mathrm{PCM}} / \rho_{\mathrm{PCM}} \tag{3}$$

where ε is the porosity of copper foams; ρ_{PCM} is density of PCM and $\dot{V}_{\mathrm{PCM}}$ is the volume of PCM participating in heat transfer per unit time

On the basis of working conditions at the inlet of the main compressor and the recompressor in the referred SCO_2 recompression Brayton cycle system of Pasch et al. (2012), two PCM-SCO_2 PCHEs are designed so as to control the changing temperature of SCO_2 in a high frequency oscillating environment. To simplify the instruction, the PCM-SCO_2 PCHE set on the inlet of the main compressor is called No.1 PCHE while the other one set on the inlet of the re-compressor is called No.2 PCHE. The parameters of the two PCM heat exchangers are shown in Table 2.

Table 2: The Thermal design parameters of chosen wax and copper foams

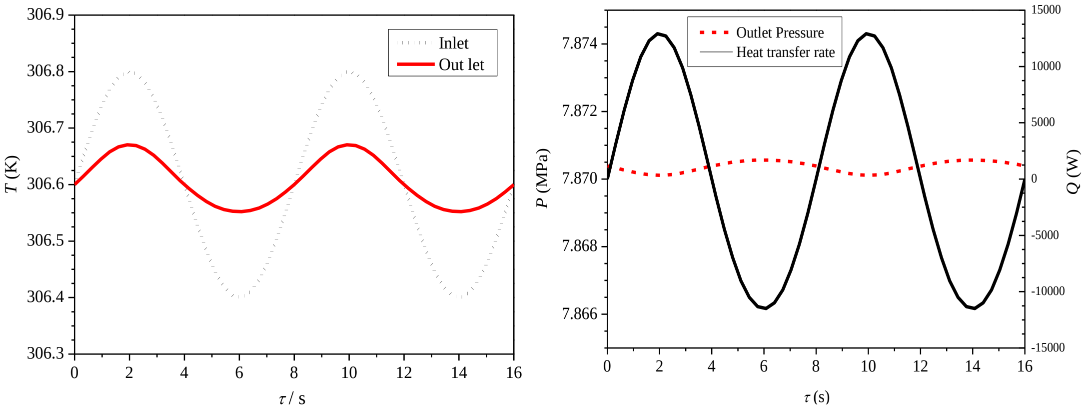
Parameters	No.1 PCHE	No.2 PCHE
Designed mass flow of SCO_2 fluid (kg·s^{-1})	3.5	2.3
Overall mass of PCM m (kg)	31.1	1.1
Length of tunnels L (m)	2.5	0.3
Diameter of SCO_2 tunnels D (mm)	1.5	1.5
Depth of PCM tunnels d (W/(m·K))	1	1
Thickness of the plates t (mm)	2	2
Number of SCO_2 plates n_{p1}	60	40
Number of PCM plates n_{p2}	100	40
Number of tunnels in single SCO_2 plate n	100	40
Storage volume for PCM in single PCM plate (mm)	2500*150*1	300*100*1

3. Dynamic performance of PCM heat exchangers

Numerical dynamic model of the two PCM-SCO_2 PCHEs are respectively developed in the MATLAB Simulink software based on the above thermodynamic design. The numerical HX models are direct-feed-through sub functions based on the continuity equation and energy equation of the overall heat transfer process. According to the assumptions in 2.2, the PCM remains in the melting state, thus an isotherm boundary condition which describes the effect caused by PCM in the heat transfer process of SCO_2 is acceptable. Each model is able to calculate the outlet parameters of SCO_2 with the input data. After the model reached steady working conditions, the input signal of SCO_2 temperature becomes to a sine wave. The test of No.1 PCHE is considered as the instance. In this test, the sine temperature signal has a period of 8 s and amplitude of 0.2 K.

Figure 2 (a) shows the contrast between the responses of the inlet and outlet temperatures of SCO_2 in No.1 PCHE under the changing input signal. It's easy to observe that the outlet temperature of SCO_2 changes with the same period of the inlet temperature. However, it's worth noticing that the transient trend of outlet temperature is not a sine wave, different from that of inlet temperature. During the first half part of single period, when the SCO_2 in the heat exchanger are hotter than the PCM, the outlet temperature changes sharper. Yet in the second half period, the temperature of SCO_2 is lower than PCM's, and the response of outlet temperature changes more gently. For the convenience of expression, the first and the second half period are called cooling and heating process. The amplitudes of SCO_2 outlet temperature in each process are different as well. In the cooling process, the highest temperature of outlet SCO_2 is 0.07 K less than inlet temperature, reduced for about 65 %. While during the heating process the lowest temperature has increased for 0.05 K, which is approximately 75 % in proportion. The difference between performances of the PCM heat exchanger in cooling and heating process is because of the dramatically changing properties of SCO_2 with temperature while being close to its critical point, which is near the working condition of No.1 PCHE. As a result, the heat transfer performance of SCO_2 has apparent difference while temperature changes. Therefore, the discussion of the heat transfer process of SCO_2 in the specific PCM heat exchanger should be based on two individual processes.

The responses of heat transfer rate and outlet pressure of SCO_2 in No.1 PCHE are shown in Figure 2 (b). It's easy to find out that sinusoidal variation appears in response of both outlet pressure and heat transfer rate with the same period of inlet temperature. Due to the difference of heat transfer performance influenced by the properties of SCO_2 in the two processes, the response of heat transfer rate shows differences in cooling and heating process. The maximum cooling rate is 12900 W, while the highest heating rate achieves to 11500 W. Since the heat that SCO_2 transfer to the wax in the cooling period is more than the heat transferred in heating process, energy stored in the wax changes for a bit during one single period. Therefore, the heat stored in the PCM will increase continually, which means the excess heat should be carried out from the PCM heat exchanger somehow before it grows over the overall latent heat of the wax in the PCM heat exchanger, such as a small water circulatory system. The outlet pressure of SCO_2 in No.1 PCHE, which directly represents the pressure-drop of the PCM heat exchanger due to the stable inlet pressure, shows an opposite trend to the above parameters. Because of the sharping changing properties of SCO_2 near the working condition, there are complex relationships among the factors of flow and heat transfer. The range of the response of is 200 Pa, which is far smaller than the value of outlet pressure of SCO_2. Thus the transient characteristics of pressure-drop have little influence on the performance of the PCM heat exchanger.



(a) Inlet and outlet temperature

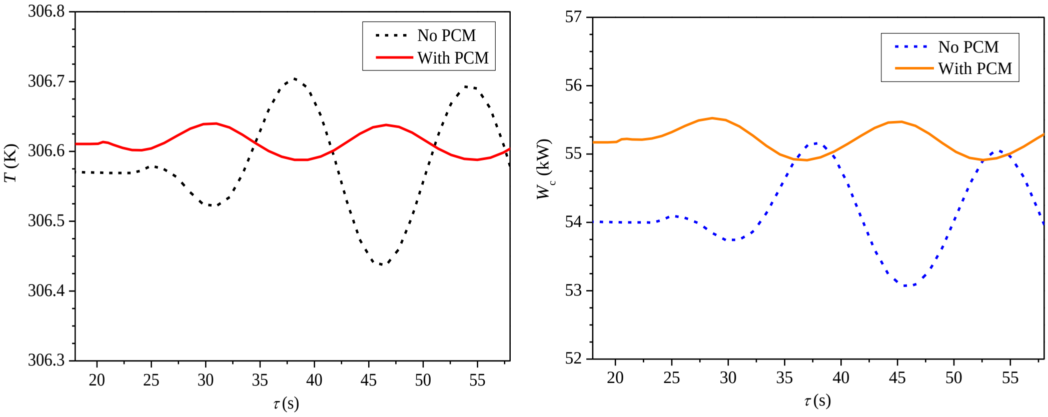
(b) Out let pressure and heat transfer rate

Figure 2: Response of parameters of SCO_2 in No.1 PCHE

4. Result of cycle transients

The above models of PCM-SCO2 PCHE are added in the developed transient model of SCO2 recompression Brayton cycle, which refers to the SCO2 Brayton recompression cycle of Pasch et al. (2012). In order to study the influence of PCM-SCO2 PCHE to the cycle transients under oscillating environment, a sine disturbance signal is applied to the inlet temperature of the hot-side SCO2. The analysis focuses on the different transient performance of cycle parameters before and after the No.1 PCHE is set at the inlet node of the main compressor. The source disturbance signal with a period of 16 s and amplitude of 25 K is added into the hot-side inlet temperature of HTR (high temperature recuperator).

Figure 3 shows the response of inlet temperature and the compression power in the main compressor before and after No.1 PCHE is set. Since the selected initial temperature of the wax in No.1 PCHE has a little difference to the steady temperature of SCO2 at the monitoring working point, a tiny difference which is almost unaffected to the concerned transient characteristics exists between the absolute values of the two temperature curves. It can be found that the amplitude of the inlet temperature is about 0.13 K before No.1 PCHE installed, much larger than the response amplitude which decreases to 0.03 K due to No.1 PCHE. That means the range of response signal of main compressor inlet temperature is reduced significantly for almost 77 % by the PCM heat exchanger, which proves that No.1 PCHE is effective to limit the changing range of SCO2 temperature under oscillating environment. What's more, it's easy to obtain that No.1 PCHE significantly affects the power of main compressor. Without the PCM heat exchanger, the power of main compressor has a range for about 0.95 kW, which is reduced to 0.27 kW when No.1 PCHE is set. The response range of compressing power decreases by 71 % approximately, which is a bit less than the decline of temperature range. This is because that the change of power in compressor is caused by the temperature change, and is weakened in the parameter passing process.



(a) Inlet temperature *(b) Compression power*

Figure 3: the response of inlet temperature and the compression power of the main compressor before and after No.1 PCHE installed

However, No.1 PCHE has a scant influence to the other parameters in the cycle. The comparison between the responses of output turbine power and cycle efficiency before and after No.1 PCHE installed is shown in Fig. 4. The amplitude of turbine power response is about 18 kW without the PCM heat exchanger. When No.1 PCHE is added into the system, the response amplitude of turbine power only decreases to 16 kW, which is 11 % in proportion. The reason is considered to be that the turbine is relatively far away from the main compressor in the entire cycle layout, thus the change of working parameters in the main compressor has a little impact to the performance of the turbine. And when No.1 PCHE is set, the range of cycle efficiency only decreases for about 0.03 % in value, which is nearly 1 % comparing with the amount of cycle efficiency. This is because that the power of turbine reaches 400 kW approximately while the power of main compressor is only about 50 kW. Therefore, the turbine power has a much larger proportion than compression power in the calculation formula of cycle efficiency, that's the reason why the PCM heat exchanger installed at the inlet of main compressor has little influence to the cycle efficiency.

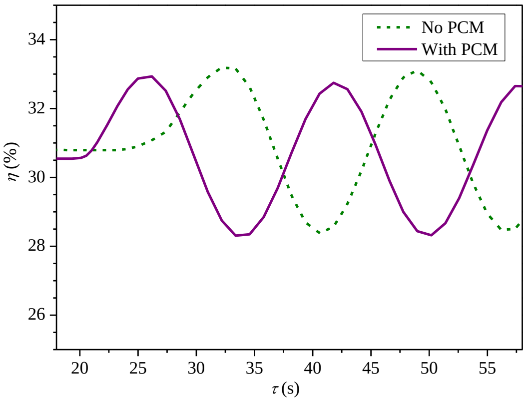


Figure 4: the response of turbine power and cycle efficiency before and after No.1 PCHE installed

5. Conclusions

On the basis of transient characteristics of SCO_2 recompression Brayton cycle working in a high frequency oscillating environment, a controlling method using new type of PCM heat exchangers which are designed to locate on the inlet of compressors focusing on reducing the response range of cycle parameters is proposed. The thermodynamic design and numerical model of the PCM heat exchanger are also developed. The simulation results show that under the effect of the designed PCM heat exchanger, the working temperature and compressing power of main compressor respectively decreased by 77 % and 71 % of in response ranges. Yet these decreases only caused a slight effect on reducing the response range of cycle efficiency, which decreased for 1% in proportion. It can be predicted that the specific PCM heat exchanger will make a greater impact to the transient performance of SCO_2 recompression Brayton cycle if it's used to control the turbine parameters by designed for a much higher temperature.

Acknowledgments

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