Paper ID APEN-MIT-2019_010
Applied Energy Symposium: MIT A+B
May 22-24, 2019 • Boston, USA

The heat transfer analysis of low temperature recuperator in supercritical CO_2 Brayton cycle

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Abstract—The vector analysis indicates that the heat recuperation depends not only on the values of heat transfer coefficient and temperature difference, but also on their coordination for the supercritical fluids. The splitting flow improves the coordination degree between temperature difference and heat transfer coefficient in low temperature recuperator, and increases the inlet temperature of heater and reduces the heat exhaust in the precooler, which leads to the performance improvement of supercritical CO_2 Brayton cycle. The present work is helpful to the system optimization and mechanism analysis of supercritical CO_2 Brayton cycle.

Keywords—supercritical CO_2, heat exchanger, Brayton cycle, coordination optimization, vector analysis.

I. INTRODUCTION

The supercritical CO_2 (S-CO_2) power cycle has very high efficiency and high compactness, which has competitive advantages at the mild turbine inlet temperature range (450–650) [1, 2]. The S-CO_2 power cycle become more and more attractive in recent years since its promising potentials in nuclear and solar energy, etc [3]. Recuperator is one of the most important components in S-CO_2 power cycles, whose performance has important influences on the efficiency and stable running of the cycles [4]. The heat transfer and fluid flow of S-CO_2 are very complex due to the drastic variation of thermophysical properties near the pseudo-critical point as shown in Fig. 1. The drastic variations of thermophysical properties occur simultaneously in both sides of recuperator, therefore, the studies on the coupled heat transfer in both sides are necessary for the design and optimization of recuperator [4].

The thermophysical properties of supercritical fluids change violently, which challenges the conventional recuperator design seriously. In the present work, the effect of recuperator on the performance of S-CO_2 Brayton cycle is discussed and analyzed, the heat transfer mechanism of recuperator is revisited from the viewpoint of coordination optimization.

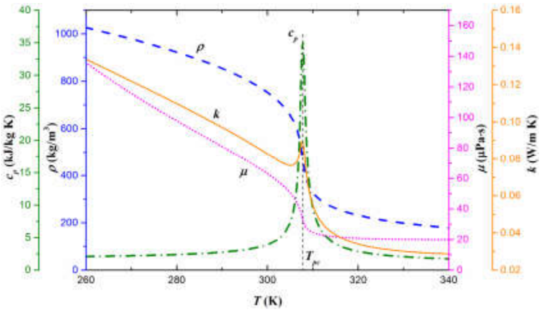


Fig. 1. The thermo-physical properties of CO_2 versus temperature at P=8 MPa.

II. THE THEORETICAL ANALYSIS

To accommodate the drastic variations of thermophysical properties, the segmental design is employed for S-CO_2 recuperator as shown in Fig. 2. The recuperator is uniformly divided into N sub-heat exchange units along the flow direction of hot fluid, so the heat transfer coefficient and temperature difference along the recuperator can be written in the form of vectors:

$$\mathbf{K_{tot}} = \left[K_{tot,1}, K_{tot,2}, \cdots, K_{tot,j}, \cdots K_{tot,N}\right] \quad (1)$$

$$\mathbf{\Delta T} = \left[\Delta t_1, \Delta t_2, \cdots, \Delta t_j, \cdots, \Delta t_N\right] \quad (2)$$

Since the heat transfer area is evenly distributed in recuperator, the total heat load can be written as follows:

$$Q_{tot} = \langle \mathbf{K_{tot}}, \mathbf{\Delta T} \rangle \cdot \frac{A_{tot}}{N} = K_{tot,1}\Delta t_1 \frac{A_{tot}}{N} + \cdots + K_{tot,j}\Delta t_j \frac{A_{tot}}{N} + \cdots K_{tot,N}\Delta t_N \frac{A_{tot}}{N} \quad (3)$$

where A represents heat transfer area, the angle brackets represent inner production of two vectors. According to Cauchy-Schwarz inequality, the term in angle brackets can be written as:

$$\langle \mathbf{K_{tot}}, \mathbf{\Delta T} \rangle \le \sqrt{\sum_{j=1}^{N} K_{tot,j}^2} \cdot \sqrt{\sum_{j=1}^{N} \Delta t_j^2} \quad (4)$$

Eq. (4) can be further written as:

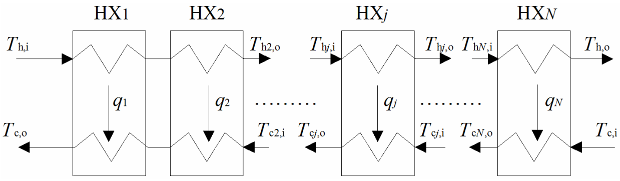


Fig. 2. The schematic diagram of sub-heat exchangers.

$$\cos\theta = \frac{\langle \mathbf{K_{tot}}, \mathbf{\Delta T} \rangle}{\sqrt{\sum_{j=1}^{N} K_{tot,j}^2} \cdot \sqrt{\sum_{j=1}^{N} \Delta t_j^2}} \le 1 \tag{5}$$

where θ is the coordination angle between the two vectors of $\mathbf{K_{tot}}$ and $\mathbf{\Delta T}$. Therefore, the total heat load in Eq. (3) can be written as:

$$Q_{tot} = \langle \mathbf{K_{tot}}, \mathbf{\Delta T} \rangle \cdot \frac{A_{tot}}{N} = \|\mathbf{K_{tot}}\| \cdot \|\mathbf{\Delta T}\| \cos\theta \cdot \frac{A_{tot}}{N} \tag{6}$$

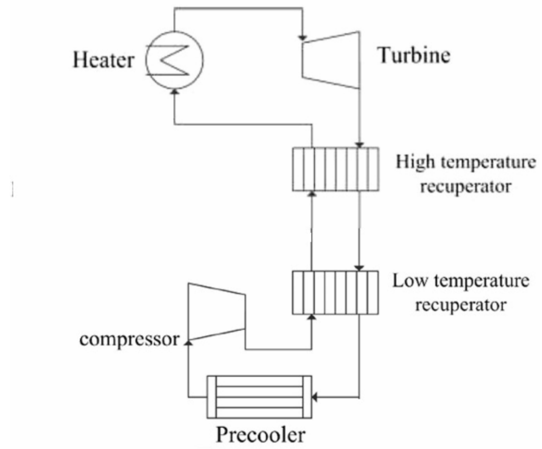
If and only if $\mathbf{K_{tot}} = c\mathbf{\Delta T}$ (c is constant), the equality holds in Eq. (4) and the coordination angle is zero. Eq. (6) demonstrates that the total heat load depends not only on the values of heat transfer coefficient and temperature difference, but also on the coordination of both vectors. The better the coordination degree between the heat transfer coefficient and temperature difference along the heat exchanger corresponds to the more total heat load when the other conditions remain the same. From Eq. (5), the coordination angle can be obtained as follows:

$$\theta = \arccos\left(\frac{\langle \mathbf{K_{tot}}, \mathbf{\Delta T} \rangle}{\sqrt{\sum_{j=1}^{N} K_{tot,j}^2} \cdot \sqrt{\sum_{j=1}^{N} \Delta t_j^2}} \right), \ 0 \le \theta \le \pi/2 \tag{7}$$

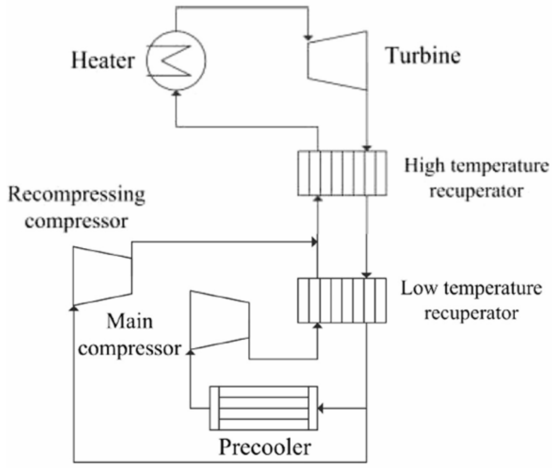
Obviously, the smaller coordination angle represents the better coordination degree between total heat transfer coefficient and temperature difference, and the more total heat load under the same other conditions. Therefore, the coordination angle can be used as an evaluation index to measure the coordination degree between the distributions of total heat transfer coefficient and temperature difference along the heat exchanger.

III. THE MECHANISM ANALYSIS FOR RECUPERATOR

Two types of supercritical CO_2 brayton cycle layouts are presented in Fig. 3. Compared with the simple cycle layout as shown in Fig. 3 (a), an additional compressor is added in the recompressing cycle to compress the splitting flow as shown in Fig. 3 (b). It is generally recognized that the recompressing cycle has the best performance among the numerous S-CO_2 Brayton cycle layouts. Fig. 4 demonstrates the relations of thermal efficiency with the splitting fraction for the recompressing cycle, and the initial data for the cycle is listed in Table 1. Clearly, the thermal efficiency increases firstly as the splitting fraction increases and then decreases, and the peak value of thermal efficiency appears at about splitting fraction=0.3. When the splitting fraction is zero, the recompressing cycle reduces to the simple cycle. From Fig. 3, one can see that the compression work is larger in the recompressing cycle than in the simple cycle, and the mass flow rate in cold side decreases as the splitting fraction increases. It is generally believed that the splitting flow is to compensate for the specific heat difference between both sides in low temperature recuperator, so the heat recuperation increases in the recompressing layout [5]. The heat transfer mechanism in the low temperature recuperator is discussed from the viewpoint of coordination optimization.



(a) Simple cycle layout



(b) Recompressing cycle layout

Fig. 3. Supercritical CO_2 Brayton cycle.

TABLE I. INITIAL DATA FOR THE CYCLE SYSTEM.

Parameters	values
Turbine inlet temperature, K	773.15
Turbine inlet pressure, MPa	20
Turbine outlet pressure, MPa	7.75
Mass flow rate, kg/s	0.001
Compressor inlet temperature, K	304.4
Compressor inlet pressure, MPa	7.4
Compressor outlet pressure, MPa	20.35
Turbine efficiency	0.92
Compressor efficiency	0.88
Total length of low temperature recuperator, m	1.2

The distributions of temperature difference and heat transfer coefficient along the heat exchanger are demonstrated in Fig. 5. Generally, the temperature difference increases as the splitting fraction increases, while the heat transfer coefficient decreases. When the splitting fraction is zero, the temperature difference decreases along the heat exchanger while the heat transfer coefficient increases, the both parameters have bad coordination. When the splitting fraction is 0.4, the temperature difference increases firstly and then decreases, and the heat transfer coefficient increases, the two parameters have good coordination in the most region of heat exchanger. The relations of coordination angle and the total heat transfer rate with the splitting fraction are demonstrated in Fig. 6. Fig. 5 presents the distributed law of the temperature difference and the heat transfer coefficient qualitatively, while Fig. 6 (a) further presents the quantitative distributed regularity of the two parameters. Clearly, the coordination angle decreases as the splitting fraction increases.

This indicates that the coordination degree between temperature difference and heat transfer coefficient improves as the splitting fraction increases within the ranges selected in the present work. This verifies the inference from Fig. 5. Fig. 6 (b) shows that the total heat transfer rate increases as the splitting fraction increases. Therefore, the total heat transfer rate of low temperature recuperator has direct relations with the coordination angle between the temperature difference and the heat transfer coefficient. From above analysis, we may come to the conclusions that the split flow in the recompressing cycle is to improve the coordination degree between the temperature difference and the heat transfer coefficient, and to improve the inlet temperature of heater and reduce the heat discharge in the precooler, which leads to the increase of thermal efficiency of recompressing cycle finally.

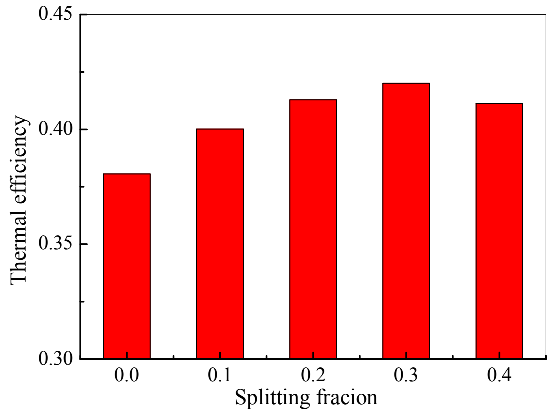


Fig. 4. The relations of thermal efficiency with the splitting fraction.

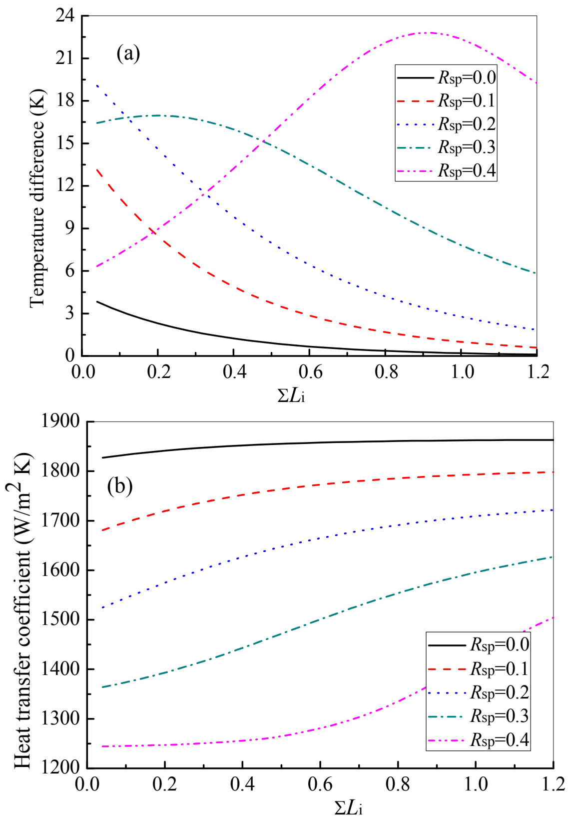


Fig. 5. The distributions of local parameters (a) local temperature difference, (b) local heat transfer coefficient.

IV. Conclusions

The splitting flow is beneficial to the performance improvement of supercritical CO_2 Brayton cycle, there exists an optimal splitting fraction for the maximum thermal efficiency. The vector analysis demonstrates that the heat duty does depends not only on the value of heat transfer coefficient and temperature difference, but also on their coordination, the decrease of coordination angle improves the heat duty at the same other conditions. The splitting flow improves the coordination degree between temperature difference and the heat transfer coefficient in the low temperature recuperator, and increases the inlet temperature of heater and reduces the heat exhaust in the preccoler, resulting in the improvement of thermal efficiency for the supercritical CO_2 Brayton cycle.

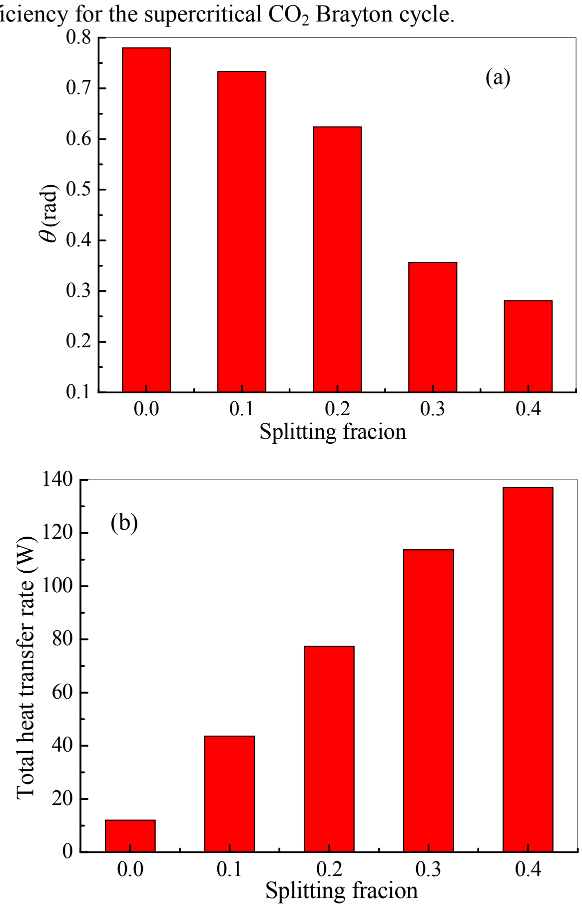


Fig. 6. The relations of (a) coordination angle and (b) total heat transfer rate with splitting fraction..

Acknowledgment

Our work is supported by the National key research and development program of China (2017YFB0601803), National Natural Science Foundation of China (51676185).

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