Applied Thermal Engineering 138 (2018) 513–522

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

An adaptive flow path regenerator used in supercritical carbon dioxide Brayton cycle

Miao Ding, Jian Liu, Wen-Long Cheng*, Wen-Xu Huang, Qi-Nie Liu, Lei Yang, Shi-Yi Liu

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230027, China

HIGHLIGHTS

- An adaptive flow path regenerator used in SCO_2–Brayton cycle is proposed.
- The pressure loss of the adaptive flow path regenerator can be reduced up to 69%.
- The effectiveness of the new regenerator can be increased by nearly 2%.
- The compactness and heat transfer rate of the new regenerator can be improved.
- The regenerator is manufactured by metal 3D printing and tested by a SCO_2 experimental platform.

ARTICLE INFO

Keywords:
Supercritical CO_2
Adaptive flow path
Low-temperature regenerator
Numerical simulation
Experimental platform

ABSTRACT

The supercritical CO_2 recompression Brayton cycle is proposed to be used as a typical application in 4th generation reactors. In the cycle, the performance of the regenerator has a significant impact on the performance of the entire cycle. As the specific heat capacity and density of SCO_2 change significantly with the temperature and pressure. Therefore, in this paper, a new adaptive flow path regenerator is proposed and designed in order to further improve the performance of the regenerator, in which the flow path sizes varied with the CO_2 density when the CO_2 flowing through the regenerator. Firstly, the heat transfer performance and hydraulic performance of the adaptive flow path regenerators are analyzed in detail by simulation, and it is verified in theory that the design of new adaptive regenerator is feasible. Then, a new adaptive flow path regenerator with S-shaped fins is manufactured by metal 3D printing technology and the performances of the new regenerator are tested by a SCO_2 experimental platform. The experimental results are consistent with simulation results and show that the performances of the new regenerator are significantly improved: the pressure loss can be reduced up to 69%, the effectiveness can be increased by nearly 2%, and the compactness and heat transfer rate can be improved at the same time.

1. Introduction

The supercritical CO_2(SCO_2), which is a natural and environmental friendly substance, has clean and safety characteristics, CO_2 behaves as a supercritical fluid above its critical temperature (304.25 K) and critical pressure (7.39 MPa), expanding to fill its container like a gas but with a density like that of a liquid. Therefore, the supercritical CO_2 Brayton cycle (SCO_2-BC) is proposed to be used as the concept of fast cooled reactor, which is a typical application of 4th generation reactors [1]. The SCO_2-BC has many advantages including higher energy conversion efficiency, better safety and more compact system structure, etc.[2,3]. Due to the large change of specific heat capacity and density of SCO_2 with temperature and pressure as shown in Fig. 1, the volume of the regenerator in the SCO_2-BC is relatively large, and the efficiency of heat exchange is relatively low. Then, the recompression SCO_2-BC is proposed [4–6], which could provide a higher thermal efficiency and is considered to be one of the most feasible cycle to solve the pinch problem of regenerator through two-stage regenerator (high-temperature and low-temperature regenerator) and shunt technology[7], Fig. 2 shows the layout of SCO_2 recompression Brayton cycle, according to global parameters analysis of SCO_2 recompression Brayton cycle, the heat exchange efficiency and pressure loss of the low-temperature regenerator (LTR) have significant impacts on the cycle efficiency [8]. Therefore, this article focuses on the critical component of the SCO_2 Brayton recompression cycle: low-temperature regenerator.

The conventional shell and tube heat exchanger is not suitable for

* Corresponding author.
E-mail address: wlcheng515@163.com (W.-L. Cheng).

https://doi.org/10.1016/j.applthermaleng.2018.04.055
Received 10 January 2018; Received in revised form 5 April 2018; Accepted 11 April 2018
Available online 11 April 2018

Nomenclature

q	heat transfer rate (W)
m	mass flow rate ($kg \cdot h^{-1}$)
T	temperature (K)
C_P	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
f	Darcy friction factor
p	pressure (MPa)
ρ	density
D_h	hydraulic diameter
u_m	average flow velocity
Re	Reynolds number
A_C	flow cross-sectional area
d_f	fin width
d_y	distance among fins in y-direction
l_x	fin length in x-directions
P	wet cycle
Nu	Nusselt number
Pr	Prandtl number
k	thermal conductivity
ε	effectiveness of regenerator

Greek symbols

φ, ψ	fin angle

Subscripts

in	inlet
out	outlet
c	low temperature (high pressure) side
h	high temperature (low pressure) side

using in SCO_2-BC because of the extreme pressure differences. Therefore, a new printed circuit heat exchanger (PCHE) is proposed and commercial promoted [9], the compactness of PCHE comparing with shell and tube heat exchanger can be improved more than 85% under the same thermal power conditions [10]. Researchers have been concentrated on heat transfer characteristics and hydraulic performance of various flow path structures of PCHEs through experimental investigations and numerical simulations [10–21].

The zigzag channel was the most commonly used channel type of PCHE, which was proposed by Hamid et al. [11,12]. The effect of the attack angle on heat transfer effect was studied through experimental and numerical simulation [13]. The results showed that the bend of zigzag channel can improve the heat transfer efficiency by increasing the turbulence intensity of SCO_2 and the heat transfer area compared to straight channel. However, the zigzag channel has the worse hydraulic performance and will increase the pressure loss and local heat transfer deterioration at the same time [14–16]. In order to overcome the high pressure drop of zigzag channel, some new type channels have been developed in recently years. A smooth serpentine channel PCHE was proposed and studied by Waleed et al. [17,18]. They found that fluid velocity distribution is more uniform within the serpentine channel, the pressure loss and heat transfer deterioration can be reduced. What‘s more, the heat transfer performance is better in the serpentine tube than in the straight tube due to the secondary flow. Tsuzuki et al. [19] developed the new channel PCHEs with non-continuous S-shaped fins. The comparison between zigzag and S-shape channels indicated that the heat transfer performance of S-shape fins channel decreases slightly, while its pressure drop decreases significantly [20]. Xu et al. proposed

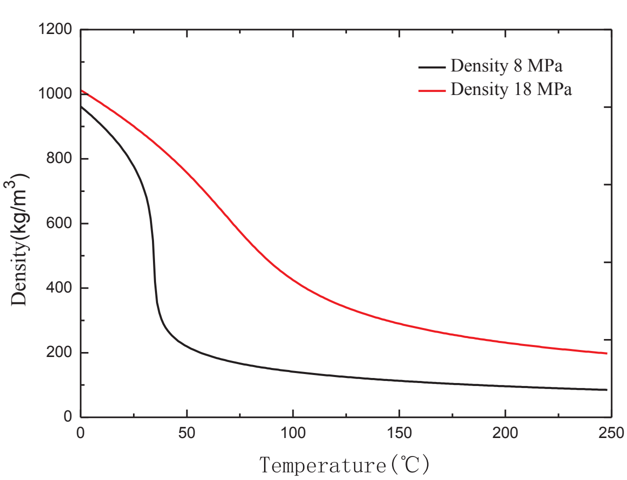

Fig. 1. Physical properties of CO_2 at different pressures.

that reduce the flow resistance along the flow direction can improve the comprehensive thermal hydraulic performance of the PCHE [21].

However, the design of the previous regenerator used in the SCO_2-BC did not consider the influence of the thermal properties change of carbon dioxide during the heat exchanger. Due to the large changes of CO_2 thermodynamic properties near the critical point. The conventional PCHE used in SCO_2-BC has some disadvantages such as: large flow resistance, low heat transfer coefficient and heat transfer efficiency. Therefore, in the present paper, a new adaptive flow path regenerator is proposed and designed in order to further improve the performance of the regenerator, in which the flow path size varied with the CO_2 density when the CO_2 flowing through the regenerator. The width of the flow path increases with the increasing of CO_2 temperature and vice versa, and the flow path sizes of the inlet and outlet are calculated by the operating parameters of the regenerator. Moreover, the adaptive flow path can combine with different flow path structures as mentioned above, and the adaptive flow path regenerator has applied for the invention patent [22]. The heat transfer performance and flow performance of ordinary and adaptive flow path regenerators were analyzed in detail by simulation. The simulation results showed that adaptive flow path regenerator has obvious advantages in both heat transfer performance and flow performance: reduce the pressure loss, improve compactness and local convection heat transfer coefficient of the regenerator, and improve the heat transfer rate and effectiveness. Therefore, it was verified in theory that the method that the regenerator flow path sizes changed with the CO_2 density to increase regenerator performance was feasible.

Then an adaptive flow path combined S-shaped fins regenerator was designed. The new regenerator was fabricated by metal 3D printing technology because of its complex flow path structure. The heat transfer and hydraulic performance of the new regenerator was tested by a SCO_2 test platform. The experimental results consistent with the numerical simulation results and show that the performance of the new regenerator are significantly improved: the pressure loss can be reduced up to 69%, the effectiveness can be increased by 2% averagely, and the heat transfer rate can be improved at the same time compared with ordinary S-shaped fins PCHE.

2. The numerical simulation of the adaptive flow path

2.1. Physical model

In order to verify the accuracy of the design idea of the adaptive flow path, the heat transfer and hydraulic performance were simulated and analyzed of two different flow path structures as shown in Fig. 3. The length and height of the flow path are 500 mm and 1 mm, respectively, and the inlet and outlet width of two kinds of flow path are